Systematic Design Methodology for Prognostic and Health Management Systems to Support Aircraft Predictive Maintenance

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Systematic Design Methodology for Prognostic and Health Management Systems

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for the purpose of obtaining the degree of doctor
at Delft University of Technology,
by the authority of the Rector Magnificus, prof. dr. ir. T. H. J. J. van der Hagen,
chair of the Board for Doctorates,
to be defended publicly on
Tuesday 29 September 2020 at 10:00 o'clock

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cultivate your virtues
seek for the truth
foucus on your study
restrain your actions

To my family

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Rui Li
Delft, February 2020

SUMMARY

With the rapid development in the past century, the air transport network has become one of the most important infrastructure networks for both the domestic and global economy. Within an airline, the maintenance area is responsible for planning and executing all preventive actions required to meet safety standards including maintenance tasks, etc. for each aircraft, demanding skilled jobs, e.g., aircraft mechanics, avionics systems experts, electricians, cabin experts. Aircraft maintenance concerns the maintenance, repair, and overhaul (MRO), inspection or modification to retain an aircraft and its aircraft systems, components and structures in an airworthy condition. A variety of strategies are available to guide determination, planning, and execution of appropriate maintenance actions for given capital assets. These include Condition-Based Maintenance (CBM), where the detection of an abnormal condition directly triggers a maintenance task, and predictive maintenance, where the optimal maintenance interval is predicted based on condition, time, usage or loads.

Prognostic Health Management (PHM) is a common method to ensure the safety, reliability, and maintainability of aircraft, including condition assessment, fault diagnosis, and remaining useful life prediction. Aircraft maintenance has been further developed to predictive maintenance instead of solely condition-based maintenance. The application of new technologies can promote cooperation among PHM, use real-time and historical state information of subsystems and components to provide actionable information, enabling intelligent decision-making. Therefore, PHM systems can reduce time and costs for the maintenance of products or processes through efficient and cost-effective diagnostic and prognostic activities. However, PHM is still an emerging field, and much of the published work has been either too exploratory or too limited in scope. Future smart maintenance systems will require PHM capabilities that overcome current challenges, while meeting future needs based on best practices, for implementation of diagnostics and prognostics. Particularly, the existing research lacked a methodology toward guidance for engineering a PHM system. There is no single design methodology formulating all methodological aspects comprehensively for engineering a PHM system to support aircraft maintenance.

The purpose of this dissertation is to develop a systematic design methodology toward the design of a PHM system in a comprehensive manner to support aircraft predictive maintenance. To progress from application-specific solutions towards structured, consistent and efficient PHM system implementations, the development and/or use of suitable methodology is essential. In this context, the field of Systems Engineering (SE) is chosen as the direction of inquiry, as SE is well-established and can provide high-level theoretical knowledge and guidance towards the development of a systematic design methodology for PHM. In the whole SE life-cycle, the principles consist of system design processes, product realization processes, and management processes. This dissertation focuses on system design processes for PHM systems, which are used to transi-

tion through design phases. Therefore, the expected outcome of this dissertation is a systematic design methodology formulating specific aspects in detail. According to the SE knowledge, our proposed design methodology consists of the primary tasks: Task 1: stakeholder expectations definition; Task 2: System requirements definition; Task 3: system architecture definition; Task 4: Design solution definition; Task 5: Implementation (limitation); and Task 6: Validation and verification.

This dissertation considers each task to be represented via a specific process. Firstly, it defines a stakeholder-oriented design methodology for PHM systems. Regarding stakeholder involvement and interest, different levels are identified in the methodology to lead towards more precise and better design information. The process comprehensively covers the characteristics of traceability, consistency, and reusability to capture and define stakeholders and their expectations to aid in the design of PHM systems. Secondly, this thesis proposes a methodology of requirements definition for the PHM system in detail; and it considers requirements validation and requirements flow-down from stakeholders' expectations to system requirements, and further flow-down to lower level consensus. Such a step-by-step process can guide the requirements specification of a generic PHM system. Such a generic PHM system can be used in tandem to validate the requirements specification step of the methodology. Subsequently, we develop a methodological contribution for PHM architecture (etc.). Similarly, we also apply it to the architecture definition of a generic PHM system. Further, such generic architecture is validated and verified in case studies, to demonstrate the reasonability of steps and applicability of the methodology. Finally, this dissertation proposes a novel practical framework for data-driven prognostic approaches. This practical framework can enhance a comprehensive understanding of prognostics and provides a practical framework to identify data-driven prognostic approaches for subsequent implementation and RUL prediction. Besides, we perform comparative case studies between statistical approaches and machine learning approaches to examine the correctness and applicability of the proposed framework.

In summary, the established methodology incorporates various aspects/tasks with descriptions and interpretations. It has sufficient detail to ensure that: 1) the concepts and terminology used are well-defined, without being open to multiple competing interpretations; 2) it covers all essential steps in developing a PHM system; 3) researchers and practitioners alike can apply the methodology in a straightforward fashion.

The main novelty of the dissertation is to develop a systematic design methodology toward the design of a PHM system in a comprehensive manner for the implementation of aircraft predictive maintenance. Synthesizing those aspects/tasks, the definition of the PHM system is an iterative process that takes into consideration the maturity and trade-offs of traceability, consistency, and reusability design content (e.g. requirements, architectures, design solutions), to ensure the compliance with stakeholders' expectations/needs. The application of the methodology can provide effort to develop a prognostic system, ensure that all the possible design options have been considered, and provide a means to compare different prognostic algorithms consistently. These advantages are explored and supported by the case studies conducted during the research. Therefore, the designers/engineers can perform development and design activities under the proposed methodology as guidance to design and engineering a PHM system. A successful engineered PHM system provides solutions to the airline operators and MROs,

who can prognoses the health condition and predict the remaining useful life (RUL) of critical system/comments. Besides, predictive maintenance via PHM systems can potentially optimize maintenance operations and reduce aircraft maintenance costs.

This dissertation provides significant contributions, yet there still are challenges related to the gap between theory and practice. On one hand, prognostic algorithm selection is a key activity to achieve consistency throughout the design process. In practice, it is difficult to determine the prognostics algorithms through a cause-effect flowchart as this requires a thorough understanding of the underlying data and/or physical processes to counter different sources of uncertainty that affect prognostics. Future research should provide efforts to define a more complete decision framework for design solutions (e.g., the selection of prognostics or diagnostics) based on analysis of failure modes and safety analysis and requirements. On the other hand, a major remaining challenge concerns validation and verification. In academics, it is difficult to perform verification activities on a completely realistic PHM system due to the constraints of engineering; mostly, simulation or laboratory environments are used for research purposes instead of real-life operations. More efforts are required in developing and engineering PHM systems and related functionalities, such as the approach selection, health management, performance evaluation, uncertainty treatment, application economics, as well as environmental issues, to build the best practices. Despite these limitations, this dissertation successfully explores a unique opportunity to advance the field of PHM systems and predictive maintenance for airline maintenance.

NOMENCLATURE

ACARS	Aircraft Communications and Reporting System
ADEPS	Assisted Design for Engineering Prognostic System
AG	Advisory Generation
ANN	Arthitecture Neural Network
BDD	Block Definition Diagram
C-MAPPS	Commercial-Modular Aero-Propulsion System Simulation
CBM	Condition-based Maintenance
CNN	Convolution Neural Network
ConOps	Concept of Operations
COTS	Commercial off-the-shelf
CSC	China Scholarship Council
DA	Data Acquisition
DCA	Diagnostic Assessment
DM	Data Manipulation
DNN	Deep Neural Network
DP	Data Processing
E&M	Engineering and Maintenance
EA	Enterprise Architecture
EC	European Commission
FA	Functional Analysis
FDA	Fault Diagnostic Assessment
FDM	Flight Data Management
FFBD	Functional Flow Block Diagram
FFT	Fast-Fourier Transforms

FHA Functional Hazard Assessment

FOQA Flight Operations Quality Assurance

FTA Fault Tree Analysis

Gen-PHM Generic Prognostic and Health Management

HA Health Assessment

HI Health Indicator

HM Health Management

IBD Internal Block Diagram

IFHM Integrated Fleet Health Management

IVHM Integrated Vehicle Health Management

KPI Key Performance Indicators

LSTM Long Short-term Memory

ML Machine Learning

MRO Maintenance, Repair, and Overhaul

MSE Mean Squared Error

NASA National Aeronautics and Space Administration

NASA National Aeronautics and Space Administration

OAMs Original Aircraft Manufacturers

OEMs Original Equipment Manufacturers

OMS Onboard Maintenance System

OSA-CBM Open System Architecture for Condition-Based Maintenance

PA Prognostic Assessment

PCA Principal Component Analysis

PHM Prognostic and Health Management

PSS Product-Service System

RE Requirements Engineering

ReMAP Real-time Condition-based Maintenance for Adaptive Aircraft Maintenance Planning

RFLP Requirements, Functional, Logical and Physical architectures

RISDM Requirements Inspection Systems Design Methodology

RNN Recurrent Neural Network

RSE Root Squared Error

RUL Remaining Useful Life

RVM Relevance Vector Machine

SD State Detection

SE System Engineering

SoS System of Systems

SRMT Safety, Reliability, Maintainability, Test

SVM Support Vector Machine

SysML Systems Modeling Language

TRA Sea-level Temperature

TRL Technology Readiness Level

V&V Validation and Verification

CONTENTS

1

INTRODUCTION

1.1. RESEARCH CONTEXT

Air transport fulfills an essential part of today's global market. The world of civil aviation has a significant impact on the world economy. It plays a vital role in fostering trade and making the world quickly accessible and connected. The airline industry has experienced profound changes in the last decades due to deregulation, resulting in intense competition among carriers [1]. To enable safe and economically viable air transport, proper aircraft maintenance is crucial. The airline operator is responsible for continued aircraft airworthiness to ensure full efficiency and guarantee all safety requirements. Costs associated with maintenance can contribute significantly to an airline's expenditure; historical estimates for maintenance costs range between 10–15% of the overall expenditure incurred by airlines [2]. The cost of aircraft maintenance represents the third largest expense item after labor and fuel costs for both regional and national airlines [3]. A global fleet market forecast commentary reports that the aerospace industry spent around $82 billion for Maintenance Repair and Overhaul (MRO) of commercial aircraft in 2019 and this is expected to go up to $116 billion by 2029 [1]. Thus, aircraft maintenance plays a critical role in airline operations for achieving cost savings and competitive advantage while preserving airline availability.

Aircraft maintenance consists of maintenance, repair, overhaul, inspection, and modification to retain an aircraft and the related aircraft systems and components, as well as structures in an airworthy condition [4]. The aircraft operators aim to retain or restore the reliability and safety levels of an aircraft at a minimum cost, while the purpose of an independent MRO is to achieve high service levels and to maximize profits. Regarding saving cost, a useful way is to move towards scheduled maintenance instead of unscheduled maintenance, enabling the optimization of the allocation of spare parts, and the assignment of manpower and maintenance tasks [5]. Yet, the fact is that unscheduled maintenance still accounts for roughly 50% of overall maintenance effort, as maintenance events and associated required maintenance interventions are hard to predict.

Condition-based maintenance (CBM) is a method to resolve such problems, through the use of historical data or run-time data to determine the machinery operating con-

1

dition, and hence, its current fault/failure condition, which supports the scheduling of the repair and maintenance actions before breakdown [6]. Predictive maintenance techniques are designed to help determine the condition of in-service equipment to estimate when maintenance should be performed. Thus, it is regarded as condition-based maintenance carried out as suggested by estimations of the degradation state. Prognostics, as the prediction of events related to the condition of engineering systems is known, can support the practice of predictive maintenance with advanced fault detection capabilities as well as technologies for the prediction of useful lifetimes [7]. Recently, the novel concept of prognostic and health management (PHM) is used as an engineering system integrating the fundamentals of diagnostics, prognostics and health management. The relevance of these terms used in this dissertation is identified in Figure 1.1.

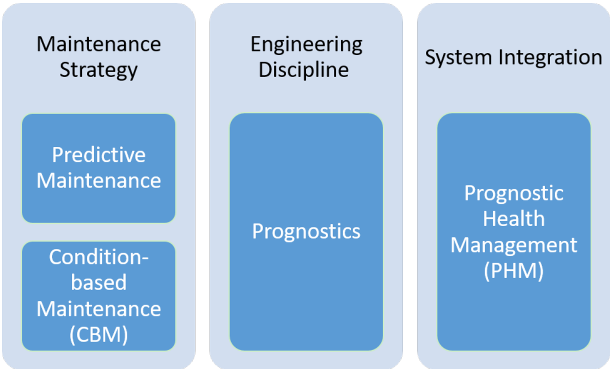

Figure 1.1: Relevance of terms

Prognostic and health management (PHM) is a common method to ensure the safety, reliability, and maintainability of aircraft, including condition assessment, fault diagnosis, and remaining useful life (RUL) prediction [8]. Hence, the application of new technologies can promote the combination of PHM, maintenance systems, and support systems to improve the efficiency of maintenance support and save maintenance costs [9]. A PHM system mainly consists of the capability of diagnostics, prognostics and health management. The diagnostics concern the process of determining the state of a component to perform its functions, with a high degree of fault detection and fault isolation capability with very low alarm rate. Moving up in complexity, the term prognostics refers to the actual material condition assessment which includes predicting and determining the useful life and RUL of systems/components. Specifically, prognostics can enable the reduction of the lead time for procurement and planning within maintenance. It relies on its capacity to anticipate the evolution of anomalous conditions in time [10]. Finally, the process of health management involves informed, appropriate decisions about maintenance and logistics actions based on diagnostics/prognostics information [11]. Summarizing, prognostics aims to predict the future status of a system, whereas the process of health management uses the information generated as advisory to instigate actions to return the system to a healthy state. With the growing requirements of high reliability of modern engineered systems, PHM receives increasing attention from academia and industry communities [12].

1.2. RESEARCH QUESTIONS

A substantial amount of research has been performed concerning PHM via accurate health prediction and efficient maintenance decisions, to improve the effective operation for critical complex systems [13–15]. Pecht and Jaai [16] provide a comprehensive investigation of PHM applied in the electronics area. Xia et al. [17] address recent advances in PHM for manufacturing paradigms to forecast health trends, avoid production breakdowns, reduce maintenance costs and achieve rapid decision-making. Discussing aircraft engines in particular, Than et al. [18] provide a literature review of recently developed engine performance monitoring, diagnostics and prognostics techniques to enhance the maintenance decision-making scheme. The main causes of gas turbine performance deterioration are discussed as well .

With rapid development, the relevant PHM techniques, methods, and applications are leading to the perception of its field as an engineering discipline based on in situ monitoring and advanced methods for assessing degradation trends of a system [10]. The study of prognostics degradation modeling focuses on how to utilize degradation signals/data to predict the RULs in a fixed operation environment. For practitioners, how to design a PHM system and implement related technologies is interrelated to the capabilities and knowledge about prognostics algorithms, tools, etc. [19]. A systematic methodology to design and implement PHM in a complex system is crucial to achieving the goal of high reliability and low maintenance cost.

From an engineering perspective, a series of studies has investigated the key factors of design methodologies for PHM system development. For example, Lee et al.[20] present a comprehensive review of PHM design methodology, covering systematic design and implementation, critical component identification, tool selection method, and presenting some brief industrial case studies. Lee et al. also identify that an effective and efficient design methodology regards the terms of design objectives and design solution determination, and is to be applied at each consecutive design step, which guides designers when performing a specific project. Saxena et al. [21] present elements incorporated into a framework for functional PHM system development, and connect this with user requirements. The authors conducted a literature review to enhance the knowledge about the state of the art in PHM and discuss the associated challenges. In parallel, a series of research studies have investigated the application of SE towards system design [22–26]. To illustrate, Saxena et al. [27] define a systems engineering view towards the requirements specification process and present a method for the flow-down process. However, the authors do not state the process or steps to develop the requirements and flow-down to lower levels. Dumargue et al. [23] express a simple system engineering methodology, considering the common constraints, components, and stakeholders in PHM design for turbofan engines and such projects, to support in engineering .

The state of the art of design methodology has achieved major contributions in the field of PHM. However, the research regarding design methodology is not sufficient for engineering a PHM system, especially for methodological elements, such as stakeholders, requirements, architecture, algorithms, etc. In summary, this research is motivated by the following shortcomings in the state of the art: 1) Existing research lacks the formulation of a systematic and comprehensive methodology; existing efforts do not cover all aspects of designing and engineering a PHM system. The process of defining stakeholders and capturing their expectations and requirements is lacking specifics, being highly conceptual and not having sufficient focus on aspects of traceability, consistency, and reusability. 2) Existing methodological approaches towards requirements definition for PHM systems lack the specifics and in-depth detail for PHM design, especially the description of practicable steps in a systematic manner. 3) A systematic methodology towards a consistent definition of PHM architectures has not been well established. The characteristics of architectures have not been dealt with in-depth. 4) The proposition of advanced techniques for prognostics (such as statistical or machine learning techniques) leads to challenges in the practical uptake of prognostics, as interpretability of and prior experience with these techniques is often lacking. As such, it is difficult to make a prior determination of specific methods to construct an accurate prediction in practical applications.

These research inadequacies motivate the core research question of this thesis:

- **How can a systematic and comprehensive design methodology for PHM systems be developed in the context of aircraft predictive maintenance?**

1.3. Research Methodology

This research question helps formulate the research goal with both specific and generic considerations in this work, providing associated focus and direction. As a result, the core research goal is extracted as:

To develop a systematic design methodology toward the design of a PHM system in a comprehensive manner to support aircraft predictive maintenance.

To progress from application-specific solutions towards structured, consistent and efficient PHM system implementations, the development and/or use of suitable methodology is essential [28]. Such a systematic design methodology should address the following high-level requirements: 1) it should be unambiguous, i.e., the concepts and terminology used should be defined well, without being open to multiple competing interpretations; 2) it should be comprehensive, i.e., it should cover all essential steps in developing a PHM system; 3) it should be pragmatic, i.e., researchers and practitioners alike should be able to apply the methodology in a straight forward fashion.

For these purposes, the theoretical principles of System Engineering (SE) and Product-Service System (PSS) are applied to build the design methodology along different axes. Specifically, SE is an interdisciplinary field of engineering and engineering management that concentrates on how to design and manage complex systems over their life cycles. It emphasizes defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation [29]. Thus, the design of PHM systems can make the use of SE principles to ensure a more robust and efficient design. On the other axis, a PSS is an integrated combination of products and services. This concept embraces a service-led competitive strategy, environmental sustainability, and the basis to differentiate from competitors who simply offer lower-priced products [30]. Establishing design methodologies for a PSS has become a much-discussed endeavor that enables such a manufacturer to generate a valuable new PSS or improve the possibility of a PSS systematically [31]. As an example of a PSS system, the relevant knowledge provides empirical knowledge and reference content for PHM design methodology.

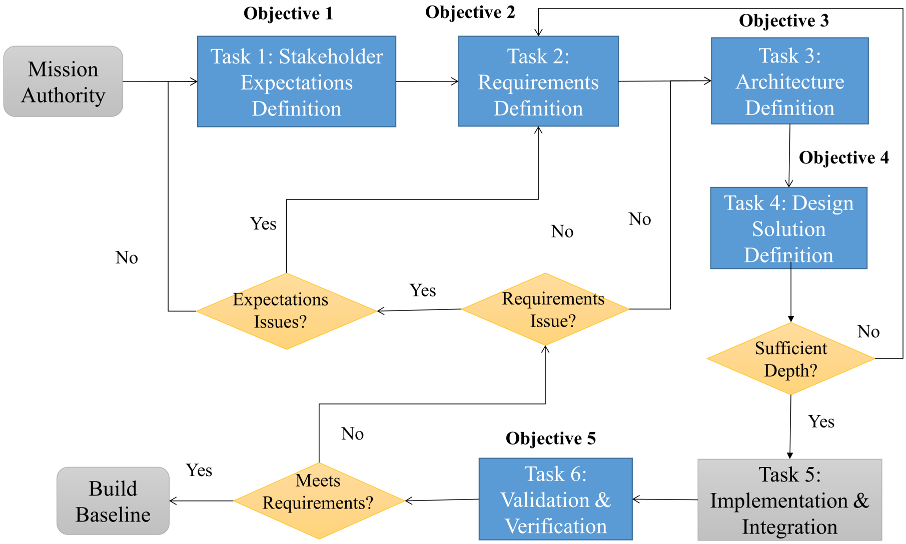

Figure 1.2: Research methodology

This dissertation proposes a systematic design methodology for engineering PHM systems, contributing to a consistent and re-useable representation of the design, as shown in Figure 1.2. This methodology regards the identification and selection of (a) suitable prognostics technique(s) according to the stakeholder requirements, in addition to traceability between design requirements and architecture, as well as validation and verification (V&V) considerations for system development. Besides, it formulates a methodological approach towards requirements definition and flow-down based on function hierarchy. Meanwhile, it concerns the process of system architecture definition with details in sub-systems, components and, interfaces between the elements inside and outside the system boundary for a PHM system. In practice, the decision gates in this methodology provide a means of exploiting an iterative design loop, ensuring the quality of development. When an issue occurs, it allows checking the roots and feedback to the previous process for iterative design and configuration. The depth of the design effort should be sufficient to allow analytical V&V of the design requirements. The design should be feasible and credible when judged by a knowledgeable independent reviewer. As present in Figure 1.2, the systematic methodology incorporates the primary tasks, including Task 1: stakeholder expectations definition; Task 2: System requirements definition; Task 3: system architecture definition; Task 4: Design solution definition; Task 5: Implementation (limitation); and Task 6: Validation and verification.

To achieve the research goal, this dissertation will accomplish the following sub-objectives respectively:

1). To develop a systematic and comprehensive methodology for the PHM system, and emphasize a method of stakeholders' expectation definition (Ref to Task 1).

2). To develop a requirement definition methodology that describes the practicable steps in detail (Ref to Task 2).

3). To propose a methodology for PHM architecture definition that can guide the design of the architecture (Ref to Task 3).

4). To present a practical framework for data-driven prognostics approaches that can support the practices of prognostics (Ref to Task 4).

5). To address the validation and verification activities that can ensure the design quality (Ref to Task 6).

1.4. OVERVIEW OF DISSERTATION

This dissertation significantly advances the current design and practice in the field of PHM systems. A systematic design methodology, covering all special items (stakeholders, requirements, architectures, etc.), is set up in detail to address the gaps for developing and engineering PHM systems. To this aim, Figure 1.3 illustrates a schematic layout of this dissertation, consisting of six chapters. The main body of the thesis is based on the author's peer-reviewed journal/conference papers. In each chapter, there is an introductory paragraph that places the chapter into the context of the full thesis. This thesis is organized into the main content sections (i.e., Chapter 2 to Chapter 5), relating to each respective research objective, alongside the introduction (Figure 1.3) and conclusion (Chapter 6).

Following the introduction, Chapter 2 proposes a stakeholder-oriented design methodology for developing a PHM system. Moreover, it emphasizes the detailed definition of stakeholder expectations. Subsequently, regarding the development of a system, a systematic methodology is proposed in Chapter 3, as guidance toward requirements definition for the PHM system. Further, Chapter 4 develops a systematic methodology for PHM architecture definition to ensure a more complete and consistent design during the development phase of the product lifecycle. As a specific case of a design solution, Chapter 5 introduces a generic data-driven prognostics process with five technical steps, and also correspondingly presents a practical framework for data-driven prognostics. Finally, Chapter 6 presents the contributions of the dissertation, conclusions, and recommendations for future work.

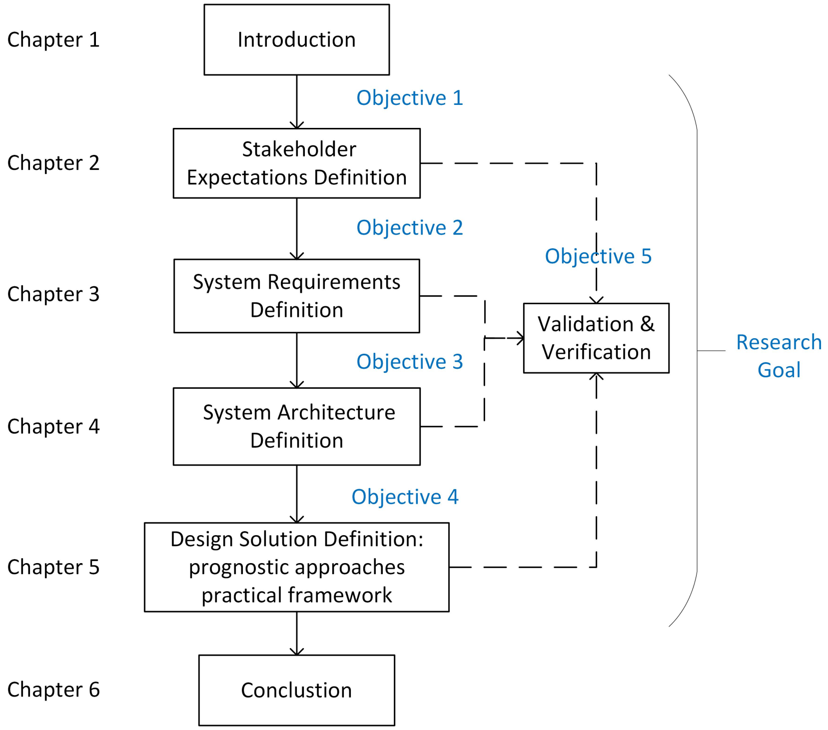

Figure 1.3: Overview of dissertation

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2

DESIGN METHODOLOGY OF STAKEHOLDER EXPECTATION DEFINITION

This chapter develops a systematic and comprehensive methodology for the PHM system, emphasizing the method of stakeholders' expectation definition. The state of the art lacks a stakeholder-oriented methodology with the formulation of all facets of designing and engineering a PHM system. Existing efforts do not cover detailed descriptions of how to capture stakeholders' expectations. This chapter proposes a stakeholder-oriented design methodology for developing a PHM system. Furthermore, it highlights the method of how to identify and define stakeholders' expectations. Considerations regarding stakeholder involvement and interest levels are identified in the methodology to lead towards more precise and better design information. Through V&V activities, this chapter comprehensively covers the aspects of traceability, consistency, and reusability to capture and define stakeholders and their expectations to aid in the design of PHM systems. Hence, the output of this chapter covers the methodology for stakeholders' expectations definition, as well as an applicable case study, to address the gaps in existing research.

This chapter is based on following article:

Li, R., Verhagen, W. J., & Curran, R. (2020). Stakeholder-oriented systematic design methodology for prognostic and health management system: Stakeholder expectation definition. Advanced Engineering Informatics, 43, 101041.

Prognostic and health management (PHM) describes a set of capabilities that enable to detect anomalies, diagnose faults and predict remaining useful lifetime (RUL), leading to the effective and efficient maintenance and operation of assets such as aircraft. Prior research has considered the methodological factors of PHM system design, but typically, only one or a few aspects are addressed. For example, several studies address system engineering (SE) principles for application towards PHM design methodology, and a concept of requirements from a theoretical standpoint, while other papers present requirement specification and flow-down approaches for PHM systems. However, the state of the art lacks a systematic methodology that formulates all aspects of designing and comprehensively engineering a PHM system. Meanwhile, the process and specific implementation of capturing stakeholders' expectations and requirements are usually lacking details. To overcome these drawbacks, this paper proposes a stakeholder-oriented design methodology for developing a PHM system from a systems engineering perspective, contributing to a consistent and reusable representation of the design. Further, it emphasizes the process and deployment of stakeholder expectations definition in detail, involving the steps of identifying stakeholders, capture their expectations/requirements, and stakeholder and requirement analysis. Two case studies illustrate the applicability of the proposed methodology. The proposed stakeholder-oriented design methodology enables the integration of the bespoke main tasks to design a PHM system, in which sufficient stakeholder involvement and consideration of their interests can lead to more precise and better design information. Moreover, the methodology comprehensively covers the aspects of traceability, consistency, and reusability to capture and define stakeholders and their expectations for a successful design.

2.1. INTRODUCTION

Costs associated with aircraft maintenance can contribute significantly to an airline's expenditure; historical estimates for maintenance cost range between 10–15% of the overall expenditure incurred by airlines [1]. To reduce the cost of aircraft maintenance, an advantageous way is to predict unscheduled maintenance such that it can be 'converted' into scheduled maintenance, such that allocation of spare parts, assignment of manpower, and management of maintenance tasks can be optimized [2]. In this sense, condition-based maintenance (CBM) is an approach with considerable potential to deal with this problem, as it employs machinery run-time data or historical data to determine the machinery condition, and hence, its current fault/failure condition, which can be used to schedule required maintenance prior to breakdown [3, 4].

Prognostic and health management (PHM) constitutes a key element within CBM. PHM covers, amongst other things, the development of algorithms to detect anomalies, diagnose faults and predict remaining useful lifetime (RUL). CBM applications can be seen as instances of a product-service system, as the latter can be defined as a "market proposition that extends the traditional functionality of a product by incorporating additional services" [5]. In the case of CBM and PHM, capabilities are built-in at the product design phase to enable key service functionalities in the operational and support lifecycle stages to enable a more efficient and economic asset utilization, for example through the diagnostic and predictive capabilities mentioned above. The rapid developments in PHM research, including methods, techniques, and applications have led to the perception of PHM as a dedicated engineering discipline based on the use of in-situ monitoring and advanced methods for assessing degradation trends of a system and determining the RUL [6].

From a manufacturing perspective, the Product-Service System (PSS) has been established as a prominent business model that promises sustainability for both customers and organizations [7]. The smart PSS is endowed with unique features including connectivity, integration, autonomy, and digitalization, and has shown its uniqueness in its solution design process [8]. The success of Smart PSS relies much on the quality of product-service bundles that to what extent the system satisfies the users' requirements [9]. As an example of a PSS system, the design of the PHM system also needs to focus on the satisfaction of users' requirements. Therefore, a significant amount of research primarily focuses on PHM technical facets, such as the development of diagnostic and/or prognostic techniques, with the aim to underpin CBM [10, 11]. In parallel, several studies have investigated PHM design methodologies and associated transversal methodological factors (e.g. requirements, techniques, tools) [12–14]. Those two worlds do cross sometimes to put systems design into perspective and to provide methodological considerations concerning characteristics and design throughout the development phase. Existing literature provides several contributions regarding conceptual design methodologies for PHM systems. However, the aforementioned methodologies lack detail in several key facets, which drive the research questions as follows:

a) What is a stakeholder-oriented methodology, which formulates all aspects of designing and engineering a PHM system in a comprehensive manner?

b) What is the process of capturing and defining stakeholders and their expectations, being highly conceptual and having an insufficient focus on aspects of traceability, consistency, and reusability?

This constitutes the major research questions and hurdles towards the successful implementation of prognostics systems in industrial practice. To overcome them, this chapter defines a stakeholder-oriented systematic design methodology for PHM systems. A detailed description of stakeholders' expectations and requirements elicitation is given, which covers a sequence of specific technical steps. A case study identifies and defines the stakeholders and their expectation for PHM system design through SysML modeling. This case study validates the process of identifying and capture stakeholder expectations, performed with respect to traceability, consistency, and reusability. Besides, an application-oriented case study of stakeholders' expectations is delineated, involving ongoing research applications within a major European research project on real-time condition-based maintenance for adaptive aircraft maintenance planning (ReMAP).

The structure of the chapter is as follows. Section 2.2 addresses the state of the art of design methodology and systems engineering applications in PHM. In Section 2.3, the principles and concepts of the proposed systematic design methodology are introduced. Two case studies are undertaken to indicate the applicability of the proposed stakeholders' expectation definition (in Section 2.4 and Section 2.5 respectively). Finally, Section 2.6 gives conclusions regarding the main contributions of this work and outlines several opportunities for further research.

2

2.2. STATE OF THE ART

This section summarizes the state of the art of PHM systems and associated technologies and methodologies necessary for system development. Existing research can be expressed by considering various perspectives:

a). **Design Methodology**

A series of studies has investigated the key factors of design methodologies for PHM system development. For example, Lee et al. [15][15] present a comprehensive review of PHM design methodology, covering systematic design and implementation, critical component identification, tool selection method, and presenting some brief industrial case studies. Aizpura et al. [16, 17] formalize a novel design methodology entitled assisted design for engineering prognostic systems (ADEPS), including synthesis of a safety assessment model, prioritization of failure modes, systematic prognostics model selection and verification of the adequacy of the results of the prognostics for requirements. Yet, the research only focuses on an approach for the selection and application of prognostics approaches. That is a part of the design, but itself does not constitute a methodology for a systematic design. While, Saito et al. [18]] introduce a requirements inspection systems design methodology (RISDM), incorporating a meta-model and design process, pragmatic quality model, and a technique to generate inspection question set. Lemazurier et al. [19] define a tooled method with the different design perspectives: requirement view, a context view, and a behavioral view, toward the designers to express requirements, structure their architecture design. However, the importance and role of stakeholders in requirements and specifications are not fully premeditated.

b). **Methodological aspects**

A multitude of research has investigated the application of SE towards system design [20, 21]. As an example, Jennions et al. [22] propose an integrated vehicle health management (IVHM) design methodology with respect to integration and asset design. Furthermore, some articles address the general depiction of stakeholders and their expectations, whereas several authors discuss requirements specification and flow-down for prognostic systems. Saxena et al. [23] define a systems engineering view towards the requirements specification process and present a method for the flow-down process. However, the authors do not state the process or steps to develop the requirements and flow-down to lower levels. In practice, Mao et al. [24] address that modeling is a helpful visualization method to understand the PHM system, and has been used to present the operation conditions, relevance, and completeness. Yet, this research only discusses a PHM framework based on system modeling language without addressing the methodological principles. Likewise, Kuhn et al. [25] express the concept and needs of model-based specifications to specify the basic behavior of aircraft systems, and methods to check requirements. That work addresses the principles of SE from a theoretical standpoint but lacks detailed description and methodological practice.

c). **Considerations of stakeholders**

A successful system design should meet the stakeholders' requirements. Hence, capturing stakeholders and their expectations is one methodological factor to address in PHM system design [26–28]. Dumargue et al. [29] express the common constraints, components and stakeholders in the design of a PHM system for turbofan engines and pose that such projects, therefore, need to apply the systems engineering methodology to be successful. Nastov et al. [30] propose a tool-equipped method for combination and implementation of all validation and verification (V&V) strategies to provide stakeholders with a high level of confidence in decision-making.

Despite some available methodological prescripts, only a few studies mention the role of stakeholders in design methodology, whereas literature on identifying stakeholders and their expectations is even more limited. In other words, the method(s) for capturing stakeholders and extracting their requirements in detail to drive system design is rarely addressed. Summarizing, the drawbacks of the state of art are:

- A stakeholder-oriented methodology that formulates all facets of designing and engineering a PHM system in a comprehensive manner, is lacking in the literature.
- The process of defining stakeholders and capturing their expectations and requirements is usually lacking detail, being highly conceptual and not having sufficient focus on aspects of traceability, consistency and reusability.

2.3. SYSTEM DESIGN METHODOLOGY

To address the research question a), this section provides a fundamental introduction of this methodology with all development phases. Further, it concentrates on the detailed description of Task 1 (stakeholder expectations definition), given that the stakeholders and their expectations play a critical role in this stakeholder-oriented design methodology. Particularly, The following novel facets are addressed:

- Proposing a systematic design methodology of the whole PHM life-cycle in Subsection 2.3.1 and
- Combining the principles of SE into a consistent PHM design methodology;
- Providing a detailed description of stakeholder definition and requirements elicitation for PHM system in Subsection 2.3.2.

2.3.1. METHODOLOGY OVERVIEW

A mature design methodology ensures the consensus of interdisciplinary cooperation and interaction among the independent parts. Therefore, this paper firstly proposes a stakeholder-oriented design methodology, consisting of the manipulation of basic design concepts, recognizing and analyzing aspects of the system such as functional entities, actions, and interactions. It regards the identification and selection of (a) suitable prognostic technique(s) according to the stakeholder requirements, in addition to traceability between design requirements and architecture, and V&V considerations. To ensure sustainable development, the traceability between high-level stakeholders requirements for mission planning and execution to performance specifications for prognostics capabilities at the lower technical level is addressed in detail [31]. This methodology incorporates the primary tasks, as shown in Figure 2.1, including: Task 1: Stakeholder expectations definition; Task 2: System requirements definition; Task 3: System architecture definition; Task 4: Design solution definition; Task 5: Implementation; and Task 6: Validation and Verification.

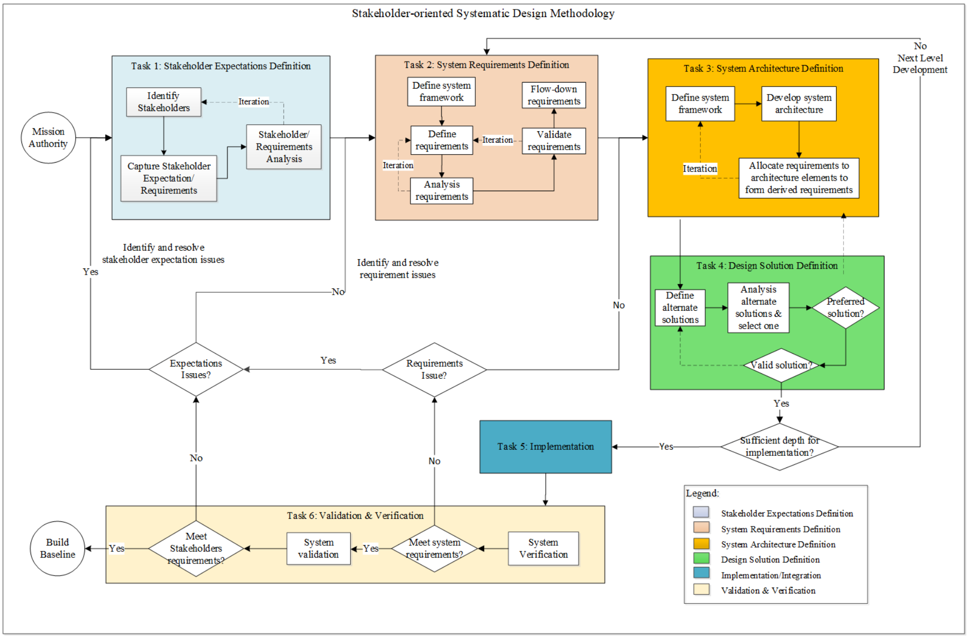

Figure 2.1: Stakeholder-oriented systematic design methodology

The tasks (task 2- task 4) should be consistent with each other and require iterations and design decisions for improvement [32]. Once the consistency is achieved, it is necessary to check whether the design has attained "sufficient depth for implementation" or not. Sufficient depth means that the design maturity allows for the implementation of the desired end products and enabling products, including developing a new product, buying an existing product, or reusing an existing product [21]. When the implementation is completed, the end product/system should be validated and verified against the requirements and stakeholders' expectations. At last, it is necessary to build a major baseline when completing a design loop. Alternatively, it is still possible to build some minor baselines during the design life-cycle. For example, the engineers can build a minor baseline before the validation and verification activities to provide a basis for measurement. Under these circumstances, it demonstrates that the success of the PHM design is on the basis of stakeholders' expectations achievement and satisfaction.

This methodology provides several iterative loops and reactions among each task, as shown in Figure 2.1. The application of iteration and recursion to the life cycle processes with the appropriate feedback loops supports communication that accounts for ongoing learning and decisions [33]. As a result, a specific and iterative set of steps that engineers use to evaluate and refine potential solutions to problems or challenges in practice is covered. For example, iteration provides the solution to accommodate stakeholder decisions and evolving understanding, accounting for architectural constraints. If there are any issues, the iteration and recursion loops provide pathways to solve these issues, ensuring design quality and consistency.

2.3.2. TASK 1: STAKEHOLDER EXPECTATIONS DEFINITION

To resolve the research question b), a detailed description of the first task (Task 1: stakeholder expectations definition) is given in this subsection. The stakeholder expectation definition task outlines the steps of stakeholder identification, capturing stakeholder expectations/requirements, as well as the analysis to externalize the system capabilities and operation services.

TASK 1.1: IDENTIFY STAKEHOLDERS

A stakeholder is a group or individuals who are affected by or are in some way accountable for the outcome of a specific undertaking. Stakeholders can be classified as customers and other interested parties. Some examples of major stakeholders are the roles of creditors, directors, employees, government, owners, suppliers, unions, and the community from which the business draws its resources [34]. Customers are those who will receive the products or services and are the direct beneficiaries of the project. Other interested parties are those who affect the project by providing broad, overarching constraints within which the customers' needs must be achieved [26].

When nominating stakeholders, business management will take into account all those who may be affected by or able to influence the system. Typically, they would take into account users, operators, organization decision makers, parties to an agreement, regulatory bodies, developing agencies, support organizations and society at large [34]. In general, the output is a representative and persuasive list of stakeholders with the assumptions and constraints of a specific project.

TASK 1.2: CAPTURE STAKEHOLDER EXPECTATION/REQUIREMENTS

Subsequently, the methodology takes into account stakeholders expectations. These comprise the vision of a particular stakeholder, while specifying what is desired as an end state or as an item to be produced and putting bounds upon the achievement of the goals [28]. Different stakeholders may have various expectations of the products/system since they have different interests or constraints in a specific project. The stakeholders' expectations generally include the following [31]:

- operational concepts, scenarios, use cases;
- end products and enabling products;
- factors such as safety, quality, security, reliability, availability, maintainability, electromagnetic compatibility, interoperability, testability, transportability, supportability, usability, and applicability;
- technical authority, standards, regulations, and laws;
- expected skills and capabilities of operators or users;
- expected number of simultaneous users;

- System and human performance criteria.

When the stakeholders' expectations are captured, it is necessary to transform them into requirements. Stakeholder requirements are the specification of health, safety, security, environment, assurance, and functions that relate to critical qualities, as well as the statement of the requirements consistent with scenarios, interactions, and constraints [20]. A system requirement is a statement that identifies a system, product, or process characteristic or constraint, which is unambiguous, clear, unique, consistent, stand-alone, and verifiable, and is deemed necessary for stakeholder acceptability [20]. In other words, the stakeholder requirement is a problem-oriented statement, e.g. "The aircraft shall communicate with the air traffic center." On the other hand, the system requirement is a solution-oriented statement, e.g. the following (incomplete) requirement: "The aircraft shall provide a redundant radio communication system."

Ryan et al. [35] present "expectations or needs are typically considered to be expectations stated in the language of those at the business management level or of stakeholders at the business operations level. Requirements are considered to be formal statements that are structured and can be verified and validated". The purpose of translating needs is to transform a natural language expression into a more formal one, as clearly as possible, and without introducing any bias, for which various methods and means are available [36, 37]. In practice, the engineers will transform stakeholder expectations based on guidance on specifying requirements to document the structured stakeholder requirements specification in a clear and unambiguous form [38, 39].

TASK 1.3: STAKEHOLDER AND REQUIREMENTS ANALYSIS

The analysis of the stakeholders and expectations/requirements ensures the validation and quality and enables updates if necessary, which constitutes an iterative process for incremental development improvement. Stakeholders and their requirements can be analyzed and validated through the followed means:

- Categorizing the stakeholders;
- Investigating the characteristics of stakeholders;
- Assessing the power and influence of stakeholders;
- Identifying stakeholder conflict matrix.

Derakhshan et al. [40] identify the functions of the governance mechanisms as directing and controlling the organization, balancing goals (economic, social, environmental, individual) and defining rights and responsibilities of stakeholders . This classification provides a framework for categorizing stakeholders. In literature [41], depending on the nature of the problem or purpose it may be particularly important to scrutinize the characteristics of stakeholders in terms of the basis (e.g. age, background), location, ownership (e.g. managers, staff, trade unions), function (e.g. consumers, suppliers, regulators), etc. Moreover, it is necessary to determine whether stakeholders in a position of strong influence with negative interests may be critical to project success, which can be reached by conducting a formal assessment of each stakeholder's level of importance and influence of the project [42]. Finally, constructing a stakeholder conflict matrix can capture the relationship between stakeholders to investigate aspects of conflict and co-operation.

FLOW-DOWN AND ITERATION CONSIDERATIONS

The captured and validated stakeholders' requirements need to be maintained and managed as they function as the compliance standard throughout the development life-cycle. Refer to SE "V" model, the system design follows a top-down design for each end product in the system structure, and it follows a bottom-up realization for each end product in the system structure

Likewise, for PHM systems design, the stakeholders' requirements flow down and prioritized into desired functions and constraints as shown in Figure 2.2. These specific functions and constraints then flow down to system level, where first an assessment of feasibility is carried out keeping in mind the constraints of resources and if needed an iterative refinement and negotiation process takes place between the stakeholder level and system level [23]. Further, these requirements may flow down to lower levels and eventually to the lowest levels specifying requirements for prognostic algorithm performance.

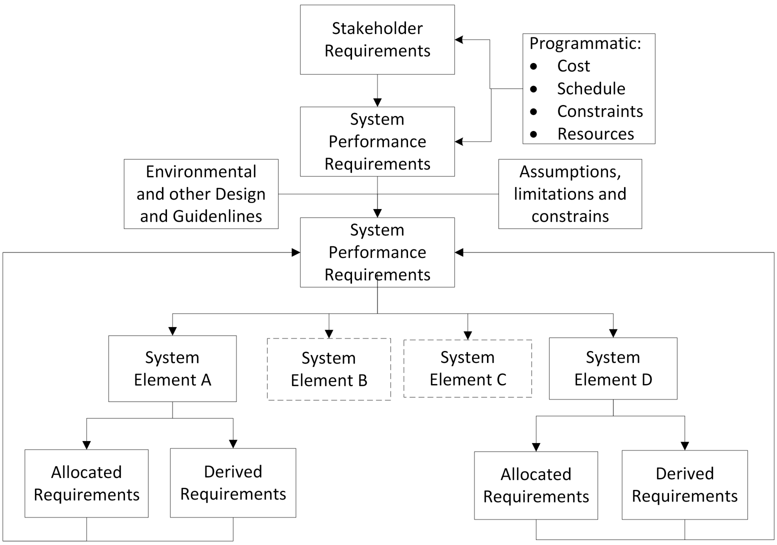

Figure 2.2: Systems engineering life-cycle "V" model

The proactive iteration with the stakeholders throughout the systems engineering process is the way that all parties can come to an exact understanding of what should be done and what it takes to do the job. It is important to know who the primary stakeholders are and who has the decision authority to help resolve conflicts [31]. As shown in Figure 2.1, iterative activities in the process of stakeholders' expectations definition are allowed. Multiple iterations of these activities provide feedback for the improvement of the maturity of stakeholders' expectations and requirements. For example, the engineers may find some issues in the activity of stakeholders and requirements analysis. Accordingly, the process allows turning back to task 1.1 for modifying the stakeholder list or to go back to task 1.2 for updating or modifying the related stakeholders' expectations or requirements. As a result, the iteration process can improve the maturity of the stakeholder's requirements. However, the time available for proceeding with iterations is generally limited due to technical or managerial considerations. The need for further iterations is generally tied to project milestones and reviews [43].

VALIDATION AND VERIFICATION CONSIDERATIONS

Verification refers to the basics (structure) of the item being verified, ensuring that it meets requirements that drive the creation of the item, whether it rules on well-formed requirements, standards and best practices on the design, or requirements on the system [34]. Validation is the set of activities ensuring and gaining confidence that a system can accomplish its intended use, goals, and objectives (i.e., meet stakeholder requirements or top-level functions) in the intended operational environment [34]. It is required to ensure the correctness and quality of the identified stakeholders and defined expectations, according to the proposed methodology for stakeholder expectation definition. Several methods can support the activities of validation and/or verification, such as traceability, analysis, modeling, testing, and engineering review. For example, modeling and simulation used during architecture definition can verify the design items and reduces the risk of failure in satisfying the system mission and performance requirements [34]. The methods of compliance matrix and checklist can be used to ensure the development activities are compliant with the defined processes. Figure 2.3 expresses the V&V activities through the system development process. This paper focuses primarily on the process of stakeholders' expectations definition, therefore the scope of V&V activities is delimited in Figure 2.3 (red line), with the objectives as follows:

Figure 2.3 expresses the V&V activities through the system development process. This paper focuses primarily on the process of stakeholders' expectations definition and does not cover the whole system development process [44]. Therefore, the scope of V&V activities in this research is delimited in Figure 2.3 (red line), with the objectives as follows:

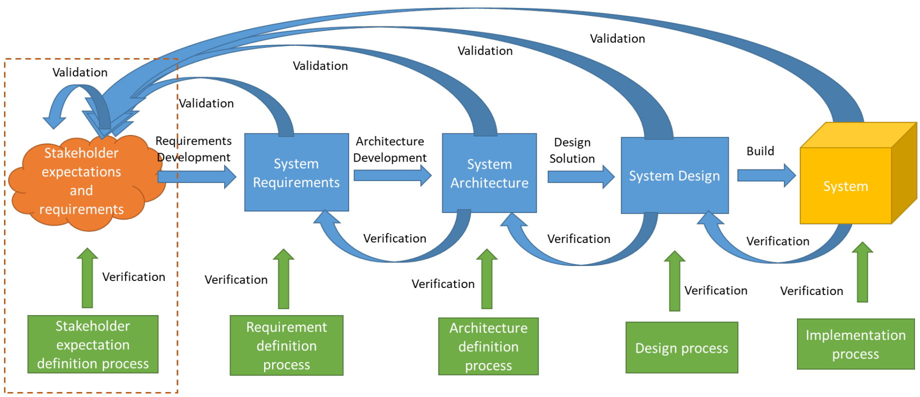

Figure 2.3: V&V process during system development [44]

a) Validate the stakeholders' expectations/requirements to ensure the correctness of stakeholders and the requirement satisfying relevant stakeholders' expectations;

b) Verify that the activities of identifying the stakeholders and capturing the expectations/requirements are compliant with the proposed methodology of Task 1: stakeholder expectation definition (Subsection 2.3.2).

2

To accomplish the above objectives, relevant methods are expressed in Figure 2.4, when contemplating the specific practices of PHM system development. Related aspects are addressed from two perspectives: traceability, consistency and reusability; and applicability.

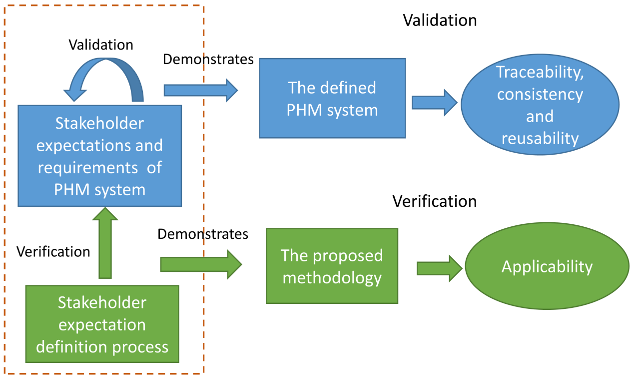

Figure 2.4: Specific V&V objectives

a). Traceability, consistency and reusability

The aspects of traceability, consistency, and reusability are crucial characteristics in the development of a complex system. Building a complex system in a unified and unambiguous manner is a key point for a successful systematic design. such a development process incorporates multi-level and interdisciplinary design, involving multiple sets of expertise, as well as a set of development and management tools. Therefore, a multi-view model with the representation of systematic characteristics is necessary. These different views have to be linked alongside with traceability links and be consistent with each other. Providing traceability between stakeholders' expectations and design items (e.g. objectives, missions, requirements, etc.) yields advantages for quantity assurance. A set of requirements or design elements has to be consistent in that the requirements are not contradictory nor duplicated. In the aviation domain, reusability provides an excellent benefit for the development cost. For example, modeling artifacts can be refined and reused in other applications to underpin product line and evolutionary development approaches, thereby saving the cost of design and developments and improving the design effectively [44].

b). Applicability

Furthermore, verification activities enable evaluation of the practical applicability of the proposed design methodology. Applicability means that the proposed methodology can be used by an organization that has a family of similar product lines or a group of system development [45]. The applicability verifies suitability of implementation of a design methodology for a particular application, i.e., PHM, IVHM systems or others health management systems [46]. Through different applications in the aviation industry, the applicability of the proposed methodology can be determined in implementation, yet practical applications are lacking to an extent in literature. To refine the methodology and further demonstrate its applicability, two case studies will be applied to reduce the possible subjective (qualitative) criteria in this research.

Performance Metric		KPIs	Target	Evaluated
Product		Overall equipment effectiveness (%)	+positive	B
		Capacity utilization rate (%)	+positive	A
		Machine flexibility rate (%)	+positive	A
		Product Management (%)	+positive	A
		Manufacturing defect rate (%)	-negative	D
Time		Schedule adherence rate (%)	+positive	B
Cost		Cost adherence rate (%)	+positive	A
Quality	Traceability	Traceability rate (%)	+positive	A
		Complex matrix rate (%)	+positive	B
	Consistency	Consistency rate(%)	+positive	A
		Rework rate (%)	-negative	D
		Reject rate (%)	-negative	D
	Reusability	Reusability rate (%)	+positive	B
		Module partitioning rate (%)	+positive	B
	Applicability	Applicability rate (%)	+positive	A
		Constraints degree	-negative	C

Evaluated level A: 76-99%, B: 51%-75%, C: 26%-50%, D: 0-25%, NA: not available

Figure 2.5: An example of KPI evaluation [47, 48]

Given the above aspects, it is necessary to consider how to measure them from quantitative and/or qualitative perspectives. One possible way to evaluate these characteristics is to measure performance, relying on key performance indicators (KPI) and associated metrics. KPIs represent a set of measures with a major emphasis on those aspects of organizational performance that are the most critical for the current and future success of the organization [47]. A visualization example of KPIs evaluation for system development is shown in Figure 2.5. The overall visualization follows the same principle as this representation and can, therefore, be anticipated on the basis of the knowledge and experiences [48]. Figure 2.5 shows a set of KPIs for the quantitative evaluation from diverse factors, in which the aspects of traceability, consistency, reusability, and applicability are considered in a comprehensive view. However, the evaluation of KPIs in industry is often performed based on expertise or engineering judgment, which is one of the constraints when considering academic research.

Having specified the major sub-tasks of the stakeholder expectations definition step in detail, two case studies will be addressed with emphasis on the application of this step towards a generic and a specific PHM design problem, respectively.

2.4. CASE STUDY: PHM SYSTEM MODELING

A case study considering generic PHM system modeling establishes a SysML modeling project to implement the process of task 1 in the stakeholder-oriented systematic design methodology. This case study aims to identify the relevant stakeholders and their expectations, and it makes use of SysML modeling to validate the technical material produced in this task. Moreover, it performs the traceability analysis as validation means to check compliance and consistency. The SysML modeling project of a generic PHM system design is built using the tool of Sparx Enterprise Architecture [49]. This case study applies the methodology, and predominantly considers the process of stakeholder expectation definition. Thus, the implementation of this case study is compliant with the defined tasks in the methodology, which correspond to the case study subsections as follows:

1) Task 1.1: covered in section 4.2.1 and 4.2.2 (step 1 and step 2).

2) Task 1.2: covered in section 4.2.3, 4.2.4, and 4.2.5 (step 3-5).

3) Task 1.3: covered in section 4.2.4 and Subsection 2.4.3 (step 4 and traceability analysis).

2.4.1. CASE STUDY APPROACH

SysML modeling provides the capability to establish models for specification, design, analysis, and verification of an integrated system by capturing multiple aspects of the system including its requirements, structure, behavior, and elements relationships [24]. Accordingly, it enables the validation of stakeholder's expectations definition, involving identifying the stakeholders and determining what problem needs to be addressed by the mission. This case study is conducted according to the procedures defined in Figure 2.6, including the following steps:

1) Create a viewpoint diagram to identify stakeholders and problems to be addressed as mission authority;

2) Define the top level use cases to represent the mission objectives;

3) Develop the stakeholders' requirements that support the mission objectives;

4) Create a domain model to identify the system and external system and users;

5) Create mission activity diagrams to represent the mission level behavior.

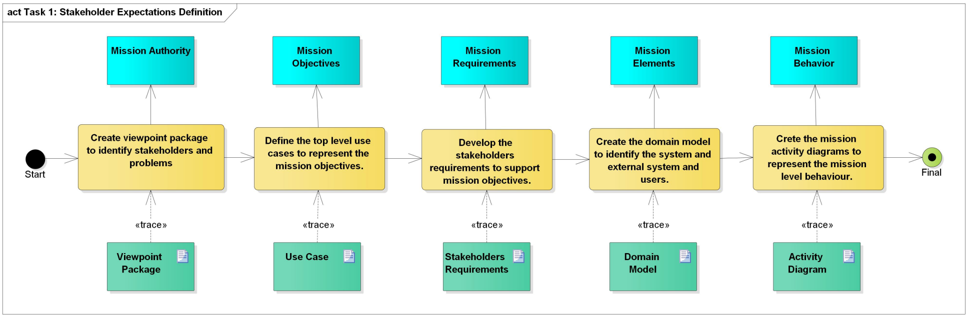

Figure 2.6: Activity diagram for the task of capture stakeholder expectations [50]

2.4.2. MODELING FOR PHM SYSTEM

STEP 1: VIEWPOINT DIAGRAM

The viewpoint diagram represents the concerns of specific stakeholder in terms of what they care about, and a view conforms to a particular viewpoint by presenting the relevant information from the system model that addresses the stakeholders concerns [50]. The case study generates the viewpoint diagram package to capture the stakeholders, viewpoints and views for system design. In Figure 2.7 , the stakeholders are the one who represent concerns about the cost and project plan (e.g. program manager), the functional and operational performance provided by PHM system, (e.g. engineering and maintenance (E&M) department), how to operate this system (e.g. fleet management), and how to improve the performance of maintenance (e.g. maintenance, repair & overhaul (MRO) supplies). These groups are deemed as the primary stakeholders as they are generally the customers, user, and operators, who drive the design/development. Whereas, the secondary stakeholders are developers, who are responsible for system design and development, as well as the integrator, suppliers, passengers and other organizations, who support the development life-cycle.

STEP 2: USE CASE DIAGRAM

Subsequently, use case diagrams are generated to represent the mission objectives directly related to stakeholder value. A use case diagram can describe the goals (mission objectives) of a system, and the external systems called actors that participate in achieving the goal [50]. The main mission objectives of a PHM system are “predict maintenance services” and “health management” from the fundamental view, as reflected in Figure 2.8. The prediction services mission performs the function of diagnostic assessment and prognostic assessment, whereas the mission of health management is implemented by the services of maintenance decision making and maintenance management. To achieve the missions, the capabilities of data processing and data monitoring are required to enable embedded algorithms for diagnostics and prognostics. This diagram also identifies the stakeholders of E&M department, developer, fleet management department and MRO department as the actors who are responsible for the specific use case. For example, the E&M department is generally responsible for developing policies, standards, and recommendations to contemplate all aspects of safe and efficient aircraft E&M activities. The fleet management department is able to provide the in-flight data,

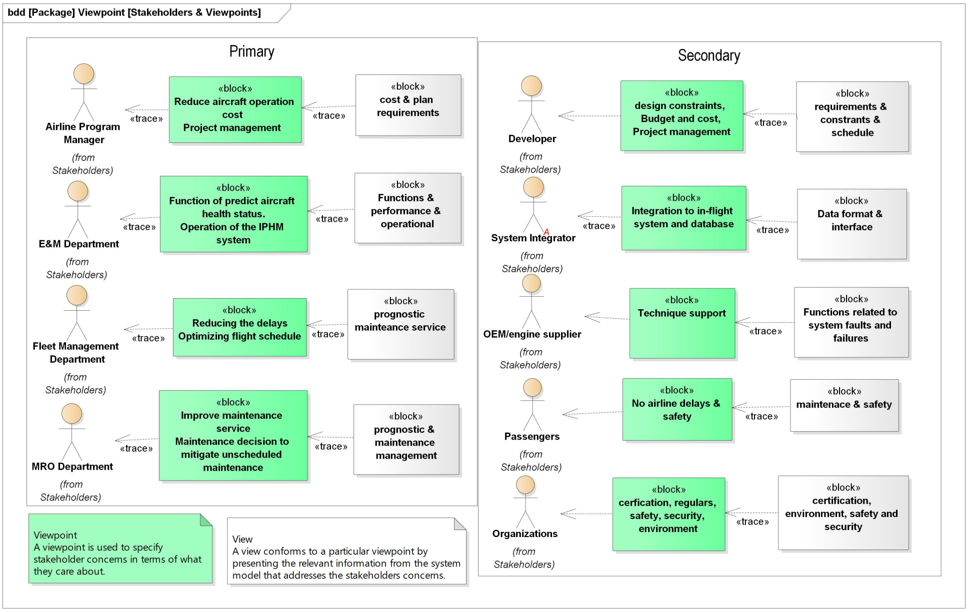

Figure 2.7: Viewpoint diagram for stakeholders

while the MRO can implement maintenance services to the aircraft based on prior maintenance decision making. Besides, another diagram enables the description of project life-cycle scenarios with the phases of development/integration, operation, and services with respect to the relevant actors, as shown in Figure 2.9.

STEP 3: REQUIREMENTS DIAGRAM

As have been stated, stakeholder requirements define the system specification of functions, performance, operations, environment, and some other accessibility functions integrated to provide the services [50]. The mission requirements are the further specification of characteristics, functional and operational capabilities for the PHM system, as identified in Figure 2.10. These requirements are elaborated by several other requirements that specify the functional, performance, operation and interface requirements, as well as discuss the safety, security, reliability, maintenance, testing, certification, regulations as the configured support requirements. Moreover, the requirements of project management, such as cost, schedule, risk, and constraints, also play a critical role during the development phase.

The functional requirements define the capabilities of a system to satisfy the identified mission objectives. For example, the followed are some functional requirements:

- The PHM system shall be able to predict the faults/failures of the monitored system defined in the functional hazard assessment (FHA).
- The PHM system shall be able to estimate the RULs of the monitored system.

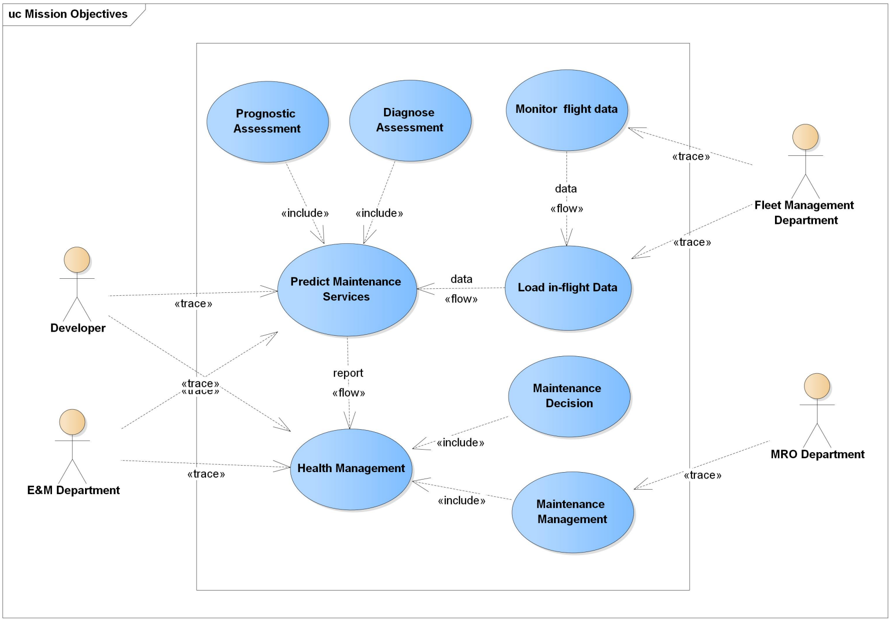

Figure 2.8: Use case diagram for mission objectives-functions

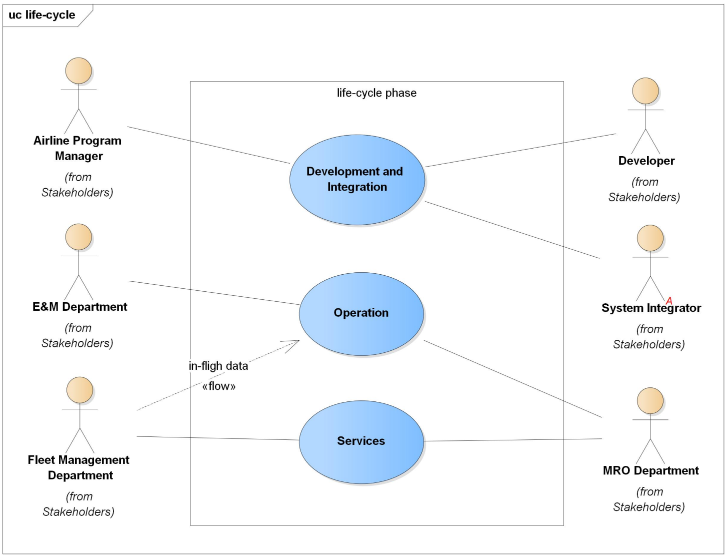

Figure 2.9: Use case diagram for project life-cycle scenarios

- The PHM system shall have the capability to make a decision about operational system configuration and maintenance actions based on assessment reports.

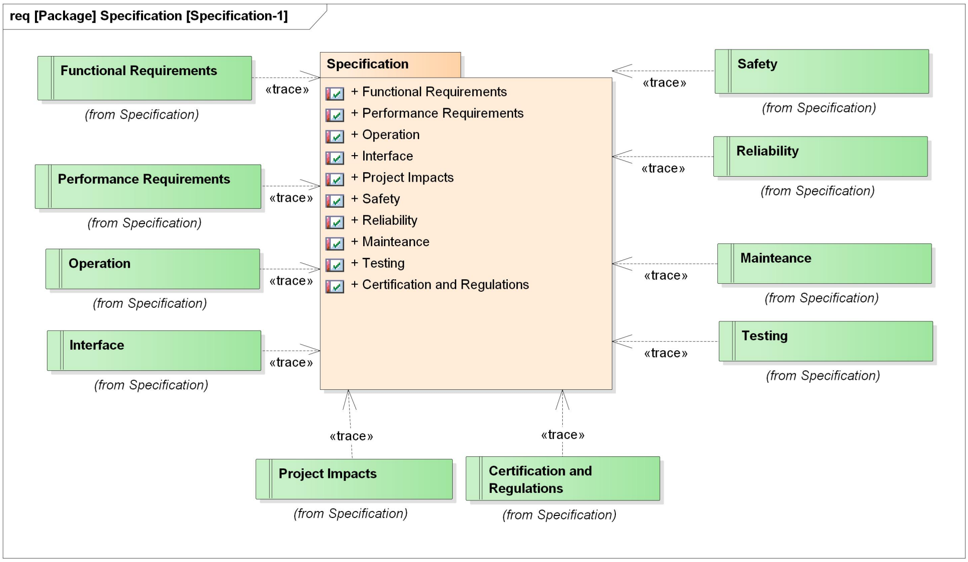

Figure 2.10: Stakeholder requirements diagram

This procedure requires further dissection and augmentation with additional information to extract specific requirements and constraints as such performance, operation, interface, safety, and cost and so on. Some examples of the stakeholder's requirements are defined as follows:

- The project timeline shall avoid delays and comply with the project deadline.
- The PHM project shall minimize implementation cost and stay within stipulated budgets.
- The PHM system shall have a probability of loss of infrastructure of 1.0E-5 per operating hour.

STEP 4: DOMAIN MODEL

Afterward, a domain model (e.g. block definition diagram) is built to express the mission elements that the PHM system directly or indirectly interacts with throughout its mission, which includes other systems, users and the environment [50]. In this generic example of PHM system development, the domain model characterizes the mission elements of data acquisition and processing, diagnostics, prognostics assessment and health management as the main configuration functions of a generic PHM system in Figure 2.11. In particular, it indirectly interacts with the in-flight health management system and data sharing network. Moreover, it has direct interfaces with a database in this diagram. It also identifies the related users/operators as the mission elements, including the stakeholders of MRO, E&M department, and fleet management department in Figure 2.11.

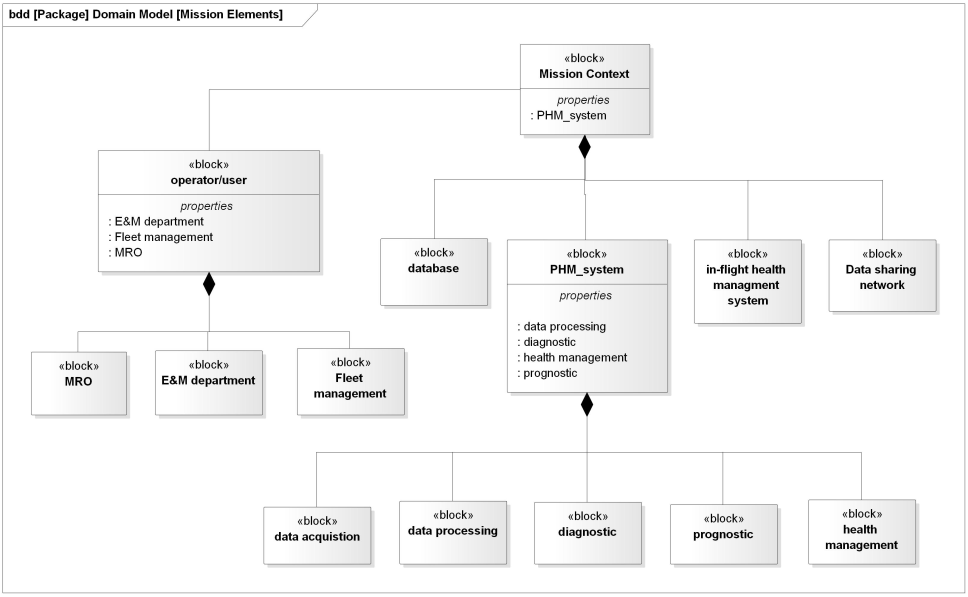

Figure 2.11: Domain model for mission elements

STEP 5: MISSION ACTIVITY DIAGRAMS

Finally, activity diagrams are created, with the description of how these activities perform the configured system functions based on certain sequences and logic decisions, to visualize the system operational procedures. Figure 2.12 represents the mission level behavior of the PHM system performing top-level functions with the aim of satisfying mission objectives while outlining the fundamental flow in a logical sequence. The activity starts with data acquisition and processing to provide the data performed in the algorithms hosted on the functions of diagnostics and prognostics, assessing the health status and estimating the RUL for the target system. Then it makes maintenance decision and manages the maintenance services tasks like the function of health management.

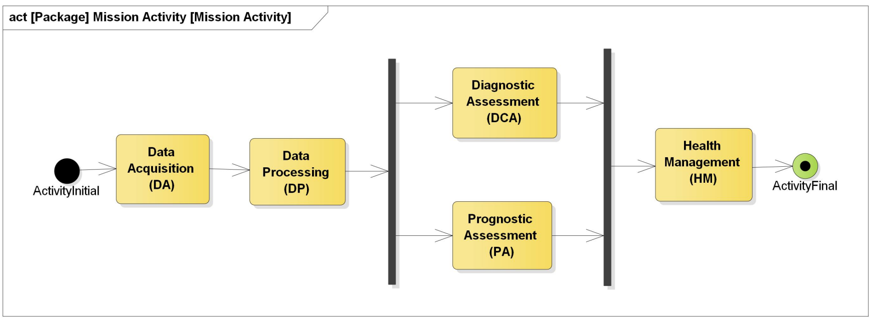

Figure 2.12: Domain model for mission elements

2.4.3. DISCUSSION

This section mainly discusses the characteristics of the traceability, consistency, and reusability of PHM design, as well as the applicability of methodology.

a). Traceability, consistency and reusability

Firstly, the aspects of traceability and consistency analysis are evaluated alongside with each other. The traceability indicates the linkage among the related set of items (whether there is traceability of all items?), and in-depth, the consistency evaluates the relationship (whether the linked items are consistent?). The SysML modeling tool enables traceability management via informatics linkages, even for multiple individual packages, which are organized consistently. In Figure 2.13, each package represents a corresponding design step as defined, and the virtual linkage can present the traceability in a controlled manner. Moreover, the stakeholder expectation folder consists of the packages of stakeholders, viewpoint, use case, domain model, stakeholders' requirements and mission activity, as illustrated in Figure 2.13.

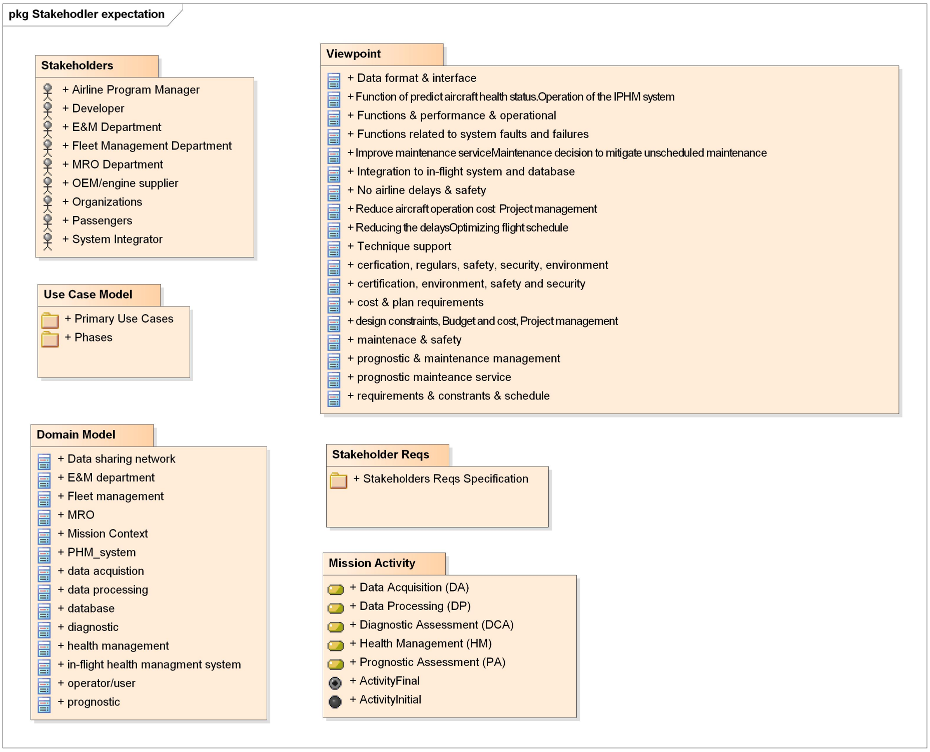

Figure 2.13: Modeling packages of stakeholder expectations definition

The viewpoint diagram (Figure 2.7), use case diagrams (Figure 2.8 and Figure 2.9), and requirements diagram (Figure 2.10) are established to model, appraise and analyze the technical items of the mission authority, mission objectives, and mission requirements respectively. On the basis of stakeholder-oriented motivation, the traceability from stakeholders flow-down to mission authority, mission objectives, and requirements are summarized in Table 2.1. The engineers and/or specialists can check the consistency among the relevant technical elements in accordance with the traceability in **??**. For instance, the mission authority of E&M is the definition of system functions, performance, and operations, for the mission objectives of predicting maintenance services and health management. Under this circumstance, the E&M stakeholders' expectations are related to the mission requirements of functional, performance and operation of the PHM system. Likewise, all the linked mission aspects are checked to ensure consistency during the process.

Table 2.1: Traceability and consistency from stakeholder to mission aspects

Stakeholders	**Mission Authority**	**Mission Objectives**	**Mission Requirements**
Airline program manager	Cost, plan, requirements	Project management	Cost, schedule, risk, functions and performance.
E&M	Functions, performance, operation	Predict maintenance services and health management	Functional, performance and operation
Fleet manager	Prognostic and maintenance services	In-flight data collection and loading	Functional, performance and operation
MRO	Prognostic and maintenance services	Maintenance services	Functions, operation
Developer	Requirements, constraints and schedule	Predict maintenance services, health management, project management	Requirements specification
System integrators	Data format, interfaces	Support-integration	Functional, performance, operation, interfaces
Original equipment manufacturers (OEM) /engine suppliers	Functions	Support-technique	Functions and operation
Passengers	Maintenance and safety	Support-safety, and security concern	Safety and security.
Organizations	Certification, safety and security.	Support-certification and regulations concern	Certification and regulations

Afterward, the mission elements and their behaviors incorporated into system are utilized to satisfy the configured top-level functions related to mission objectives. Then, the compliance relationships among those elements are illustrated in Table 2.2, including all the elements identified in Figure 2.11 and Figure 2.12. To demonstrate the consistency, shows the traceability from top-level functions with the traced mission elements and behaviors respectively.

This case study has been undertaken using modeling diagrams to capture the stakeholders and their expectations for a generic PHM system, enabling the reuse of the established technical material for other projects. A first pitfall appears here with the use of SysML and the freedom and wide range of possibilities it offers, which can rapidly con-

Table 2.2: Traceability consistency from function to mission elements and behavior

Functions	Elements	Mission Behavior
Data acquisition (DA)	DA module	It has the capability to collect the digitized sensors and operational data from the in-flight systems through the data sharing network.
Data processing (DP)	DP module	It is responsible for manipulating the data to the desired form which characterizes specific descriptors (features) of interest in the machine condition monitoring and diagnostic process.
Fault diagnostic assessment (FDA)	FDA module	It is able to detect and isolate faults or failures based on the analysis of monitored data.
Prognostic assessment (PA)	PA module	It is able to determine the current health state based on analyzing the features extracting from the selected sensors data, andfurther predicting the failure and estimating the RUL of the monitored system.
Health Management (HM)	HM module	It is able to integrate the information from FDA and PA functions and consolidate with the constraints (safety, environmental,budgetary, etc.) to generate maintenance advisories.

fuse both the modeler and the model user if not standardized throughout the project. In this case study, we use the Enterprise Architecture tool with a Snecma SysML profile developed to fit the design needs. Correspondingly, it provides high-quality assurance for development and enables the capability of reusability.

b). Applicability

This case study has been presented to show how the design methodology guides designers toward the identification of stakeholders' expectations for a generic PHM system development. The results indicate the applicability of the methodology to design a generic PHM system, in view of successfully and consistently defining the stakeholders and their relevant expectations. Nevertheless, the implementation of an application case study requires several steps/procedures and tools for supporting, applicability resources, which are different from each other in a specific case. Thereupon, it means that the applicability of design methodology should meet some specific constraints and requirements in practice (e.g. cost constraints, schedule constraints, tools, etc.). This implies that there is a limitation regarding quantitative evaluation (e.g. through performance metrics and/or KPIs). In practice, the evaluation results are based on the judgment of experts and engineers, who were not available in this case study. In this context, the KPI evaluation of this case study is presented in Table 2.3. The KPIs related to quality performance are evaluated according to the aforementioned analysis. However, KPI evaluation related to product, time and cost are not taken forward in analysis due to limitations on available data.

2

Table 2.3: KPIs evaluation results

Performance Metric		KPIs	Target	Evaluated
Quality	Traceability	Traceability rate (%)	+positive	A
		Complex matrix rate (%)	+positive	A
	Consistency	Consistency rate(%)	+positive	A
		Rework rate (%)	-negative	D
		Reject rate (%)	-negative	D
	Reusability	Reusability rate (%)	+positive	B
		Module partitioning rate (%)	+positive	B
	Applicability	Applicability rate (%)	+positive	B
		Constraints degree	-negative	C
Evaluated level A: 76-99%, B: 51%-75%, C: 26%-50%, D: 0-25%, NA: not available				

2.5. CASE STUDY: REMAP APPLICATION CASE

This section presents an application case study involving the H2020 ReMAP project. This case study mainly applies the analysis method identified in Subsection 2.3.2 and modeling to validate the process of stakeholder expectations definition. It is an ongoing research application of the ReMAP project so that the outcomes are associated with the ongoing progress. It emphasizes defining stakeholders and capturing their expectations, which is generally in the early phases of a project. The technical information in this case study is primarily based on publically available documents, which has been subject to validate by the primary stakeholders as part of the project execution. Thus, this case study is sufficient to provide high maturity and credibility concerning the included information [51].

2.5.1. PROJECT DESCRIPTION

This case study presents an application of PHM system development related to ReMAP project. This project aims to contribute to aircraft maintenance by developing an open-source PHM and decision support solution for aircraft maintenance, the integrated fleet health management (IFHM) system [52]. By replacing fixed-interval inspections with adaptive condition-based interventions, ReMAP contributes towards a decrease in maintenance costs, a reduction in unscheduled maintenance events, and increased aircraft availability [52]. One goal of this project is to develop health diagnostics and prognostics of aircraft systems and structures using innovative data-driven machine learning techniques and physics models. This case study leverages this aspect with a major emphasis on stakeholder identification, categorization, and requirements elicitation, as being in line with the goals of the presented research.

2.5.2. STAKEHOLDERS

CATEGORIZATION OF STAKEHOLDERS

The success of this project comprises the achievement of ReMAP scientific and technological goal but also depends on the impact that it has in the aviation industry and among its main stakeholders. ReMAP stakeholders can refer to individuals, groups or organizations that may affect or be affected by decisions, activities or outcomes of the project [51]. An exhaustive set of stakeholders that are relevant to the project are identified in Figure 2.14.

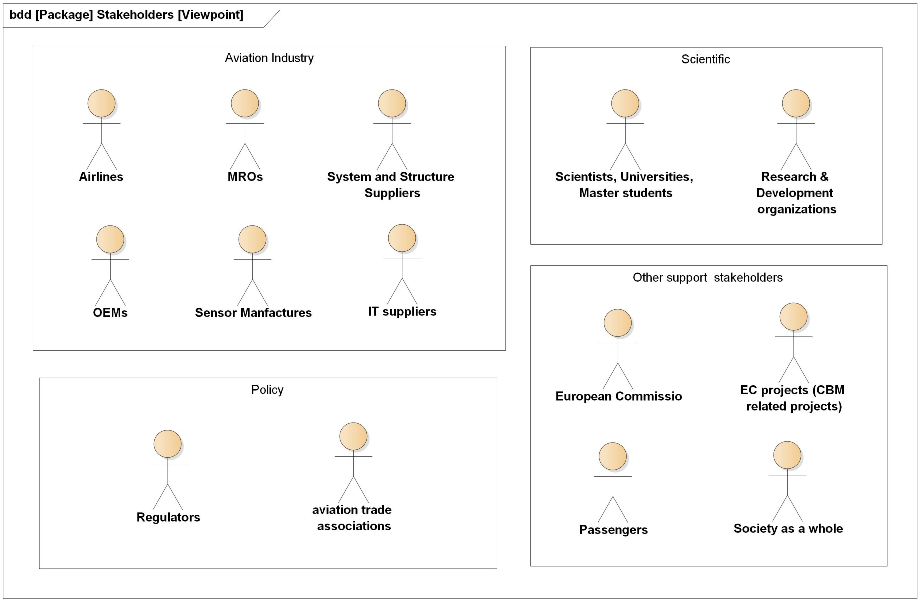

Figure 2.14: Stakeholders of ReMAP project

An approach for understanding a system by identifying the major stakeholders in the system, and assessing their respective interests in that system, contributes towards developing strategies for improving the effectiveness of project execution and reducing any obstacles to successful implementation. All relevant stakeholders are categorized according to criteria relevant for the specific project after obtaining the stakeholder's list, as illustrated in Table 2.4.

POWER AND INTEREST ANALYSIS

The stakeholders' power and interest analysis of the ReMAP project is defined in Figure 2.15 , identifying the high power and interest (high importance and influences) stakeholders for project success. The stakeholders, who have the characteristics of high power and high interest, play the most important roles to ensure effective development and provide significantly influence/power of that project [51].

For example, the airlines, OEMs, and MROs are the key users and/or investors of the project, thus they have a high power and high level of interest in Figure 2.15 . Although the MROs can obtain the most interests from ReMAP project to achieve effective aircraft maintenance, the airlines lead the project, and consequently, they have higher power than the MROs. Secondly, since the regulators are responsible for defining the standards and regulars, as well as the right of certification review, they are involved as the stakeholders with the high power, but low interest (as they are only indirectly involved in the

Table 2.4: ReMAP project stakeholders list [51].

Groups	Stakeholders	Motivations
Aviation industry	Airlines OEMs MRO companies Sensor manufacturers System and structures suppliers IT suppliers	˘ Guarantee that all contents and actions covered in ReMAP are understood by all partners ˘ Influence policy makers and regulators ˘ Stimulate an early adoption of technologies ˘ Disseminate the EC role in the aviation industry ˘ Stimulate future cooperation between academia and industry
Scientific	Scientists, universities, master students Research & development organizations	˘ Stimulate research and development in CBM ˘ Stimulate future cooperation between academia and industry
Policy	Regulators National and European aviation trade associations	˘ Regulatory, and certification of industrial process ˘ Important inputs on how to address these difficulties as well as to influence future regulations in this area.
European commission (EC)	Project officer	˘ Address the objectives of EC research and innovation funding
EC projects	CBM related projects	˘ Peer discussion with other EC related projects. ˘ Exchange of non-confidential information
General public	Passengers Society as a whole	˘ General public to make their travels safer and more reliable.

project). The aviation trade associations are stakeholders with low power and high level of interest. It is therefore recommended to keep relationships with these stakeholders but it is not essential to involve them actively. However, managers need to build a well-working relationship with these stakeholders to ensure an effective coalition of support for the activity. In conclusion, these stakeholders control the strategic resources, determine the project's objectives and deliverables, and define the relations with other stakeholders [53].

2.5.3. DOMAIN MODEL

After identifying the stakeholders, the high-level domain model is established, with the aim to develop health diagnostics and prognostics of aircraft system and structures. Figure 2.16 characterizes the high-level users/operators, and developers to implement this project, which includes the specific stakeholders of regulators, original aircraft manufacturers (OAMs), operator, MROs and OEMs. Meanwhile, a set of aircraft systems and components are monitored for diagnostic and prognostic, as identified in Figure 2.16. Moreover, the implementation of diagnostic and prognostic functions support to make a smart decision for a maintenance program, involving the fundamental attributions of maintenance instructions and procedures handbook.

To achieve the project goal, we capture the scopes of target maintenance systems or components to identify the health diagnostics and prognostics applications embedded in this IFHM platform. More specific, the targeted aircraft systems primarily consist of engine anti-ice, integration cooling system, and others; the main components include

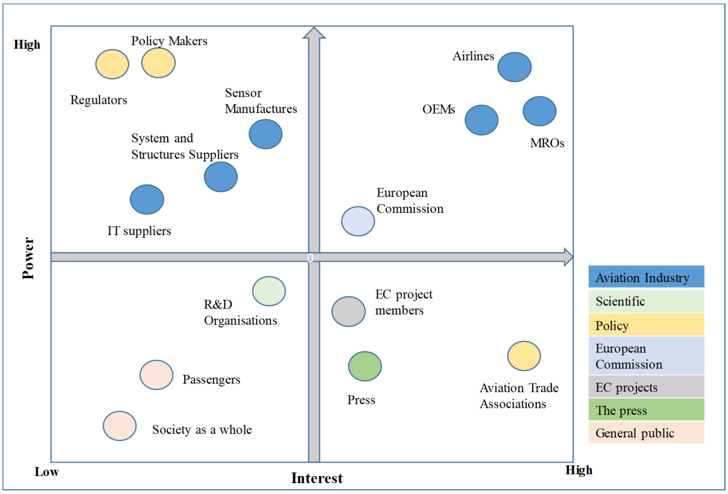

Figure 2.15: Power and interest analysis [51].

auxiliary power unit, fans, wheels, etc., as illustrated in Figure 2.17.

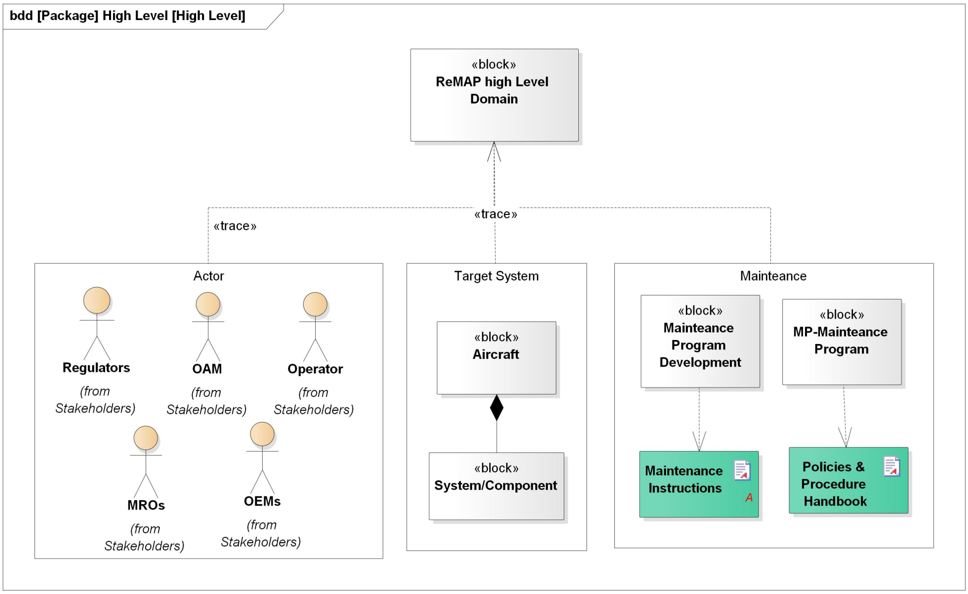

Figure 2.16: High-level domain diagram

2.5.4. USE CASE

A use case diagram can describe the goals (mission objectives) for ReMAP project. As aforementioned, the major goals of this project consists of the development of IFHM

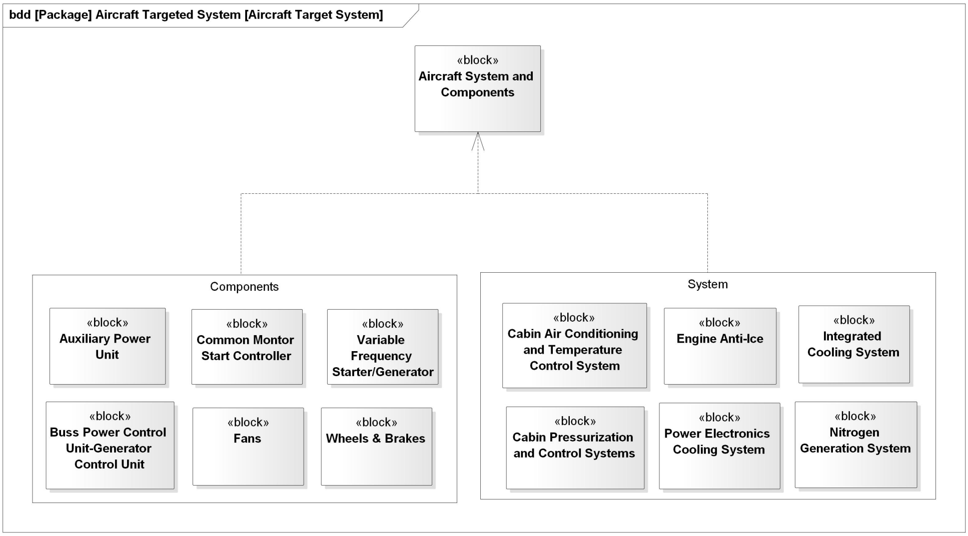

Figure 2.17: Domain diagram of maintenance targets

system, enabling to reduce unscheduled aircraft maintenance events, so as to increase aircraft availability and decrease maintenance cost. This project aims to plan an important role in outspreading the implementation of Condition-based health management from two-fold perspectives: advancing the scientific and technological framework and addressing relevant regulatory barriers [51]. As a result, it will implement the main goals as present in Figure 2.18

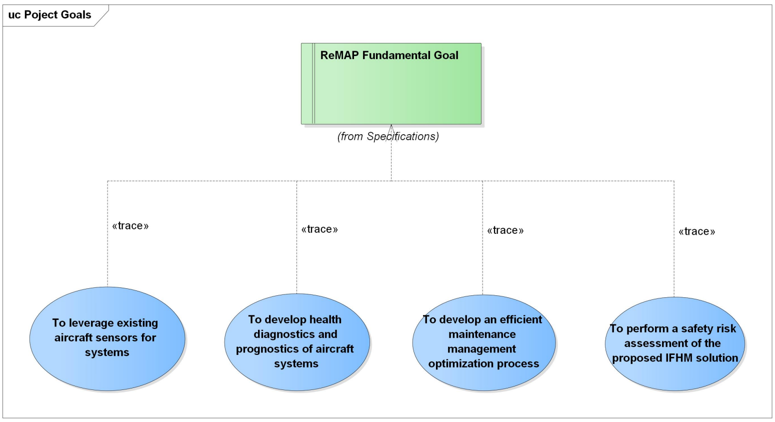

Figure 2.18: Use case of ReMAP high-level goals

Furthermore, ReMAP is aimed at achieving a strong impact in the aeronautics industry, in its scientific, operational or regulatory dimensions. To achieve the project goals, the stakeholders need to work together in organized relevant activities and cooperate with each other. In terms of contents creation, all partners are responsible for creating and sending contents to be communicated and disseminated, as presented in Figure 2.19 [51]. The goals of the low-level users in the ReMAP project are identified in Figure 2.20, which states the specific tasks during the development of this product.

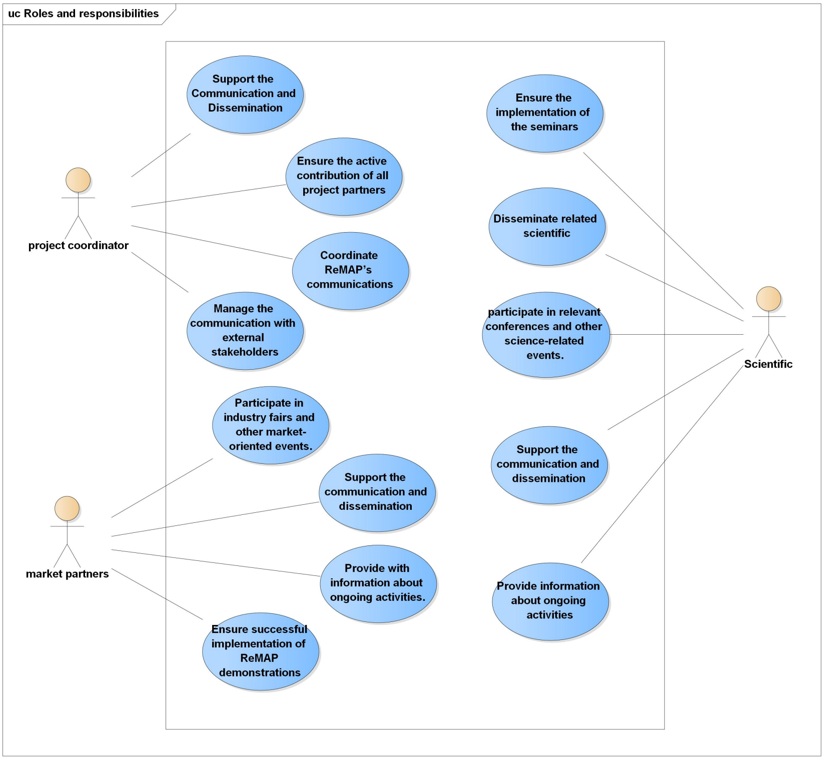

Figure 2.19: Use case of communication and dissemination roles

2.5.5. DISCUSSION

The respects of traceability, consistency, and reusability are crucial characteristics in ReMAP project. Similar to the previous case study, the SysML modeling tool is able to organize all the diagrams into multiple individual packages with the traceability links. For instance, the design package for the ReMAP project is delineated in Figure 2.21.

This case study validates the application of the proposed methodology as an application case. The content of this case study is on the basis of the published document of ReMAP project [52]. This document has been reviewed by the project coordinators, experts and other stakeholders (peer-review), so as to be delivered as a baseline version. As a consequence, it is deemed that this case study provides high-quality material for defining and analyzing stakeholders and their expectations. Further, it can support the validation of the application of the proposed methodology through analysis of stakeholders, modeling of domain diagrams and use case diagrams.

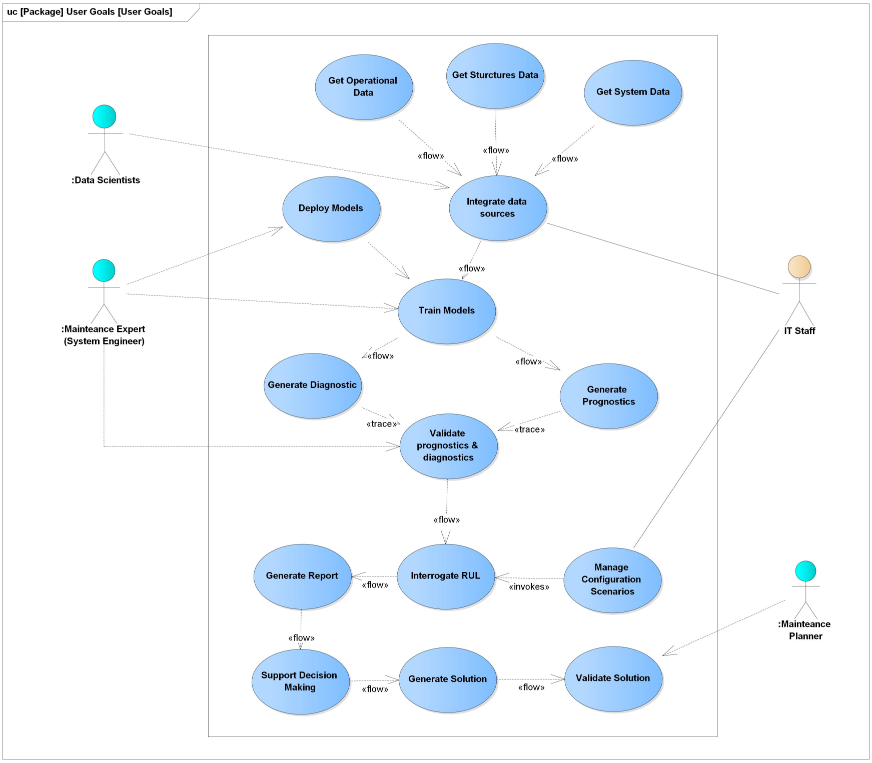

Figure 2.20: Use case of users goals of ReMAP project

Additionally, the available information concentrates on identifying stakeholders (Task 1.1 and Task 1.3), domain model (Task 1.1 and Task 1.2) and use case establishment (Task 1.2). Thus, the created modeling diagrams are relevant to the specific tasks of the proposed methodology, which can determine the applicability of the proposed methodology. Similar to the first case study, there is the limitation of quantitative performance evaluation, described in Subsection 2.3.2, due to an underlying cause of the project constraints and associated confidentiality clauses.

2.6. CONCLUSION

This chapter proposes a stakeholder-oriented methodology that formulates all elements of designing and engineering a PHM system as illustrated in Figure 2.1. Whereas, it emphasizes the process and deployment of Task 1 (stakeholder expectations definition) in details, involving in the steps of identifying stakeholder, capture stakeholder expectations/requirements, as well as stakeholder and requirement analysis.

Two case studies are utilized for V&V. Firstly, an experimental generic case study (Section 2.4) is established to determine the stakeholders and their expectations/requirements through SysML modeling. Besides, an application-oriented case study (Section 2.5) is presented, which is an ongoing effort based on the ReMAP research project. In practice,

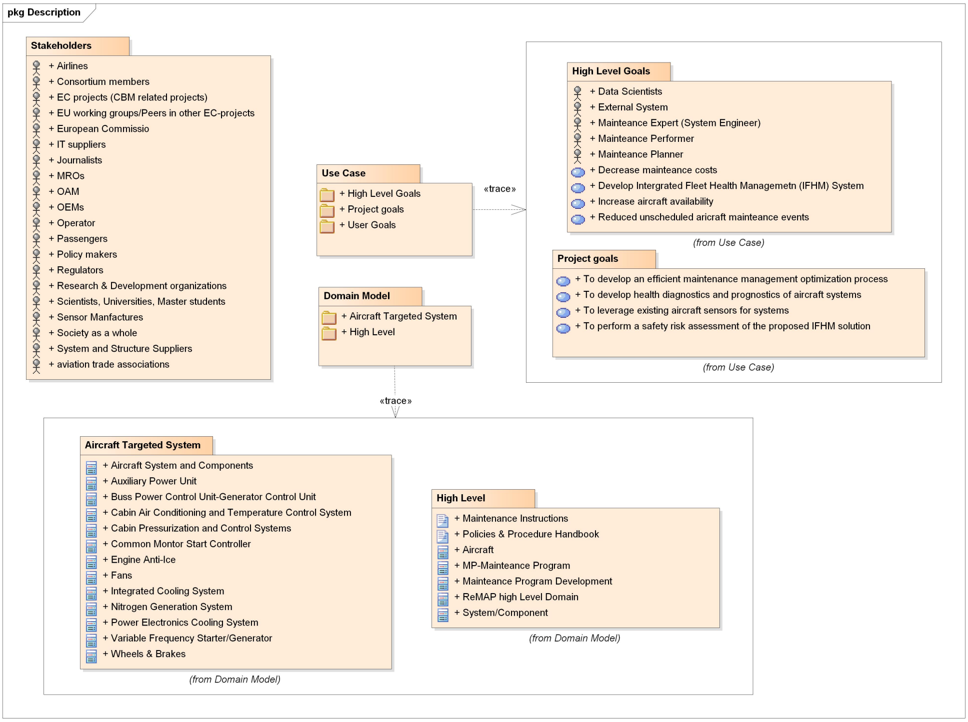

Figure 2.21: Modeling packages of stakeholder expectations definition

there is a tendency on the part of technology developers to make use of the maturity and applicability of a technology/methodology that is required to design/implement a system. Particularly, these two case studies verify the stakeholder expectation definition process from a different perspective, including a generic project of PHM system design, as well as an application case for ReMAP research project. Summaries of these two case studies demonstrate that the stakeholder-oriented methodology has the applicability to be applied in a group of similar projects. Moreover, the established stakeholders' expectations and requirements of a generic PHM system have the aspects of traceability, consistency, and reusability.

As discussed and applied in this paper, to draw that our research effects to fill the corresponding research questions, the research can be associated with three main novel contributions:

- A stakeholder-oriented innovation design methodology enables the integration the bespoke main perspectives (tasks), formulating all respects of developing a PHM system to evaluate product concept innovation comprehensively.
- As the first task, sufficient stakeholder involvement and their interests considerations can lead to more precision and improving design information. Accordingly, the proposed methodology can provide system engineers guidance toward a successful PHM development project.

- This methodology addresses traceability, consistency, and reusability to capture and define stakeholders and their expectations for the successful design of PHM systems.

When considering the research so far, there are still some challenges and opportunities. For one thing, this research addresses the process of stakeholder expectations definition (Task 1) in detail, but not all tasks are covered. Another point for further research concerns KPI evaluation, which is not fully addressed in the current set of case studies. Extended efforts should include the definition and application of a comprehensive set of evaluation metrics. Moreover, the presented stakeholder-oriented systematic design methodology, however, is not comprehensive and can be extended to improve the design effective and quality through additional support processes or tools. It is akin to a basic skeleton to which other methods can be added. For example, trade-off and decision-making processes can be involved in performing the determination and selection of suitable prognostic technologies. As a consequence, these shortcomings point the way toward future research.

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3

Design Methodology of System Requirements Definition

This chapter primarily develops a requirement definition methodology for the PHM system that describes the practicable steps in detail. The outputs of Chapter 2*, principally the stakeholders' expectations, can generally drive the system requirements definition. However, existing options for requirements derivation are lacking details, which binds PHM system design and development. This constitutes a primary drawback and hurdle towards successfully design a PHM system in industrial practice. To address this weakness, this chapter introduces a systematic methodology for requirements definition. Additionally, it explains how each category of requirements can be derived through the appropriate analyses, along with the perspective of requirements flow-down. Regarding sufficient accuracy, this methodology also addresses the relevant solutions to perform requirements validation. As a result, the output of this chapter can guide toward developing a PHM system, especially, the requirements specification of a generic PHM system in practice.*

This chapter is based on an accepted article:

Li, R., Verhagen, W.J. and Curran, R., 2020. Toward a methodology of requirements definition for Prognostic and Health Management system to support aircraft predictive maintenance, Aerospace Science and Technology (2020): 105877

Aircraft maintenance has been further developed with predictive maintenance instead of solely condition-based maintenance. Prognostics and health management (PHM) with advanced technologies can utilize real-time and historical health state information to provide actionable information, enabling predictive maintenance decision-making. In this case, the methodology of how to design the PHM systems is an issue to be faced. The state of the art has provided several conceptual design methodologies and associated methods to support the conceptual requirements development of PHM systems. However, there is no rigorous process available for requirements definition. Existing options for requirements derivation are lacking details, which restricting PHM system design and development. This constitutes a major drawback and hurdle towards the successful design of PHM systems in practice. This paper consequently proposes a methodology for the systematic derivation of system requirements towards PHM system development. Besides, this methodology defines detailed processes for requirements definition, and positions mean through which various categories of requirements can be derived through appropriate analyses in detail. Sequences of interoperability requirements categories and associated flow-down perspectives are identified. To evaluate the applicability, this paper undertakes the case study of requirements definition for a generic PHM system, which provides a comprehensive application of the methodology. Designers can perform requirements definition under this methodology as guidance towards the design of a successful PHM system, providing solutions for predicting remaining useful life (RUL) to support aircraft predictive maintenance.

3

3.1. INTRODUCTION

Aircraft maintenance consists of maintenance, repair, overhaul, inspection, and modification to retain an aircraft and the related aircraft systems and components, as well as structures in an airworthy condition [1]. Regular maintenance prevents aircraft components and systems failures during operations. Predictive maintenance techniques are able to help determine the condition of in-service equipment to estimate when maintenance should be performed. Thus, it is regarded as condition-based maintenance carried out as suggested by estimations of the degradation state.

To practice predictive maintenance, the prognostics and health management (PHM) is used as an engineering system integrating the advanced fault detection capabilities as well as technologies for the prediction of useful lifetimes by assessing the degradation of operating conditions [2]. Particularly, prognostics enable the prediction of failures in machines resulting in benefits to plant operators such as shorter downtimes, higher operation reliability, reduced operations and maintenance cost, and more effective maintenance and logistics planning. Within this context, PHM technologies can reduce time and costs for the maintenance of products or processes through efficient and cost-effective diagnostics and prognostics activities [3].

For industrial fields, PHM systems can provide significant competitive advantages given that the relevant techniques can enable a reduction in the cost of maintenance activities and the consequences of unexpected failures [4]. The operational reliability of industrial systems and assets significantly influences the sustainability of the manufacturing and competitiveness of the industry. As the operational reliability of a complex system typically decreases as the duration of its operation progresses, ensuring reliability during the designed lifecycle of the machine becomes a critical task for maintenance [5]. Advanced manufacturing depends on the timely acquisition, distribution, and utilization of information from systems and data across spatial boundaries. Thus, these activities can enhance accuracy and reliability in predicting relevant resources , maintenance schedules, and remaining life of the targets equipment [5].

PHM is the underpinning capability that enables an effective and risk-reducing manner, monitoring and managing the asset to allow for timely maintenance - hence the argument for PHM having to be integrated from the start of the design process [6]. This requires consideration of the methodological aspects of designing PHM systems [7]. Such a methodology needs to consist of the manipulation of basic design concepts, recognizing and analyzing aspects of the system such as functional entities, actions, interoperability, as well as action points and interaction points. With rapidly growing interest in complex systems, the design of PHM systems and their components may benefit from the use of long-established system engineering (SE) principles to ensure a more robust and efficient design. Systems engineering is an interdisciplinary field of engineering and engineering management that concentrates on how to design and manage complex systems over their life cycles [8]. Requirements engineering (RE) is a subdiscipline of SE that systematically determines the goals, functions, and constraints of hardware/software systems such that top-level mission requirements are met within specifications. In this sense, requirements definition transforms the stakeholders' needs into a definition of the issues and then into a complete set of requirements specification that can be made full use for developing a design solution for the corresponding products [9].

Existing literature has provided a significant contribution towards the establishment of systematic design methodologies for developing a PHM system. In spite of that, the aspect of requirements definition is insufficiently identified and described in the existing state of the art; most literature emphasizes on discussing the high-level functional requirements but lacks flow down to algorithm level, whereas some research only discusses the importance of requirements from a conceptual view (see Section 2). To address this shortcoming, this research investigates the following main question:

- How to define a systematic methodology addressing the detailed process of requirements definition for a PHM system, and how to derive the different categories of requirements via appropriate analyses?

To fill the gap, this chapter proposes a requirements definition methodology from a SE perspective. It formulates the specific tasks and assignments for requirements definition in detail, while regarding the exhaustive aspects of requirements flow-down to other design items, as well as compliance with stakeholders' expectations. Moreover, a case study applies the proposed methodology towards the definition of a set of requirements for a PHM system. Meanwhile, it addresses the study of requirements analysis, validation, and flow-down. This requirements definition methodology provides a comprehensive approach towards PHM system design and assists in improving design maturity in early PHM design phases.

The remainder of this paper is organized as follows: Section 3.2 discusses the state of the art of design methodology, and the principles and knowledge associated with requirements definition and systems engineering associated with requirements definition for PHM systems. Additionally, Section 3.3 introduces a systematic methodology for requirements definition with detailed processes. In Section 3.4, the methodology is applied towards a case study of requirements specification for a generic PHM system. The conclusion is given in Section 3.5, along with a discussion of future work.

3.2. LITERATURE REVIEW

Predictive maintenance is a maintenance strategy aiming at monitoring the health state of the system, detecting incipient faults and forecasting potential failure in the future to trigger the maintenance actions accurately when they are needed. As introduced, the PHM systems can provide a solution for predictive maintenance. Aims to provide efforts in the design of PHM systems, at first, this section summarizes the state of the art of the PHM field and relevant methodologies for system development. When developing the requirements for a PHM system, fundamental knowledge of the PHM field is required, including definition and interpretations of key technical terms Furthermore, an understanding of basic system development principles and methodologies is necessary. In the context of this paper, the field of Systems Engineering (SE) is chosen as the primary direction of inquiry, as SE is well-established and can provide high-level theoretical knowledge and guidance towards the development of a systematic design methodology for PHM. In addition, the term requirement is a key aspect here; a requirement is a singular documented physical or functional need that particular design, product, or process aims to satisfy in product development and process optimization. Requirement specification plays a highly important role in engineering design. As shown in Figure 3.1, integrating the state of the art from these aspects enables sufficient content for developing a systematic methodology of requirement definition for a PHM system. Related works on requirements definition methodology from the perspectives mentioned previously (i.e., technical aspects of PHM systems; methodological aspects as embodied in SE theory; and technological aspects as embodied in requirements engineering) are comprehensively reviewed below.

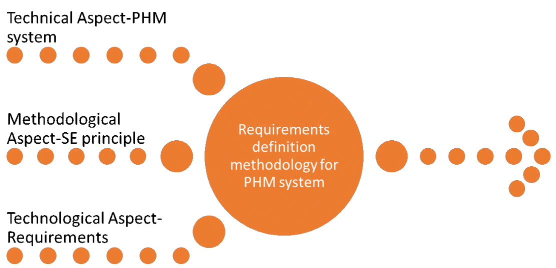

Figure 3.1: Related knowledge on requirements definition

a). PHM system

PHM technologies can reduce time and costs for the maintenance of products or processes through efficient and cost-effective diagnostic and prognostics activities [3]. Generally, a PHM system has fundamental functions involving diagnostics and prognostics: diagnostics concerns the process of fault detection and isolation, while prognostics is the process of predicting remaining useful life (RUL) according to current or historical conditions, enabling intelligent decision-making for improved performance, safety, reliability, and maintainability [1]. Specifically, prognostics enable the reduction of the lead time for procurement and planning for maintenance with the possibility of autonomic logistics. It relies on its capacity to anticipate the evolution of anomalous conditions in time.

A substantial amount of research has been performed concerning PHM to improve the effective operation for critical complex systems. Leite et al. [10] present a comprehensive review of efforts and advances in prognostics techniques, and the authors also address some RUL prediction approaches applied to the critical components of wind turbines. Similarly, Ezhilarasu et al. [11] review concerning various reasoning strategies, different reasoning systems, their architectures, components and finally their numerous applications in the field of Integrated Vehicle Health Management (IVHM). Xia et al. [12] discuss the recent advances in the technology of the PHM domain for advanced manufacturing paradigms to predict health/degradation trends, avoid system breakdowns, reduce maintenance costs and achieve rapid and smart decision making. Advanced manufacturing paradigms are still developing with the rapid upgrading and innovation of information, manufacturing, as well as management technologies, thus it leads to opportunities in the connection of PHM methodologies with manufacturing [12].

b). Design methodology (SE)

The philosophy, methodological aspects and tools of Systems Engineering (SE) are well-established. One critical aspect is the process of requirements engineering, as covered under c) below. In relation to a), a multitude of research has considered translation of SE principles towards a design methodology for PHM systems [13, 14].

For example, Saxena et al.[15], addressed the various stages in the SE process and identified activities specific to integrated vehicle health management (IVHM) design. The authors also provide a general approach for developing requirements and integrating them into the asset design. Regarding traceability, Konigs et al. [16] present a morphological schema for a traceability approach, which can intuitively display various types of dependencies between SE artifacts and can improve transparency within the system synthesis and analysis. Dumargue et al. [17] regard the whole product lifecycle (such as research, development, production, maintenance) on a variety of fields such as requirements management, validation, verification, integration or configuration management by taking a global consideration of all these elements. From a manufacturing view, Adams et al.[18] address a new method for targeting areas in a manufacturing setting that could benefit from a PHM system, and testing and comparing PHM strategies for implementation. To streamline the decision-making process before installing a PHM system, their methodology discusses the impact of PHM with regards to the manufacturing system as a whole, showing that the total cost of implementation is reduced [18].

c). Requirements engineering

A series of studies consider requirements from an application-oriented perspective [19–22]. For example, Moukhi et al. [23] recommend a requirement-based method for multidimensional design, in which they investigate a new user-driven methodology that allows guiding the user to express the requirements and ensure the evolution of the data warehouse. Wang et al.[24] propose a user requirements-oriented knowledge management concept. A novel distributed concurrent and interactive user requirement database is constructed, and a user requirement driven framework is put forward to support collaborative design knowledge management for product development. Viscio et al. [25] describe a method of requirements definition to properly perform complex space mission and systems design, which provides a general method to exploit SE analyses and relevant tools for a thorough assessment of the requirements. Moreover, the authors apply the proposed methodology to a specific case study (inflatable technology on-orbit demonstration) that has revealed that it is useful to derive in a rigorous way the requirements driving space missions and systems design. Although Viscio et al. [25] provide great insight into requirements specification for complex technical systems, their study only concentrates on the application of space missions.

Synthesizing the discussion of sections a), b) and c), the definition of PHM requirements should be an iterative process that takes into consideration the trade-offs between imposing higher safety, reliability and maintainability requirements on systems and components [26]. In prior research along these lines, Saito et al. [27] introduce a Requirements Inspection Systems Design Methodology (RISDM). That method incorporates a meta-model and design process, a pragmatic quality model, and a technique to generate inspection questions. Saxena et al. [28] provide a guideline for requirement specification for prognostics system design and development. The authors also state that the RE involves several processes to assist in specifying respective requirements for each subsystem/component, specifically including the steps of requirements definition and gathering, requirements analysis, requirements prioritization and requirement flow-down [28]. Furthermore, Saxena et al. [29] discuss a SE view towards the requirements specification process and present a method for the flow-down process. It focuses on the high-level functional requirements further flow down to lower levels and eventually to the lowest levels specifying requirements for prognostics algorithm performance. In literature [30], the authors recommend a methodology of developing requirements, that describes all the steps of requirements generation and management as it applies to IVHM systems, and demonstrate these with a "real-world" example related to designing a landing gear system. However, it lacks some detailed information about engineering practice. In summary, although several papers address requirements definition on the aspects of PHM design, a systematic methodology is still lacking in the start of the art, especially regarding detailed elements of requirements definition.

Therefore, the major shortcomings of the current state of the art include:

1). Available methodologies for requirements definition lack details and in-depth guidance for PHM design, in particular in providing specific steps and relevant guidance to practitioners from a SE perspective.

2). Existing research lacks a comprehensive understanding of requirements, which should concern how to flow-down the requirements to other design aspects (e.g.

architecture, design, etc.), and upward to stakeholders expectations consistently.

3.3. METHODOLOGY

This section defines a systematic methodology to derive system requirements for thorough engineering of the PHM system. Firstly, Subsection 3.3.1 introduces an overview of the methodology that identifies the interrelationship between requirements definition and other primary tasks in a complete system design life-cycle, as shown in Figure 3.2. Then, Subsection 3.3.2 concentrates on the requirements definition process, as presented in Figure 3.3, to properly perform PHM mission design with particular attention to the derivation of requirements using detail descriptions and comprehensive understanding.

3.3.1. DESIGN METHODOLOGY OVERVIEW

A successful methodology should contain several well-established steps, including application specifications (requirements capture), concepts (conceptual design), preliminary layout (preliminary or front end engineering design), definitive layout (detailed design), verification, validation, testing, and documentation [31]. To progress from application specific solutions towards structured and efficient prognostics implementations, the development of a pragmatic methodology is essential. The existing literature has proposed a stakeholder-oriented design methodology for engineering a PHM system from a SE manner, contributing to a consensus and re-useable representation of the design, and that methodology primarily incorporates the tasks as described in Figure 3.2. 2 : Task 1: Stakeholder expectations definition; Task 2: Requirements definition; Task 3: Architecture definition; Task 4: Design solution definition; Task 5: System implementation; Task 6: Validation and verification.

As shown in Figure 3.2, the design methodology starts with capturing stakeholders' expectations. Then, the process of requirements definition aims to conduct requirements specification transformed from stakeholders' expectations, with more detailed information from design considerations and functional decomposition. Next, the engineers or designers define the system architecture, and allocate the relevant requirements to the specific system elements, in that way transforming the requirements to functional and logical elements within the boundary of the developed system. Afterward, the process requires the determination of a "best" design solution based on all the defined alternative solutions. As a result, a preferred alternative, satisfying the technical requirements, is selected as the final design solution to subsequently implement as a product. These sub-processes should be consistent with each other and will require iterations and design decisions to achieve this consistency. Once consistency has been achieved, analyses allow verifying and validating the design against the stakeholder expectations, as the final task [31].

3.3.2. REQUIREMENTS DEFINITION METHODOLOGY

This section concentrates on a description of the requirements definition process for engineering a PHM system. In this process, the designers or engineers are responsible for capturing and defining the requirements driven from the stakeholders' expectations,

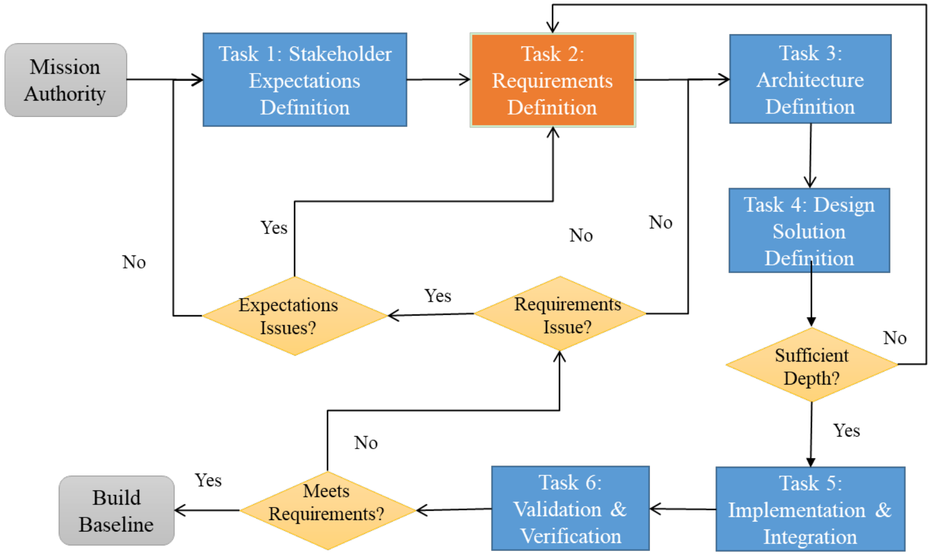

Figure 3.2: Systematic design methodology

and then they also responsible for validating them. Then, the validated requirements can flow-down to a lower-level for further design in a consistent manner. The activities included during this process can continue within the system design process recursive loop until a preferred system solution has been fully delimited.

To be precise, the essence of the requirements definition is to transform the stakeholder-oriented view of desired capabilities into a technical view of a solution that meets the operational needs of the user. That involves interfacing with the stakeholders to determine top-level requirements. The requirements specification consists of the assignments: determining operational concepts that cover scenarios for how the health management system might behave and be used; identifying a suitable interface between the health management system and rest of the world; and generating health management design requirements and a corresponding rationale for each requirement [32]. Besides, this process describes the loop for an iterative and recursive to ensure the quality and maturity of delimited requirements. Therefore, the systematic requirement definition methodology for PHM system is delineated in Figure 3.3, incorporating with the tasks of:

- Task 2.1: Capture requirements from stakeholder expectations;
- Task 2.2: Analyze and decompose requirements;
- Task 2.3: Define requirements;
- Task 2.4: Validate requirements;
- Task 2.5: Flow-down requirements.

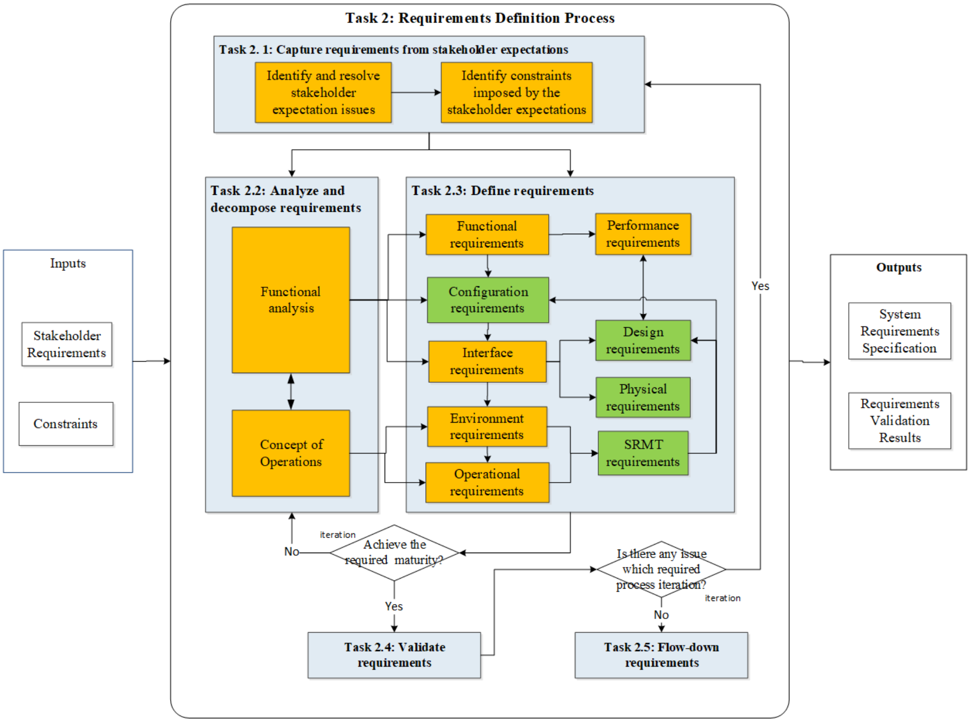

Figure 3.3: Requirements definition methodology

TASK 2.1: CAPTURE REQUIREMENTS FROM STAKEHOLDER EXPECTATIONS

Chapter 2 has introduced a stakeholder-oriented methodology, and it emphasizes the process and deployment of Task 1: stakeholder expectations definition with the details steps toward guidance to analyze stakeholders and define the relevant stakeholders' expectations. Commonly, the design methodology starts with capturing requirements from stakeholders' expectations, which build the interrelationship between stakeholders and the expected system in a technical view. It should be properly executed to obtain a complete, clear and concise statement that represents mission objectives (stakeholders' expectations). To interpret the mission objectives, the designers or engineers need to identify and resolve stakeholder expectation issues, which primarily consist of the followed aspects:

- Which system elements or components already have design solutions.
- Expected interaction/interfaces among system elements/functions (e.g. human responses, data flows, and behaviors).
- External physical and functional interfaces with other systems.
- What are the required capabilities of the target system products?

- Timing of states, logical, events, modes, and functions related to operational scenarios of the system.

Additionally, the stakeholders typically represent their interest in an associated system or sub-system capability from various perspectives. Such as, the operators principally acknowledge considering the operation capability, whereas the customers emphasize the functions and cost.

In parallel, the method requires the activity of identifying constraints imposed by the stakeholder expectations, if necessary, which are varying and depend on each specific project. Related to the design, constraints mainly involve physical constraints (e.g., color, size, weight), human constraints (e.g., operators required capabilities, and operator work environment), availability resources constraints (e.g., human, tools, and material), and the constraints from project management (e.g., schedule, technology, and cost).

TASK 2.2: ANALYZE AND DECOMPOSE REQUIREMENTS

Once obtained the mission objectives from stakeholders, requirements can be analyzed and decomposed by time, functions, behaviors, objects, data flow, states, and modes, and failures/faults and effects, to produce architectural models. The models may include functional flow block diagrams, timelines, data control flow, states and modes, behavior diagrams, operator tasks, functional failure modes, and etc. Methodologically, functional analysis (FA) and the concept of operations (ConOps) are the primary exploited means for requirements analysis. As shown in Figure 3.3, the FA and ConOps analysis the system from the different perspectives, so that the analysis results of FA and ConOps can extract the different categories of requirements. Due to this interrelationship, we interpret the process of defining requirements (Task 2.3) along with the task of requirements analysis and decomposition (Task 2.2), and these processes are iterative and recursive processes with each other.

a). Functional analysis (FA)

The FA contributes significantly to product design by focusing more specifically on the needs of the user, and and they make full use of ensuring that all functional elements of the system are described, recognized and delimited [33]. Also, the engineers can exploit the FA method, where the graph of interoperations and the functional blocks are the elements for bridge the gap between the physical product and the overall system [34]. Several tools of analysis allow defining the systems needed for the mission accomplishment, and they are interrelated to build up the functional architecture of the mission. The common tools for FA include, but are not limited to [25]:

- Functional tree: express the functions to be performed for the execution of the mission objectives;
- Product tree: decompose the product/system based on a functional tree;
- Functions/products matrix: identify the elements to accomplish the functions;

- Functional/physical block diagram: represent the building blocks linked through point-to-point connections;
- Functional flow block diagram (FFBD): a step-by-step and time-sequenced diagram of the system's functional flow, with the detailed, operational and support sequences for the system.

b). Concept of operations (ConOps)

The ConOps addresses the operational concepts and underpin strategies depend on stakeholder expected use of the system, functionality, and performance of intended uses for normal operation, relevant boundaries, constraints and assumptions, and environments in which the product(s) will operate. Support strategies include provisions for fabrication, test, deployment, operations, sustainment, and disposal as appropriate.

Typically, the analyses contained in ConOps involve evaluations of mission phases, operation timelines, command, communications strategy, operational scenarios, and data format, operational facilities, integrated logistic support and critical events [6]. For instance, the mission phases mean the terms of activities and environment that characterize them. Meanwhile, the operational scenarios mainly concern the interrelationship between the environment and other systems, human tasks and task sequences, and physical interconnections with interfacing systems or products. Thereby, this process allows describing how the system will be operated during its entire life cycle to achieve the mission objectives [25]. On the other hand, a set of environmental, operational requirements and other relevant support requirements can be identified and refined through this method.

TASK 2.3: DEFINE REQUIREMENTS

The task of requirements definition needs to make full use of stakeholder expectations and the analysis results of those expectations to extract requirements that can provide an understandable system [25]. As shown in Figure 3.3, it describes a flow-chart that identifies the interrelation between the analysis methods (FA and ConOps) and the corresponding categories of requirements. Furthermore, it also proposes the sequence of the derivation of categories of requirements, as guidance.

The requirements can be organized into various categories according to the suitable criteria (e.g., similar functionality, performance, or coupling) with the purpose to facilitate and focus analysis. As illustrated in Figure 3.4, requirements consist of the various categories. Generally, that are the functional requirements (what functions need to be performed), performance requirements (how well these functions must be performed), interface requirements (design element interface requirements), operational requirements (control mode), environmental requirements (environment and interoperations), physical requirements (physical structure), design and configuration (system configuration and design solution in a specific project), and the additional support requirements (safety/security, reliability, maintainability, and test requirements (SRMT)) [32]. For a deep understanding, the following introduces the characteristic of each category requirements as a guide toward requirements definition along with analysis activities.

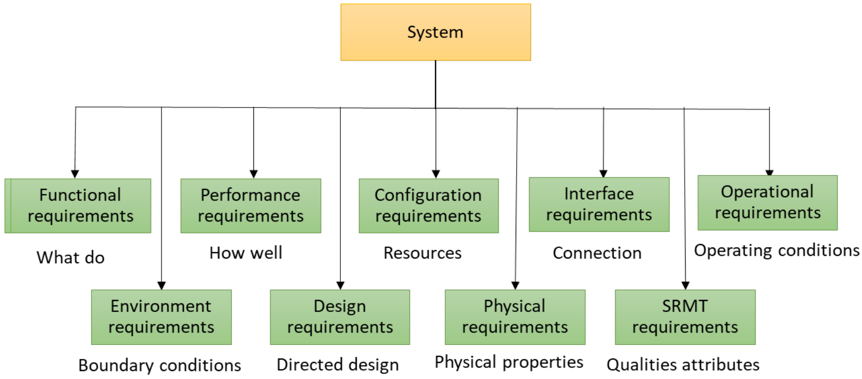

Figure 3.4: System requirements categories

a). Functional Requirements

Functional requirements are a combination of customer desires, regulatory restrictions, operational constraints, and implementation realities. These requirements focus on what functions do to accomplish the required missions and objectives, which are those necessary to obtain the expected performance of the system under the specified conditions. The functional view focuses on WHAT the system does to produce the required operational behavior. It includes required inputs, outputs, states and transformation rules. The functional requirements, in combination with physical requirements, are the primary sources of the requirements that will consequently be reflected in the system specification

Particularly, the set of functional functions specifics the details of the cases: the intended functions under normal/abnormal conditions and on specific events; Un-intend functions and how to mitigate the unintended functions in abnormal conditions; the functions regard as optional; the sub-functions into groups; and system behaviors in order related to events or conditions in each function [35]. Some examples of functional requirements are provided as [36]:

- The Core System shall be configured to a geographic boundary of its services for System Users.
- The Core System subsystems shall send status to the Service Monitor Subsystem.
- The Core System subsystems shall transition to degraded mode upon a failure.

b). Performance Requirements

The category of performance requirements provides a definition of performance values required fulfilling the intended system functions. Such requirements quantitatively describe how well the system needs to carry out the functions [28]. Commonly, performance requirements depict those attributes of the function or system that make it useful to the aircraft and costumer. More specific, performance requirements consist of function specifics such as: how often and how well, to what accuracy (e.g. how accurate the measurement needs to be), what is the quality and quantity of the output, under what stress (maximum simultaneous data requests) or environmental conditions, for what duration, at what range of values, at what tolerance, and at what maximum throughput or bandwidth capacity [31]. Wherever possible, delimit the performance requirements in terms of a threshold value (the minimum acceptable value needed for the system to carry out its mission) and the baseline level of performance desired. The examples of performance requirements in terms of thresholds are [36]:

- The Core System shall synchronize status from other Core Systems it interfaces with every 5 minutes to check availability.
- The Core System subsystems shall send a message within 30 seconds to all interfacing Core Systems upon any state change.
- The Core System shall buffer forwarding data with latency no greater than 500ms.

c). Interface requirements

The interface requirements are responsible for defining system boundaries, concerning all items that enter or leave the system boundaries, all external systems that have communication with the system. Besides, interface requirements concern the physical system and item (parts, equipment) interconnections along with the relevant characteristics of the specific information communicated. Once the systems/components are captured, a block diagram representing the major components, interconnections, and external interfaces of the system is developed to show the elements components and their interoperations [31]. For instance, a set of interface requirements are summarized following [36]:

- The Core System shall interface to System Users for data distribution.
- The Core System shall interface to System Users for misbehavior management.
- The Core System shall interface to System Users to provide status information.

d). Environment requirements

Environment requirements mainly regard the environmental conditions, in which the system will operate and provide services normally, that should be considered during design. This category focuses on formulating the external physical environment parameters, including the aspects of ambient temperature, humidity, radiation, shock, vibration, wind speed, dust, ice, etc. Further, the environment requirements also address the rate of change related to these parameters and the constraints on the effect that the system is to have on the external environment. There are some examples of the environmental requirements as follows [36]:

- The Core System's facility shall operate when exposed to a relative humidity up to 95%, including condensation.

- The Core System's facility shall operate in ambient temperatures from 0*C (32*F) to 40*C (104*F).
- The facility housing the Core System's equipment shall have an air-conditioning system capable of providing a relative humidity of 45-50%.

e). Operational requirements

Operational requirements are the statements that identify the capabilities, associated requirements, and performance measures. The series of actions undertook in effecting the results that are desired to address mission area deficiencies, evolving applications or threats, emerging technologies, or system cost improvements [37]. The operational requirements indicate the details of identifying performance assumptions and constraints for operations success. Actions, decisions, information requirements and timing constitute the majority of the operational requirements. Both normal and abnormal circumstances need to be acknowledged when defining operational requirements.

Operational requirements also characterize the interpretability between the machine and the operators. For example, "where the movement of controls is necessary to increase the value of a parameter then the directions for ON, OPEN, or NORMAL shall be as detailed below. Clockwise; or forward for the horizontal or nearly horizontal panels below eye reference level; or upward for the vertical or nearly vertical panels; or reward for the horizontal or nearly horizontal panels above the eye reference level." Likewise, the examples of typical operational requirements are defined as follows [36]]:

- The Core System shall provide sufficient backup power capacity capable of supporting the Core System for up to 4 hours.
- The Core System shall be available in normal operational state 99.5% of the time (an average of less than one hour per week or 1.83 days per year).
- The Core System shall transition to Training State when commanded by an authorized System Operator.

f). Other categories

Apart from the above, there are some other categories of requirements identified in Figure 3.3. Particularly, the engineers refine these categories via the analysis results and the information from other categories.

- Physical: The physical requirements state the required overall physical attributions of the system, such as mass, dimensions, shape, volume, weight, size, color, material, etc.
- Design: The design requirements describe the required fabrication of the system, ranging from identification of subordinate elements through to complete fabrication details.
- Configuration: the configuration requirements relate to the composition of the products or their organization within the boundary of the target system.

- SRMT: That represents the set of safety and security requirements, reliability requirements, maintenance requirements, and test requirements, which are extracted based on environmental, operational requirements, as well as constraints.

Examples of deterministic safety requirements are the incorporation of safety devices. For example, build physical hardware stops into the system to prevent the hydraulic lift/arm from extending past allowed safety height and length limits. Reliability requirements make sure that the system executes in the fixed environments and conditions as expected throughout the mission and that the system can resist a certain number and types of faults, errors, or failures.

In application, Figure 3.3 indicates that requirements are primarily driven via the process of FA and ConOps, whereas, some categories requirements are able to drive other categories. For instance, the performance requirements are interoperability to functional requirements, due to that are used to delineate the capabilities of the relevant function/functions; and the design and physical requirements are relevance to configuration and interface requirements to explain the connection in a system with the constrains. Sometimes, the sets of SRMT requirement depend on the characteristics and constraints of the environment and operational requirements, which are responsible for the quality of normal performance, or specific regarding for abnormal mode. To conclude, each category of requirements may depend and have interaction with the others from a systematic perspective.

This methodology allows for loop and iteration activities between task 2.2 and task 2.3 to improve the requirement quality, as identified in Figure 3.3. A specific and iterative set of steps that engineers use to evaluate and refine potential solutions to problems or challenges in practice is covered. Iteration provides the solution for accommodating engineers to modify the relevant requirements for evolving understanding of a system, and it also contributes pathways to solve these issues, ensuring design quality and consistency. After several times of iterations, the requirements specification of the PHM system has archived a level of maturity based on engineers' judgment, and then it is necessary to validate the requirements.

TASK 2.4: VALIDATE REQUIREMENTS

During the whole development life-cycle, there is a set of validation and verification activities as figured out in Figure 3.5. Especially, requirements validation is the process of ensuring that the specified requirements are sufficiently correct and complete, so that demonstrates that the product meet the stakeholder needs and expectations [35]. Requirements validation should produce affirmative answers to all of these questions:

During the whole development life-cycle, there is a set of validation and verification activities as figured out in Figure 3.5. Especially, requirements validation is the process of ensuring that the specified requirements are sufficiently correct and complete, so that demonstrates that the product meet the stakeholder needs and expectations [38]. Requirements validation should produce affirmative answers to all of these questions:

- "Does this collection of requirements define everything that needs to be done to achieve the requirements at the next higher level?" (Complete requirements).

- “If the system meets these requirements, will it do what the end stakeholder wants?” (Correct requirements).
- “Can these requirements be interpreted in only one way?” (Clear requirements without ambiguity).
- “Can the requirements be achieved within product technological constraints and project constraints?” (Achievable requirements).
- “For each requirement, has a method been identified for verifying it?” (Verifiable requirements).

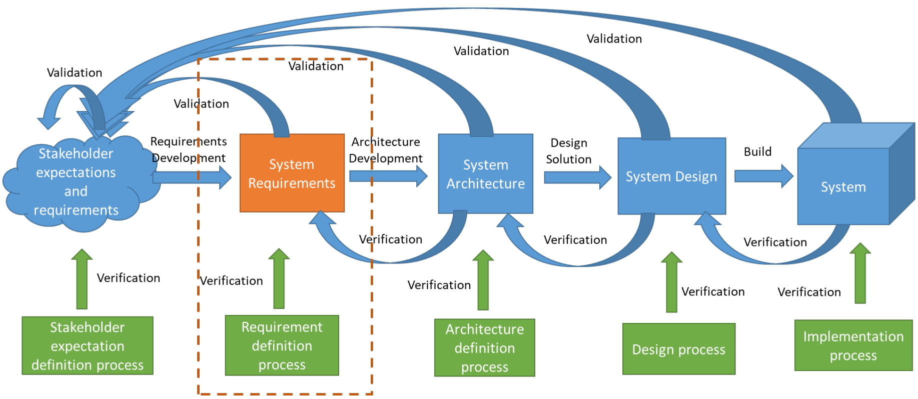

Figure 3.5: Validation activities during the life-cycle

If there are any issues about the requirements definition, this methodology allows modification through process iteration, as shown in Figure 3.3. In practice, the modification of the requirement depends on the strategy of requirements management and the process of configuration management. As an example, the assigned engineers are responsible for maintaining and modifying the requirements specifically, due to the issues discovered by requirements validation results. In this case, it allows for reviewing approved change requests to identify changes that are correct and reasonable. If changes affect stakeholder expectations or requirements, the changes will be notified to stakeholders.

The objective of requirements validation is to certify that the requirements on the set of specifications conform to the description of the system to implement and ensure that the set of specifications is essential: complete, consistent, consistent with standards standard, requirements do not conflict, does not contain technical errors, the needs are not ambiguous, etc.[39]. From the industrial view, the early validation of requirements aims to reduce the need for high-cost validation testing and corrective measures at late development stages [40]. With a major emphasis on requirements definition, this paper checks the characteristic of correctness and completeness for the defined requirements specification.

TASK 2.5: FLOW-DOWN REQUIREMENT

SE is a methodology for its projects in engineering system products, which follows a "top-down" approach for the design of each product in the system structure and a "bottom-up" product realization process. The process of requirements definition is based on system hierarchy, so that once all relevant requirements are gathered and organized they are flown-down to lower levels, as present in Figure 3.6. It means that the high-level requirements are decomposed into various categories and allocated across the system, and then further decomposed and allocated among the elements and subsystems.

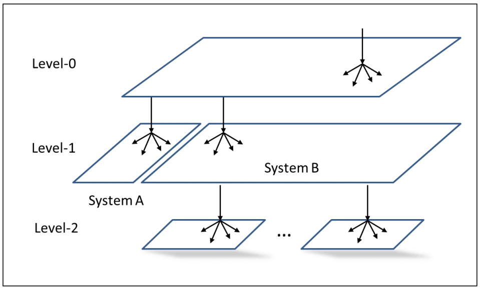

Figure 3.6: System of system

For instance, a proper set of requirements with the transfer functions that flow-down the relationship of the high-level requirement to its constituent parts depicts precisely what is wanted, but also simultaneously leaves the maximum space for creative design. The performance requirements flow-down have the purposes to describe the required performance for the specific function in a defined environment. When discussing faults decomposition, the underlying idea is that relaxation of recognition capability for some faults which have ample coverage from some tools might allow the tightening of recognition for other faults [41].

In conclusion, the outputs of this requirements definition methodology are the documentation of “system requirements specification” and “requirement validation results” in Figure 3.3. Requirements specification is one of the utmost significant output during which elicited and interpreted requirements are accurately documented for use by their stakeholders. Specify system requirements involve various categories requirements to fully describe the design system, which should be complex with stakeholders’ expectations. Besides, the output of “validation results” records the results and evidence for the activities of requirements validation.

3.4. CASE STUDY: REQUIREMENTS DEFINITION FOR PHM

This case study applies the proposed methodology to perform the tasks of requirements definition. This section provides a thorough description of how to develop requirements specification for a PHM system step by step, as an application case, though the methodology.

3.4.1. PROJECT DESCRIPTION

By replacing fixed-interval inspections with predictive maintenance, PHM systems contribute towards a decrease in maintenance costs, a reduction in unscheduled maintenance events, and increased aircraft availability. Applications of a systematic methodology to design PHM systems are scarce in both academic and industry. To tackle this, a project with the aim of designing a generic PHM system (Gen-PHM) has been set up, contributing an example case of PHM systems design with generic applicability towards practical uptake.. In other words, the project of Gen-PHM has the purpose to establish a generic case with practical translatability to develop health diagnostics and prognostics of aircraft systems (e.g. engines, and extending to components and structures).

As aforementioned in Subsection 3.3.1, the design of Gen-PHM concerns the phases of stakeholders' expectations, requirements definition, architecture definition, design solution, implementation (limitation), as well as validation and verification. Previous research has addressed the study of stakeholders and their expectations for the Gen-PHM project Chapter 2. From that case study, the outputs, principally the stakeholders' expectations, can drive the system requirements definition. With a major emphasis on requirements definition, this paper synthesizes the informative expectations from stakeholders to describe the system transparently. As a result, this paper identifies and refines the requirements specification for the Gen-PHM system detailed under the proposed methodology of requirements definition. The following sections outline the specific case study step by step.

3.4.2. REQUIREMENTS SPECIFICATION

Furthermore, in the following subsections, the main steps of the requirements definition methodology are applied in order to define the Gen-PHM requirements.

TASK 2.1: CAPTURE REQUIREMENTS FROM STAKEHOLDER EXPECTATIONS

As identified in Figure 3.3, the requirements definition process starts with the task of capturing requirements from stakeholders' expectations. That aims to determine the design missions and constraints to represent stakeholders' needs/expectations. In practice, the mission statement for a PHM design project is expressed as follows within the context of knowledge.

- Mission statement: design a generic PHM of aircraft systems and structures, using innovation data-driven techniques and physics models to support the operational decisions and post-operational maintenance activities of aviation vehicles.

Once obtaining the statement, the following step is to define the mission objectives through resolution of stakeholder expectation issues. As a result, the primary missions of this case study are as follows:

- Functional mission: provide diagnostic and prognostic capability; and provide maintenance advisories to successfully monitor the health status of aircraft systems.

- Cost mission: cost-benefit and dependability analysis.

In addition, it is necessary to regard the relevant constraints for technology, schedule, budgets allocated, and research objectives comprising successful demonstration and aircraft safety. This case study also identifies and concerns a set of constraints imposed from stakeholder expectations [29].

- Scope constraints: focus on the process of requirements definition;
- Technology constraints: monitor aircraft engines as the target, and use the data-driven prognostic approaches;
- Cost constraints: manage the project to minimize cost based on budget decomposition.
- Schedule constraints: avoid delays and finish by the project deadline.

Due to the various roles and responsibilities of different stakeholders, these stakeholders may have different interests or even conflicts of interest. Therefore, it is necessary to collect the mission objectives from various stakeholders to extract their expectations. Table 3.1 summarizes the mission objectives form stakeholders for a generic PHM system through analyzing their expectations derived from literature. As shown in Table 3.1, some stakeholders provide the needs for predictive maintenance, such as MRO organizations, who are responsible for airline maintenance.

Table 3.1: Datasets for experimental study

Stakeholders	**Mission Objectives**	**Expectations**
Airline program manager	Project management to ensure the design and development progress.	Cost, schedule, risk.
Engineering and maintenance (E&M)	Provide information of existing health management system;	Functional, performance and operation
Fleet manager	Collect and load relevant in-flight data.	Functions.
MRO	Provide existing ground facilities for design; Operate experiments and PHM system	Functions, performance, operation.
Original equipment manufacturers (OEM) /engine suppliers	Provide technical support about the physical and functional models of aircraft engines; Identify what techniques fits to predictive.	Functions.
PHM system developer	Design a generic PHM system to implement the relevant mission objectives; exploit existing technology and external facilities.	Define the requirement specification of a PHM system

TASK 2.2: ANALYZE AND DECOMPOSE REQUIREMENT

Subsequently, the next task is to elicit the feature and characteristics of the target system through the methods of FA and ConOps, as shown in Figure 3.3. The FA process examines the functions, sub-functions, and interfaces that accomplish PHM mission objectives identified in Subsection 3.3.1; The ConOps allows describing how the system will be operated during its entire life cycle to achieve the mission objectives, which is addressed in Subsection 3.3.2.

a). Functional analysis

A function is a specific action or activity that has to be performed to achieve the desired system objective (or stakeholder expectations). Besides, a function occurs within the system environment and accomplishes by one or more system elements composed of equipment (hardware, software, and firmware), people, and procedures to achieve system operations. Each function required to meet the operational requirements of a system is defined and organized into functional architecture. Therefore, the application of FA can lead the assessment of the top-level functions for the accomplishment of the functional goals of a generic PHM system.

- Functional tree

The functional tree can figure out the functional structure of a complex system, paying particular attention to maintain a high level of abstraction and definition. Especially, the top-level functions refer to the system-of-systems level, which has a direct correspondence with the segments involved in the functional missions. Then, these functions are decomposed into lower-level functions to implement specific partition functions but can be integrated into a system. Figure 3.7 presents the functional tree of a generic PHM system, which performs the core diagnostic and prognostic capabilities while in synergy with other support functions to generate maintenance advice based on monitored information.

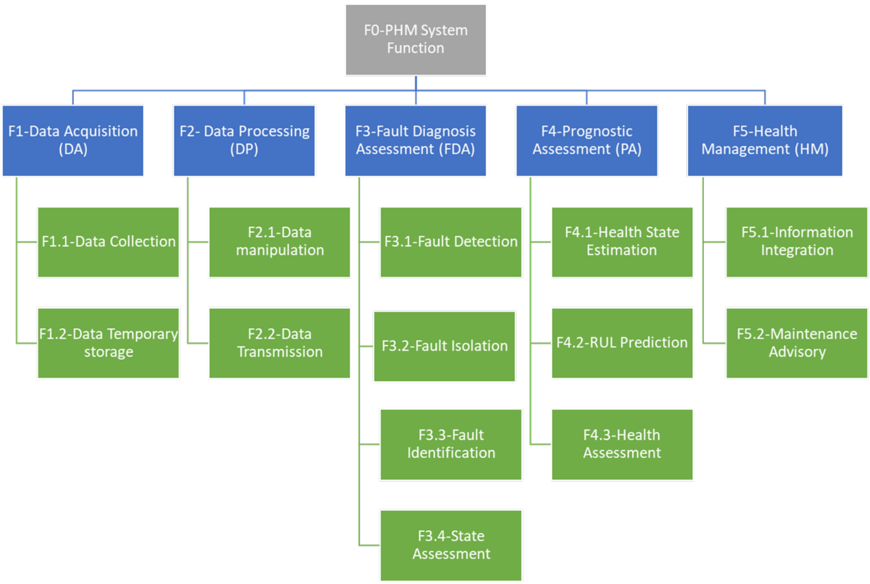

Figure 3.7: Functions tree of PHM system

- Functions/products matrix

Subsequently, the designers will acknowledge the implementation of those identified functions. It means the allocation from the functional domain mapping to the physical domain based on engineering considerations. In this case study, Table 3.2 indicates the functions/products matrix, which has led to the identification of the "elements" to be involved in the mission. According to the matrix, there are the physical elements of the cabinet (one), integrated computing module (one or multiple), and auxiliary power (one) within the boundary of a PHM system. Indeed, this matrix is dependent on the context of the physical architecture defined in the literature [42]. The core functions (in Figure 3.7) configure into the integrated computing module for implementation. Whereas the other support functions are embedded in the element of cabinet and auxiliary power, and these functions provide capabilities to support normal operating of a PHM system.

Table 3.2: An example of product and functions matrix

		Product elements		
		Cabinet	Integrated computing module	Auxiliary Power
Core Functions	F1-Data Acquisition		x	
	F2- Data Processing		x	
	F3-Fault Diagnosis Assessment		x	
	F4-Prognostic Assessment		x	
	F5-Health Management		x	
Support	Physical interface management	x		
	Power Management	x		x
	Built-in test equipment	x		

Nowadays, there are also other structures for supporting a PHM system, such as a federated architecture [43], a big data based center [44, 45], or a cloud-based one [46, 47], or a combination thereof [48], etc. For example, Mao et.al.[46] present a visual model-based framework to simulate and evaluate cloud-based prognostics and health management systems. They provide the concept of a three-abstraction-layer hierarchical architecture with the main elements: multiple distributed monitored units (each one embedded with PHM element and data sources element), the cloud-based PHM services layer for computing, and the interaction management layers with the elements of display panel and command interfaces. Compared with the proposal given in Figure 2, the relevant products are different from the one considered here. As such, it should be kept in mind that the products/elements and functions matrix is not unique, as it depends on design choices.

- Product tree

According to the product and functions matrix in Table 3.2, we can figure out the decomposition of these "elements". R. Li et al. [42] define a generic physical architecture of a ground-based PHM system that incorporates three major modules for implementation, which are the cabinet, auxiliary power module, and integrated computing module, and Figure 3.8 identifies the product tree within the boundary of a PHM system.

- Block diagrams, FFBD and work-flow

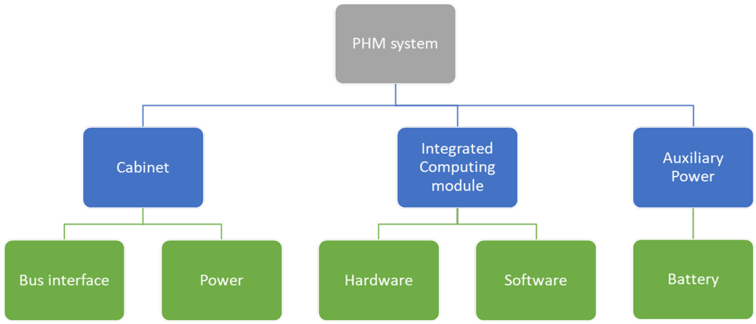

Figure 3.8: Product tree of PHM system

The functional/physical block definition diagrams are a black-box structure of the system, with the connections between components and external interfaces, and the interfaces present a whole part or composition, or communication relationship among the blocks [49]. While, the FFBD diagram analyzes the set of actions at each level in their logical, sequential relationship, with their required inputs and anticipated outputs, plus a clear link back to the multiple, higher-level task. In this case, the decomposition of high-level functions into simpler tasks leads to the definition of the sequence of operations, thus providing a compassionate system operation [25].

The literature has provided the functional/physical block diagrams and the FFBB diagrams to comprehend understanding the fundamentals and implementation of a generic PHM system [42]. Thus, this case study will not do that again. Alternatively, this research further identifies the functional work-flow of the PHM system comprehensively, as shown in Figure 3.9.

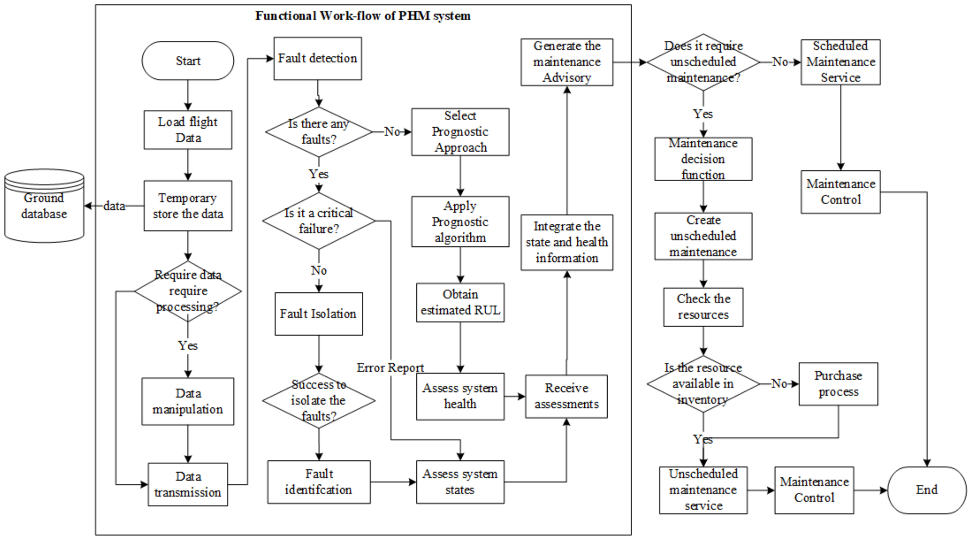

Figure 3.9: Work-flow of PHM system

b). Concept of operation

The ConOps is the description of what is impending from the system, including various modes of operation and time-critical parameters [35]. Typically, it involves evaluations of mission phases, operational scenarios, end-to-end communications strategy, operational facilities, integrated logistic support, critical events and, etc. Through the ConOps and use cases often reveals requirements and design functions that might otherwise be overlooked. An example to illustrate this point is adding system requirements to allow for communication during a particular phase of a mission. This requires an additional antenna in a specific location that may not be necessary during the nominal mission. In this case study, the PHM system is configured with the following operation modes: power on, initial, normal mode, testing mode, and power off. Table 3.3 figures out the modes of operation with the characteristics in each mode, which can drive a set of operational requirements.Figure 3.10 visualizes the mode transition though SysML modelling.

Table 3.3: Operation modes of PHM system

Mode	Description	Trigger	Transition
Power on	The system starts to operate when power on.	System power on.	initial
Initial	After power on, configure the configuration files base on the defined list, and check the required items during the initial.	Complete the power on.	normal idle testing
Normal	The normal operation to provide the defined functional capability and required performance	Complete the configuration and pass the checklist.	idle power off
Testing	This mode provides the integrators or developers a testing operation environment for integrating, testing and updating the system configuration. Check-in or check out this mode requires commands.	Required check-in commands during initial mode; required check-out commands to transform to initial mode.	initial power off
Idle	Idle any operations in a safe operating environment.	Any faults/failures in initial or normal mode, it transforms into idle mode.	normal power off
Power off	Shut down when removing the power.	Remove the power	NA

For an example of the normal mode, the term of operating states is defined for each function, including the specific operation state as well as the transition from one to another. Briefly, the transition between these states may be triggered by the receipt of a configured signal or behavior, such as a time-based event or customized event. Existing research [42] addresses the state diagrams for the functions of fault diagnostic assessment (FDA), prognostic assessment (PA), and health management (HM). Figure 3.11 presents the state diagrams of all functions in the normal mode within a PHM system boundary

TASK 2.3: DEFINE REQUIREMENTS

This paper summarizes the relevant categories of requirements, under the guidance of the proposed methodology. It means that the definition of requirements is based on the analysis results of FA and ConOps, as well as some the considerations regarding design resolution, constraints, cost limitations, etc. The functional requirements always play a critical role in system design, because they focus on the qualitative representation and capabilities of the PHM system.

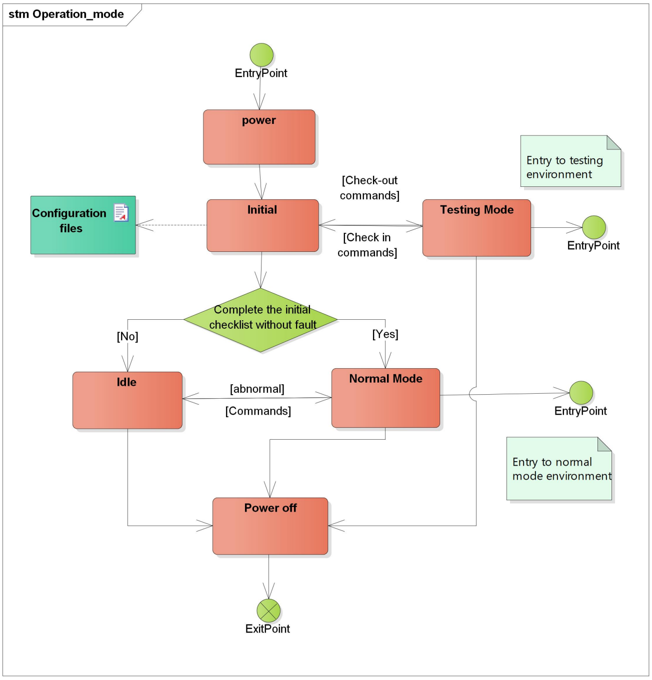

Figure 3.10: Modes of operation

The category of functional requirements describes the system's functional capabilities and characteristics of comprehensively. As examples of a case study, Table 3.4 presents a set of functional requirements for a generic PHM system. These requirements interpret the fundamental functions/capabilities of data acquisition, data processing, diagnostic assessment, prognostic assessment, and health management. Generally, such a methodology would enable the requirements specification of a system to achieve a consistent understanding, so that it provides a better understanding of what may or may not be achievable at the high level given the constraints at low levels.

Similarly important, the non-functional requirements combined with the constraints mainly provide the support for operating intended functions in a pre-defined environment. For instance, the performance requirements quantitatively describe the performance values, attributes, and features required to fulfil the intended system functions. Table 3.5 provides examples of performance requirements driven though the defined methodology for this case study. Likewise, Table 3.5 also presents requirements from other categories, for instance, representing the operating considerations, interface identification, reliability, maintenance characteristics, etc.

As explained in Figure 3.3.2, the loops and iteration between the tasks of requirements analysis and definition can improve the design maturity. In practice, engineers can define a limited set of requirements in the early phase. Subsequently, the methodology allows them to establish more requirements according to the design assumptions and design solutions in further phases. Additionally, the methodology also allows modi-

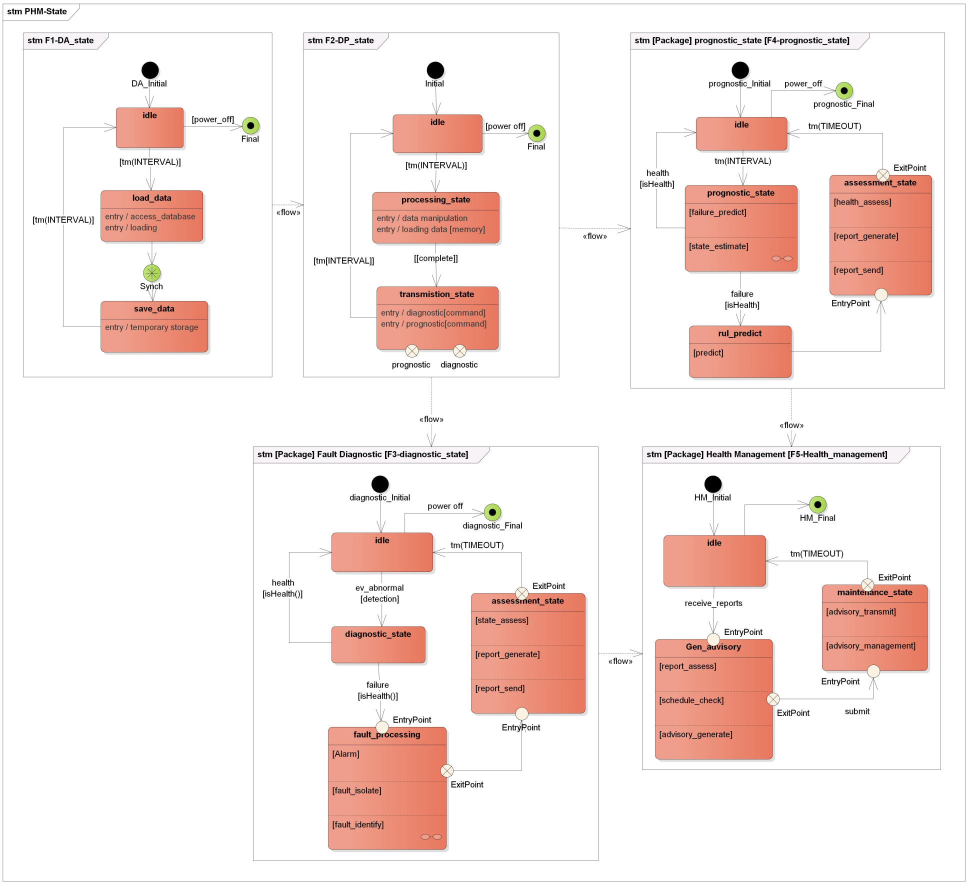

Figure 3.11: Functions operation states of PHM system

fying the requirements specification, if necessary, to deal with the identified issues throughout the whole development life-cycle. The design loops and iterations are the mechanisms to improve design quality and consistency to achieve a desired level of maturity.

TASK 2.4: VALIDATE REQUIREMENTS

Once the requirements specification archives a certain required level of maturity (depending on the project), it is possible to undertake requirements validation, as shown in Figure 3.3. This task is responsible for ensuring that output requirements from this level are individually correct and ensuring the completeness of requirements specification.

Correctness is a degree to demonstrate that an individual requirement is unambiguous, verifiable, consistent with other requirements and necessary for the requirement set. Accordingly, this case study firstly evaluates the correctness of each requirement thought a correctness checklist, as identified in Table 3.6. This checklist identifies all the criteria items to assert a good requirement, besides each requirement shall pass this check, otherwise, it means that the "not pass" requirement needs modification.

Table 3.4: Examples of functional requirements

HIGH-LEVEL
The PHM system shall relay system information to airline personnel on the ground. : Requirement
The PHM system shall collect aircraft system information on aircraft. : Requirement
The PHM system shall analyse the data to determine impending system degradation or failure. : Requirement
The PHM system shall produce actionable alerts to be addressed by the operator. : Requirement
The PHM system shall have the capability to download the data from data-sharing network. : Requirement
The PHM system shall resolve and track the alerts generated. : Requirement
ELEMENTS OWNED BY F1-Data Acquisition (DA)
The PHM system shall have the capability to download the data from data-sharing network to the ground database. : Requirement
The PHM system shall have the capability to load the data into the database module. : Requirement
The PHM system shall have the capability to access the database module. : Requirement
ELEMENTS OWNED BY F2- Data Processing (DP)
The PHM system shall have the capability to manipulate the data loading from the database. : Requirement
The PHM system shall have the capability to integrate the data information. : Requirement
The PHM system shall have the capability to transfer the data loading from the database to each module within the PHM system. : Requirement
ELEMENTS OWNED BY F3-Diagnostic Assessment (DCA)
The PHM system shall have the capability to detect abnormal operation condition(s) for the monitored system. : Requirement
The PHM system shall have the capability to detect the faults/failures of the monitored system defined in the functional hazard assessment (FHA). : Requirement
The PHM system shall have the capability to isolate any detected failures of the monitored system. : Requirement
The PHM system shall have the capability to submit the diagnostic assessment report to HM function. : Requirement
ELEMENTS OWNED BY F4-Prognostic Assessment (PA)
The PHM system shall be able to predict the failures of the monitored system defined in the functional hazard assessment (FHA). : Requirement
The PHM system shall predict the remaining useful life (RUL) of the monitored system. : Requirement
The PHM system shall have the capability to analyse the failures modes of the monitored system. : Requirement
The PHM system shall be able to submit the prognostic assessment report to HM function. : Requirement
ELEMENTS OWNED BY F5-Health Management (HM)
The PHM system shall have the capability to analyse the received assessment information. : Requirement
The PHM system shall have the capability to assess the health status for the monitored system based on the previous assessment and the last received assessment reports. : Requirement
The PHM system shall have the capability to make the appropriate decision about operational system configuration and maintenance actions based on health assessment status.: Requirement

On the other hand, it is possible to use the list of possible types of requirements and requirements templates to guarantee, as a basis for performing a completeness check of requirement, Individuals with a common stated need for the system may have unstated or unanticipated specific needs and expectations. Completeness is a probable

Table 3.5: Examples of other categories requirements

ELEMENTS OWNED BY Performance Requirements
The PHM system shall synchronize the health status to other external systems it interfaces with every 10 minutes. : Requirement
The PHM system shall diagnose 95% of all failures it is monitoring. : Requirement
The PHM system shall prognose 95% of all identified monitoring systems and components. : Requirement
The accuracy rate of RUL estimation shall be at least 85%. : Requirement
The PHM Algorithm Coverage shall be 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. : Requirement
The false negative for prognostics shall be the situation where failure occurs before predicted time (interval). : Requirement
The false positive for prognostics shall be the situation where failure does not occur until after the predicted time (interval).: Requirement
ELEMENTS OWNED BY Operation
The PHM system shall use two independent sources of power input. : Requirement
The PHM system shall have the battery device as auxiliary power. : Requirement
ELEMENTS OWNED BY Interface
The PHM system shall have the redundancy interfaces with the data-sharing network. : Requirement
ELEMENTS OWNED BY Reliability
The PHM system shall be at least 90% available for providing the configured functions in the normal mode. : Requirement
The critical components with the PHM system shall be at least 95% available for normal operations. : Requirement
ELEMENTS OWNED BY Maintenance
The critical components with the PHM system shall be at least 95% available for normal operations. : Requirement

Table 3.6: Correctness checklist

No.	Criteria checklist of a good requirement	Pass	Note
1	Are the requirements clear and unambiguous? (Are all the description of the requirement understandable?. Is there not subject to misinterpretation? Is the requirement free from indefinite pronouns (this, these) and ambiguous terms (e.g.,"maybe", "as appropriate", "and/or," "but not limited to", "etc."?))		
2	Are the requirements concise and simple?		
3	Is each requirement correct? Is each stated assumption correct? Assumptions must be confirmed before the document can be baselined.		
4	Are the requirements technically feasible?		
5	Do the requirements express only one thought per requirement statement, a standalone statement as opposed to multiple requirements in a single statement, or a paragraph that contains both requirements and rationale?		
6	Does the requirement statement have one subject and one predicate?		
7	Are all requirements at the correct level (e.g., system, segment, element, subsystem)?		

Table 3.7: Completeness checklist

No.	Criteria checklist of Completeness	Pass	Note
1	Is it apparent from the traceability and supporting rationale that the requirement(s) will satisfy the parent requirement?		
2	Are requirements stated as completely as possible?		
3	Are any requirements missing? Check it based on the categories of requirements.		
4	Are there any redundant? If there exist multiple requirements whose agent cases, whose goal cases, and whose condition cases are same nouns, respectively.		
5	Are there any inconsistent? If there exist two or more requirements whose agent cases are the same and whose condition cases are the same, but whose goal cases are different.		
6	Are there any incomplete? If there exists a noun that should respond but there is no time-response requirement whose agent case is the noun?		
7	Are the requirements stated consistently without contradicting themselves or the requirements of related systems?		

3

outcome of following a validation process that may include a combination of templates and checklists. This case study utilizes a completeness checklist, as shown in Table 3.7, to evaluate the set of requirements.

The requirement validation activities analyze the complete set of elicited requirements, including identifying and prioritizing the conflicting, missing, incomplete, ambiguous, inconsistent, incongruous or unverifiable requirements. Moreover, it also can resolve requirements problems. If there are some issues related to correctness and completeness, the proposed methodology recommends iteration activities to resolve issues through updating or modifying the requirements sets of the PHM system. However, any modifications of requirements should obtain the agreement from relevant stakeholders. Finally, it should be ensured that all the requirements are correct and the set of requirements specifications are complete.

TASK 2.5: FLOW-DOWN REQUIREMENT

The validated requirements indicate sufficient confidence to flow down from the higher-level to its constituent parts/low-levels to define precisely. One purpose of requirements flow-down is to provide the required performance for all faults. The underlying idea was that relaxation of recognition capability for some faults which have ample coverage from some tools might allow the tightening of recognition for other faults where one tool's performance is critical for the overall output [41].

This paper presents a step-by-step methodology for requirement flow-down, and this case study utilizes the methodology to explain the applicability. Figure 3.12 presents the prognostic assessment functions from top-level to lower-level, where the requirements flow-down. The prognostic assessment function, as one top-level function of the PHM system, is decomposed into three sub-functions, and further, the sub-function of health state estimation is implemented though health state evaluation, degradation models construction and threshold definition. Afterward, these functions are decomposed to lower-level till sufficient depth, as an example of PHM system design, as addressed in Figure 3.12. Along with an in-depth design, the top-level function is decomposed multiply to lower-level, which is the route of requirements specification flow-down.

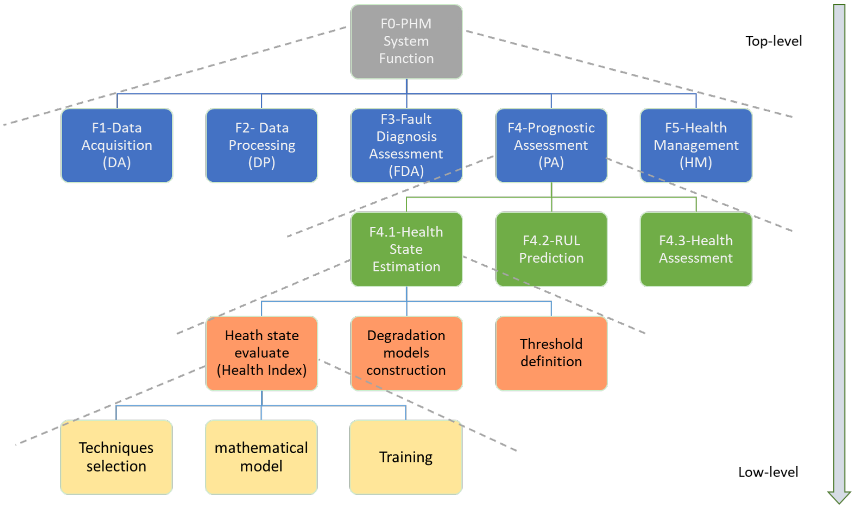

Figure 3.12: An instance of functional requirements flow-down

3.4.3. IMPLEMENTATION CONSIDERATIONS AND DISCUSSION

As PHM systems are part of a wider movement to generate intelligence maintenance decisions, it is important to discuss the correlations between the requirements definition of this case study and aircraft maintenance, particularly as this points the way towards future prototyping and implementation within industrial practice. To do so, in this final subsection, implementation considerations are discussed first, focusing on requirements management and the support of predictive maintenance. Subsequently, some general points underlying the case study are highlighted.

a). Requirement management

Requirements management is critical during any design phase, which is true for PHM design as well. Requirements management activities apply to the management of all requirements and the relevant technical material, such as requirement status, specification baseline, review information, and the traceability among the requirements.

When defining the requirements for the Gen-PHM project, all the relevant technical materials are maintained as an individual modeling project though the Sparx Enterprise Architecture . This case study establishes a modeling package, “Requirements Model”, to perform requirements definition for the Gen-PHM project. It assumes that this modeling project retains the information of stakeholders and their expectations addressed in Chapter 2. With such underpinning, this modeling project can enable traceability management via informatics linkages, even for multiple individual packages, which are organized consistently.

In particular, this case study concerns various categories of requirements to describe the specification capabilities for a generic PHM system, as shown in Figure 3.13. These requirements describe the characteristics of the system, specifying the functional, performance, operation requirements, as well as the non-functional requirements and project impacts constrains. Due to the stakeholder-oriented system design, it requires traceability from system requirements up to stakeholders' expectations to show compliance with customers' needs. Figure 3.14 presents the traceability of functional requirements up to the corresponding stakeholders' expectations, which have been defined in Chapter 2.

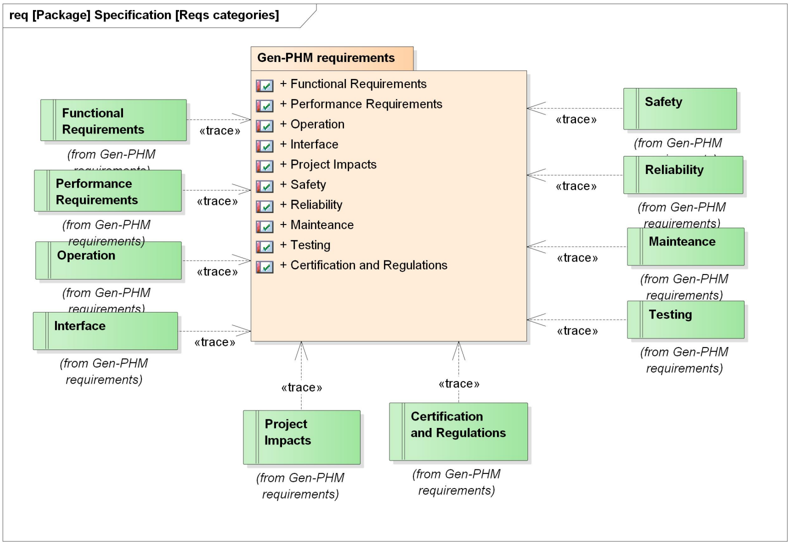

Figure 3.13: Requirements categories of Gen-PHM project

b). Support predictive maintenance

In industry, CBM and predictive maintenance are mature for some mechanical systems and components. In these cases, the degradation of mechanical equipment can be identified and used for predictions. However, the current state of research with respect to electronic equipment and the overall aircraft system is lagging behind. If accurate RUL prognostics would be consistently available, this would enable the interested parties to assess an equipment's health status and to plan future maintenance actions.

When conducting the requirements definition for Gen-PHM project, this process should consider how to design a system, which can support the aircraft predictive maintenance. This section discusses it from two perspectives. First, requirements definition involves the stakeholders, who are from the maintenance department or predictive maintenance users, e.g., MRO. As shown in Table 3.1, this group of stakeholders provides technical support about the physical and functional models of aircraft and their systems

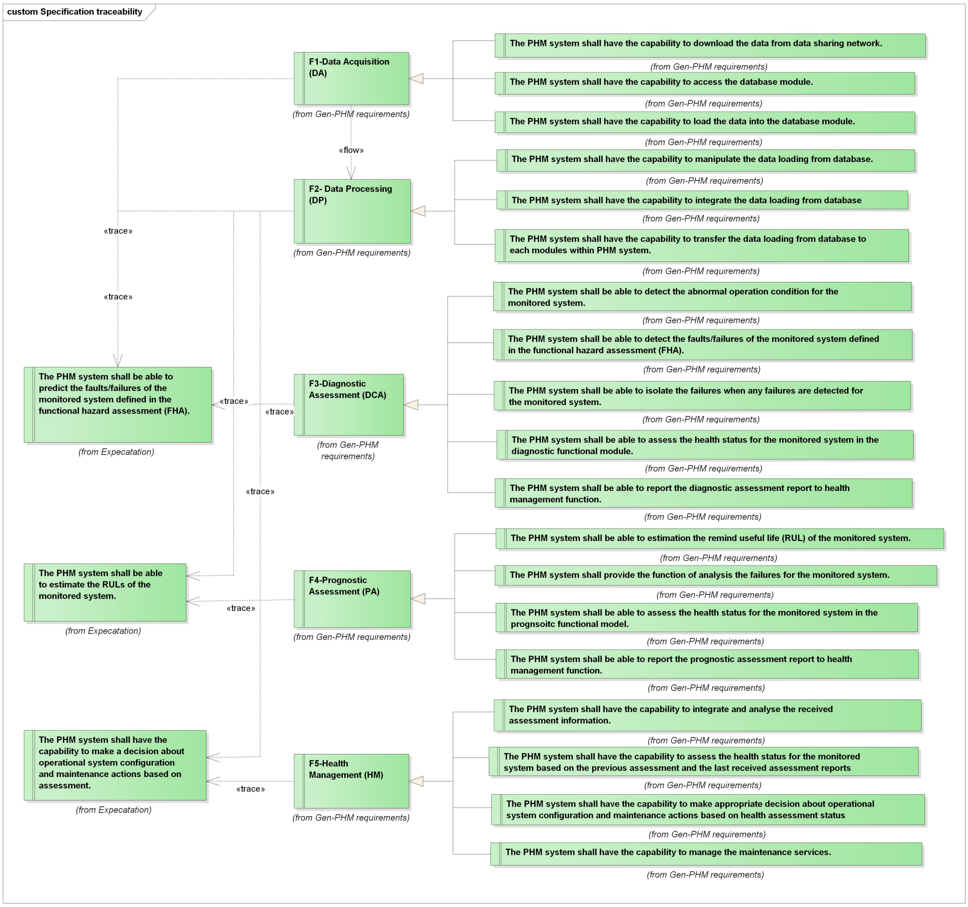

Figure 3.14: Functional requirements traceability

and identify what techniques would be fit for predictive maintenance. Accordingly, they raise the requirements of the diagnostics and prognostics from functional and performance views. Secondly, Figure 3.9 has identified the activities outside the boundary of PHM systems to perform the relevant maintenance services. As illustrated in Figure 3.9, the PHM system can generate maintenance advisories according to the current health status and the estimated RULs for the target systems. Then, a decision has to be made regarding unscheduled maintenance. If the decision is "No", the process will proceed to scheduled maintenance planning prior to performing maintenance activities. Otherwise, it is necessary to create unscheduled requests and check the available resources, potentially raising subsequent actions (e.g. purchase orders). Afterward, the unscheduled maintenance activities are performed within the management and control of maintenance operations. If Remaining Useful Life (RUL) can successfully be estimated, organizations would be able to predict the required maintenance activities before any failure. It means that the sooner an accurate RUL prediction can be made, that the sooner early maintenance actions can be planned. For example, the operators can analyze the margin between the estimated RULs and the pre-defined unhealthy threshold. When the estimated RULs are in the area of un-healthy, the operators can make the maintenance decision and scheduled the activities before any failures. Accuracy in predictive maintenance drives more accuracy in maintenance decision making. PHM systems are a key contributing technology in this regard, emphasizing the need to have a clear, unambiguous and practical requirements definition process for these systems.

c). General discussion

This case study has applied the methodology defined in Subsection 3.3.2 to define a set of requirements specifications for a generic PHM system. From an external point of view, this case study makes sure the customer needs have been fully covered and correctly understood. From an internal point of view, it settles the core requirements that will be developed at lower levels. Defining indisputable requirements and expectations, notably between two independent parties (such as with a subcontractor), is one of the guarantees to avoid future conflicts or reworks. When analyzing requirements, the following aspects are exhaustively covered: the main functions, the functional/physical elements, and the relevant use cases that show different functions, situations, and actors interacting with the system and how the system is expected to work in those cases. Table 3.4.2 presents a process to evaluate the quality of requirements from the aspects of correctness and completeness. If there are any issues, iteration and loop activities can be deployed to resolve these issues to achieve correctness and completeness. Finally, the high-quality PHM requirements specification flows down to the lower-level for further detailed design activities.

In summary, this case study establishes a typical application study of requirements definition from a systematic perspective. It also contributes towards practical considerations toward the design of a PHM system. However, to be a best practice, the case study still has some weaknesses to be addressed. For example, the iterative elements of requirements are insufficient, notably at the lower levels (e.g. software or hardware). The involvement of various stakeholders is inadequate, which calls for more corporation between academics and industry.

3.5. CONCLUSION

This paper has developed a systematic design methodology of requirements definition for PHM systems, as shown in Figure 3.3. This methodology emphasizes the processes and relevant steps regarding requirement definition, as well as means for each category of requirements to be derived through appropriate analyses. Furthermore, the proposed methodology identifies the sequence of interoperability requirements categories and the solution of requirements flow-down with step-by-step descriptions. Requirement definition activities can continue within the system design process recursive loop until a preferred system solution has been fully delimited. The case study of the Gen-PHM project is undertaken to present a comprehensive understanding of the entire methodology. The case study captures a set of requirements for the PHM system according to the stakeholders' expectations and the analysis results of FA and ConOps. To ensure the design quality, relevant validation activities were performed.

In summary, this paper develops a comprehensive requirements definition methodology and describes the practicable steps in detail, thereby achieving the primarily contributes and novelties as follows:

- The proposed methodology of defining requirements premeditates the practicable steps in detail and interprets requirements validation and requirements flowdown ensuring consistent design.
- The established Gen-PHM project of requirements specification provides examples of best practices as guidance for engineers.
- The designers can perform requirements definition under this methodology as guidance to design a successful PHM system, providing solutions for predicting remaining useful life (RUL) to support aircraft predictive maintenance.

Apart from these contributions, the research still has some shortcomings to be addressed in future work. In the field of the PHM system, it is a challenge to implement a generic PHM system with associated diagnostic and/or prognostics techniques in a practical situation. Therefore, requirements verification for a generic PHM system and interrelated techniques is lacking. Successful real-life implementation and verification of prognostics techniques are faced with tremendous challenges. More effort should be made in providing PHM best practices and effective V&V solutions and tools in real-life industries. Finally, the involvement of various stakeholders is inadequate, which calls for more corporation between academics and industrial partners.

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4

DESIGN METHODOLOGY OF SYSTEM ARCHITECTURE DEFINITION

This chapter proposes a methodology for PHM architecture definition that can guide the design of architecture. Chapter 3 *transforms the stakeholder expectations into a complete set of system requirements and both are the inputs for defining the system architecture. Nonetheless, a systematic methodology has not yet been well established towards a consistent definition of the PHM architectures. The characteristics of generic PHM architectures have not been defined in an in-depth and complete manner, which impedes the development of PHM systems in practice. Moreover, it also builds a generic PHM architecture with various characteristics under the guidance of the proposed methodology. The validated and verified PHM architecture can provide engineers a generic practice case.*

This chapter is based on following article:

Li, R., Verhagen, W.J. and Curran, R., 2020. A systematic methodology for Prognostic and Health Management system architecture definition. Reliability Engineering & System Safety, 193, p.106598.

Prognostic and Health Management (PHM) enables the prediction of failures in aircraft systems/components resulting in reduced airline maintenance costs and increased availability of assets. The researchers have developed a multitude of applications for the aircraft-specific system remaining useful life (RUL) prediction. However, the proposition of such advanced techniques leads to challenges in practical uptake of prognostics. Redefining observations into more meaningful and comprehensive health assessment, that provides crucial information, can tackle the deficiency of accurate RUL estimation. Yet, it is difficult to make a prior determination of specific practical techniques to construct an accurate prediction. Along with this, a consistent understanding of key characteristics for prognostic implementation is lacking. To overcome these drawbacks, this paper introduces a generic data-driven prognostic process for RUL prediction. Correspondingly, a practical framework of data-driven prognostics is presented, covering key characteristics of prognostic techniques with particular consideration of statistical and machine learning (ML) models. Summaries of case study results express the applicability of the generic prognostics process and the practical framework in RUL prediction. This research enhances a comprehensive understanding of prognostics and provides a practical framework to identify data-driven prognostic approaches for subsequent implementation and RUL prediction.

4.1. Introduction

Prognostics and health management (PHM) has emerged as one of the key solutions for improving system reliability, safety, maintainability, supportability, and economic affordability for major industrial assets (e.g. aircraft, power plants, trains). A growing amount of literature has evaluated diagnostic and prognostic technologies with the aim to optimize asset operations and maintenance while improving safety, reliability, and cost-effectiveness [1, 2]. Moreover, many papers discuss key aspects of system maintenance and PHM systems, such as maintenance principles [3–5], cost and efficiency [6–8], safety and reliability [9].

PHM describes a set of capabilities involving both diagnostics and prognostics: diagnostics concerns the process of fault detection and isolation, while prognostics is the process of predicting the future state or remaining useful life (RUL) according to current or historical conditions [10]. In Niu's research [11], it is stated that the design team should 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. PHM research has a specific focus towards the management of some of this complexity via monitoring, diagnostic, and prognostic technologies. The strategic application of PHM technologies has been shown to effectively reduce equipment/process downtime and lower maintenance costs [12]. Part of the challenge of PHM, particularly for manufacturers, is to know exactly how to apply PHM within the operations to gain the maximum actionable information [12].

Currently, in research a number of applications has been developed for asset-specific modeling and prediction in an independent fashion [13–15]. Consequently, there is some inconsistency in the understanding of key concepts for designing prognostic systems. In order to progress from application-specific solutions towards structured, consistent and efficient PHM system implementations, the development and/or use of suitable methodology is essential [16]. Such a methodology should address the following high-level requirements: 1) it should be unambiguous, i.e., the concepts and terminology used should be defined well, without being open to multiple competing interpretations; 2) it should be comprehensive, i.e., it should cover all essential steps in developing a PHM system; 3) it should be pragmatic, i.e., researchers and practitioners alike should be able to apply the methodology in a straightforward fashion. This paper addresses all elements identified.

In relation to point 1, it is essential to identify and define the following three key terms and their interrelations: methodology, framework, and architecture. The definitions and their interpretation are identified in Figure 4.1. Here, methodology is viewed from the lens of design, where the concept of design methodology refers to the development or method for a unique situation, with the collection of related processes, methods, and tools used to support a specific discipline [17]. As such, a methodology does not provide solutions – rather, it is the systematic study of approaches to generate solutions. Moving one step from process to actual ideation and instantiation, the term 'framework' mainly describes the layered structure of a system for a set of functions in a conceptual view. Building on this conceptual perspective, the system architecture moves to the application level and concerns the fundamental concepts or properties of a system in its environment as embodied in its elements, relationships, and in the principles of its design and evolution [18]. The concept of 'view' is important to mention in relation to the system architecture. A view is a representation of a system from the perspective of a related set of concerns, and usually, it is a work product that presents specific architectural data for a given system. A view allows a user to examine a portion of a particular interest area. For example, an information view may present all functions, organizations, technology, etc. that use a particular piece of information, while the organizational view may present all functions, technology, and information of concern to a particular organization.

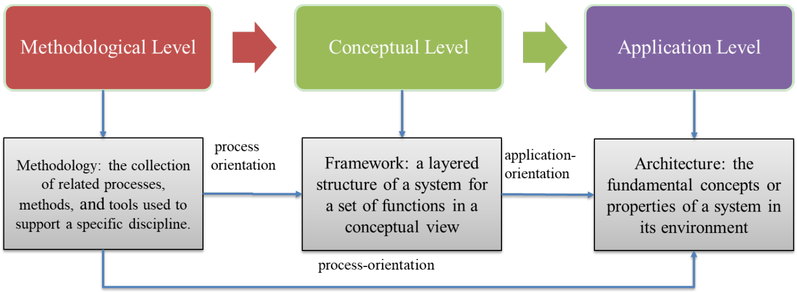

Figure 4.1: Key terms and their interrelations

Given the complexity and breadth of PHM systems and associated technologies, methodologies are necessary to initiate, sustain and complete PHM system development, thereby covering the conceptual and application levels as mentioned above. Previous research touches upon one or more of these key terms as described in more detail below:

a). Design methodologies

In existing research, a group of authors has reviewed design methodologies for PHM systems and associated techniques [19, 20]. For example, Dumargue et al (2016) present various aspects of a design methodology, including general system design, project management considerations, and transversal methodological items, such as model-based systems engineering and methods to manage the technical elements of the system [21]. Cocheteux et al. (2009) express a methodology to formalize functional and dysfunctional system knowledge and provided guidelines for designing prognostic process, including a selection of failure modes and associated prognostic tools [22]. Vogl et al. (2016) have introduced a process of PHM system development [18]. This process starts with cost and dependability analyses, and then the data management system is initialized for collection, processing, visualization, and archiving of maintenance data. Once the measurement techniques are established, the diagnostic and prognostic approaches are developed and tested. However, this process lacks discussion of the conceptual and application levels; notably, a process of developing a system architecture is missing. Aizpurua et al. (2015, 2016) formulate a methodology for designing prognostic applications (ADEPS), which is a design selection framework to guide the engineer towards a prognostic approach through a cause-effect flowchart [23]. This research primarily addresses the critical step of selecting and applying an appropriate prognostic approach for PHM applications, but does not cover PHM system development or engineering [24, 25].

b). Frameworks

A substantial amount of research has been performed with respect to PHM frameworks. As mentioned before, it is crucial that a methodology is comprehensive, Mao et al. present a visual model-based framework to simulate and evaluate cloud-based PHM systems [26]. The framework proposes a three-abstraction-layer hierarchical architecture to represent distributed data sources and a cloud-based PHM service center. The design of the framework is based on system modeling language and allows flexible implementations of functional modules and algorithms. Similarly, Yang et al. (2016) introduce a new framework on the basis of the concept of a PHM big data center and discuss the associated key technologies, scientific problems and application systems [27]. Zhang et al. (2015) recommend a framework integrating health status monitoring and health management of aircraft in order to build a suitable mechanism for managing diagnostics, prediction, and intelligent maintenance decision making [28]. As a common thread, the aforementioned papers propose PHM frameworks in a high-level manner, without a detailed description of elements and interfaces, and without an explicit connection with a governing design methodology.

c). Architecture

The architecture definition for a PHM system plays a critical role to move from a conceptual to an applied level regarding the functions of diagnostics, prognostics and predictive maintenance services for complex assets. A PHM architecture should be complete and consistent over time. To ensure this, updates for knowledge bases and algorithms should be supported, providing an advantage over static legacy systems. For aircraft, one best practice is to develop the on-board and off-board system together [18].

Alternatively, a separate off-board (ground-based) system can be developed, integrating the required diagnostic and prognostic techniques. To meet multidisciplinary requirements in PHM, Han et al. [29] define a distributed and universal platform for the implementation and verification of PHM systems using a configurable system of systems (SoS) architecture. Keller et al. [30] describe the concepts and properties of an onboard HM architecture for aerospace vehicles and how this architecture addresses affordability and can be adapted for a range of aerospace vehicles. Keller et al.'s research also provides a discussion of HM architecture aspects, such as the choice between distributed or centralized, open or proprietary, and flight critical or support critical alternatives, as well as feasible approaches to integrate the related HM functions with an existing system. Towards the use of open system architectures, PHM designers can apply various standards. For instance, the standard ISO-13374 defines an Open System Architecture for Condition-Based Maintenance (OSA-CBM) specification as a standard for moving information in a CBM system [31]. This open architecture provides guidance towards PHM design and enables the interoperability and communication between different CBM systems [32, 33]. In addition, IEEE standard 1856 [34] provides information for the implementation of PHM, which can be used by manufacturers and end users for planning implementation and the associated life-cycle operations for the system of interest. However, the architecture of OSA-CBM lacks connection with the higher-level methodology and framework. Also, it lacks to provide detailed application cases of integrating aviation health management systems into the supporting infrastructure for aircraft maintenance.

4

In summary, existing literature addresses aspects of PHM design methodology and provides PHM architecture formulations. However, a systematic methodology towards a consistent definition of PHM architectures, i.e., one that spans the conceptual and application level, has not been well established. The characteristics of generic PHM architectures have not been dealt with in an in-depth and complete manner; usually, interoperation between PHM system and the aircraft on-bound maintenance/health management systems is lacking. As PHM systems are complex, the design of these systems and their components requires the use of systems engineering methods to ensure a more complete and consistent design to mitigate possible rework and ineffectiveness issues during the development life cycle [21]. With these considerations in mind, this paper defines a systematic methodology incorporating functional, logical, and physical views for system architecture definition using a systems engineering approach. Systems engineering provides the methods and tools to design the right product (satisfying customer needs) and design the product right (functional and effective) while optimizing project aspects (quality, cost, time). In addition, a second contribution to the current state of the art is made by proposing, a generic PHM architecture is proposed, incorporating a framework, functional decomposition, functional/logical architecture description, and physical architecture.

The remainder of this article is structured as follows: Section 4.2 uses a systems engineering approach to propose a systematic methodology for PHM framework and architecture definition. In Section 4.3, a generic PHM architecture is formulated according to the systemic methodology. Section 4.4 presents a case study in which the proposed PHM architecture is modeled in SysML to subsequently verify and validate the PHM architecture. Another case study is conducted to demonstrate the consistency, applicability, and compatibility of the PHM architecture through the methods of functions analysis, interfaces analysis, traceability analysis and compliance analysis in Section 4.5. Finally, conclusions and recommendations for future research are addressed in Section 4.6.

4.2. ARCHITECTURE DEFINITION METHODOLOGY

This section introduces a design methodology for architecture definition using a systems engineering approach, and the novelty of this process is:

- Combining the concept of requirements, functional, logical and physical architectures ("RFLP") into a PHM architecture design methodology, where the concept of "RFLP" is defined in Subsection 4.2.1 and Figure 4.2;

- Proposing a systematic PHM architecture design methodology, as highlighted in Subsection 4.2.1 and Figure 4.3;

These aspects provide a guide for system designers toward the development of PHM architectures in a systematic way. The specifics are addressed in the following subsections.

4.2.1. ARCHITECTURE DEFINITION PROCESS

System architecture design has features, properties and characteristics satisfying the problem or opportunity expressed by a set of system requirements (traceable to stakeholder requirements) and life cycle concepts (e.g., operations, support). Architectures are implementable through technologies (e.g., mechanics, electronics, hydraulics, software, services, procedures) [35]. To conduct the architecture definition, this research introduces a methodology, based on the concept of "RFLP" (requirement, functional, logical, and physical architectures), as illustrated in Figure 4.2 [36, 37]. This methodology can progress from system requirements, representing the problem from the stakeholders' point of view, as independent of technology as possible, to an intermediate representation of functional/logical architecture, to a subsequent allocation of the functional elements to system elements of a candidate physical architecture, which is related to technologies and is an input of the design solution process [35].

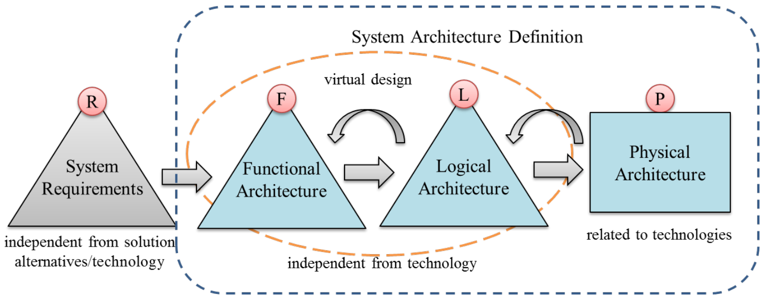

Figure 4.2: Concept of "RFLP" in Architecture Design

More specifically, this research proposes a methodology operating in a recursive and iterative manner from a system engineering perspective. The methodology flowchart is shown in Figure 4.3. Generally, it assumes that system requirements and constraints are available as input in this process. It subsequently incorporates the following primary activities:

1). Task 3.1: Define system framework;

2). Task 3.2: Develop the system architecture (functional, logical and physical views);

3). Task 3.3: Allocate requirements to architecture elements to form derived requirements.

Additionally, the system requirements and related project or technical constraints delivered from the requirements definition process are the inputs of the architecture definition process. The output is the system architecture specification with the traceability information (history, parent requirements, derived requirements, etc.) for each item. Obviously, Task 3.2 plays a crucial role in constructing a PHM architecture in details, which are highlighted in Figure 4.3. Comparing with other methodologies, this task has the novelty of defining architecture from functional, logical and physical views.

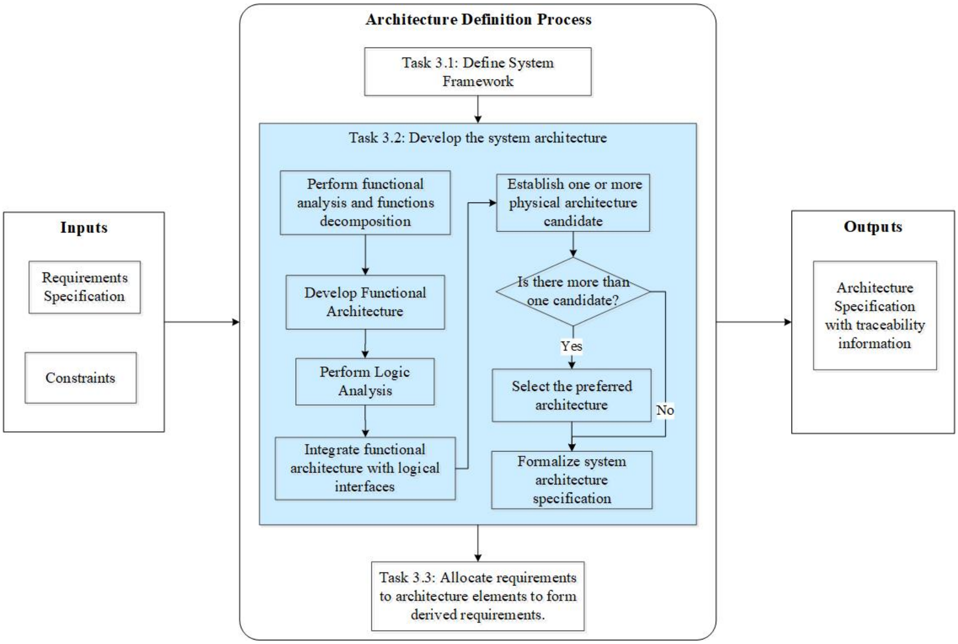

Figure 4.3: Architecture Definition Process

TASK 3.1: DEFINE SYSTEM FRAMEWORK

At first, the definition of architecture requires the necessary inputs of system requirements specification as the developed architecture should be fully compliant with requirements, as shown in Figure 4.3. While, in some cases, some constraints should be considered in the process of architecture definition, because that may impact the selection and configurations of the technique. Secondly, this process starts with a definition of the system framework. The system framework incorporates the basic structure of a system according to the requirements while comprehending the functions, performance, operational conditions, and project constraints that will influence the architecture [35]. In this case, the associated framework to assist the system architecture development is established and identified according to the defined set of stakeholders' expectations and requirements. Additionally, the system framework describes the layered structure indicating what kind of programs can or should be built and how they would interrelate, as the prototype of architecture, which is on the basis of the current technologies, legacy research, and the knowledge of system [38].

TASK 3.2: DEVELOP SYSTEM ARCHITECTURE

The next activity is to develop the system architecture in view of the established system high-level framework. The essential aspects of this task are to generate the functional, logical and physical elements and identify the interactions among systems and elements, to complete the design of a system architecture specification compliant with the given requirements and previously defined system framework. As presented in Figure 4.3, this task includes the following steps:

a). Perform functional analysis and functions decomposition

A system is intended to satisfy predefined functions, with the top-level functions defined as the stakeholder need, and a function is a characteristic action or activity that needs to be performed to achieve the desired system objective (or stakeholder need) [38]. Therefore, this task starts with the definition of top-level functions according to the stakeholders' expectations and intended system objectives. Afterward, these top-level functions are functionally decomposed to lower levels in a hierarchical structure. The process of functions decomposition may consider domain knowledge (e.g. aircraft, PHM, power plant, etc.), the availability of techniques or material (e.g. diagnostic, prognostic, data processing techniques, avionics, monitoring sensors, etc.), as well as the project mission (project objectives, resources, etc.). The functional analysis method can be used to identify and check the functions and sub-functions that accomplish the project mission.

b). Develop functional architecture

According to the previous steps, sufficient information is available to start the development of functional architecture including system boundary, functional elements, and external/internal interfaces. In addition to the list of functions from the step of "Perform functional analysis and functions decomposition", the functional architecture development involves analysis of the functions' hierarchy, input-output flows, and operational scenarios of the target system. In other words, the functional architecture is a set of functions and their sub-functions that enables to identify functional interfaces and interactions between system elements. It ensures that the system functions and the related requirements are analyzed, decomposed, and functionally detailed across the entire system in a feasible and effective manner [39]. Therefore, it can be described with a hierarchical arrangement of elements and interfaces that represent the complete system from a performance and functional perspective in the views of a context or a visual model through the commercial tools, such as Enterprise Architecture [40], CATIA V6 [41] and Rational Rhapsody [42].

c). Perform logic analysis

The logical architecture is composed of a set of related technical concepts and principles that represent the logical operation of the system. Logic analysis is performed to capture system behaviors, execution sequencing, conditions for control or data-flow, states and operation mode, as well as performance level(s) necessary to satisfy the system requirements [38]. Simultaneously, the trigger condition of the states or operation mode transmission should be identified. The trigger (a control flow) is an element that activates a function as a condition of its execution, which characterizes the logical relationship between different functions or services.

d). Integrate functional architecture with logic interaction

Comparing with functional architecture, logical architecture is a structural design that gives as much detail as possible without constraining the architecture to a particular technology or environment [35]. It is the manner in which logical components of a solution are organized and integrated, with the aims of planning and communicating architecture. Both functional and logical architectures are part of a virtual design process. This activity is used to ensure the consistency between functional elements and the sets of logical behaviors.

e). Establish one or more physical architecture candidates

Afterward, one or more physical architecture candidates are established to determine the elements that can perform system functions and organize them into a physical architecture [43]. Generally, the more candidates there are, the higher the cost will be for evaluation and selection. Due to this consideration, and to maintain effectiveness and economically sensible decision making in practice, the number of candidates is not recommended to exceed 3. In this sense, the physical elements could be materials and artifacts, such as equipment made of hardware, software and/or human roles. Practically, one requirement is that each physical architecture candidate should be compliant with the functional and logical views as well as system requirements via the implementation of related technologies. Hence, the physical elements (configuration item) and interfaces (data flow and format) are specifically identified in each physical architecture candidate.

f). Select the preferred architecture, if necessary

Once the physical architecture candidates are established, if there is more than one, the preferred one should be selected throughout a trade-off process involving all candidates. Otherwise, this step is skipped [35, 44]. It is critical to define how to evaluate the physical architecture candidates; therefore, it is required to establish guiding principles for the system design and evolution metrics, including the list of criteria items (e.g. cost, technical risk, re-usability, economic, pollution, noise) and the criteria weights, which depend on the stakeholders' expectations and project constraints. In the other words, the objective of this task is to provide the "preferred" possible architecture made of suitable system elements and interfaces, that is, the architecture that answers, all the stakeholders' needs and system requirements [44]. The process involves the creation of several candidates; analyzing and assessing the defined candidates by applying system analysis, measurement, and risk management process using the evaluation criteria; as a result, selecting the most suitable one. Moreover, the trade-off concerns the decision making actions that select a solution from various alternatives on the basis of the defined evaluation criteria.

Sometimes, the physical architecture candidates apply different technologies to satisfy the same requirements or functions. For instance, the PHM system can implement the communication function among different modules within the system boundary via the point-to-point technology (candidate A) or broadcasting technology (candidate B). Such selection requires criteria to evaluate these two candidates.

In some cases, the "preferred architecture" is not the one which delivers the highest performance. For example, a power supply system can be configured with a power supply bus as candidate A, or it can be configured with two power supply buses and an auxiliary power device (e.g. battery) as candidate B, to build the set of system implementation options. In this case, candidate B has a highly robust configuration with the consideration of redundancy (two power supply bus) and auxiliary power solution (battery) for emergency events, which is able to improve the availability and reliability of a system, in comparison with candidate A. However, candidate B may have the issues of over-weight and more cost. In the view of that, the preferred architecture selection depends on the trade-off process and the specific constraints in a project. If it is a system that not requires redundancy and auxiliary power, the preferred architecture may be candidate A due to its low-cost and acceptable performance.

g). Formal system architecture specification

Architecture and design activities require spending several iterations from functional/logical architecture definitions to physical architecture definitions and vice versa until both functional/logical and physical architectures are exhaustive and consistent [38]. Multiple iterations of these activities feed back to the evolving architectural concept as the requirements flow down and the design matures. However, the times of iterations are generally limited due to technical or managerial considerations. The need for further iterations is generally tied to project milestones and reviews. Finally, the technical material in this process is documented, which consists of the functions hierarchy, functional/logical architecture description, physical architecture description, traceability, and analysis evidence, like the initial/updated version of system architecture specification.

TASK 3.3: ALLOCATE REQUIREMENTS TO ARCHITECTURE ELEMENTS TO FORM DERIVED REQUIREMENTS. DEVELOP SYSTEM ARCHITECTURE

In practice, "system architecture development and the allocation of system requirements to item requirements are tightly coupled and iterative processes, and in each cycle, the identification and understanding of derived requirements increases and the rationale for the allocation of system-level requirements to hardware or software at the item level become clearer" [38]. Derived requirements are requirements that are not explicitly stated in the set of stakeholder requirements, yet are required to satisfy one or more of the stakeholder requirements. They arise from constraints, consideration of issues implied but not explicitly stated in the requirements baseline, factors introduced by the selected architecture and the design. These requirements become the basis for the solution-specified requirements for the system model and are a 'design-to' requirement for the system [45]. In this process, such requirements supplement the system requirements specification to improve the maturity of development life cycle.

4.2.2. VALIDATION AND VERIFICATION CONSIDERATIONS

The process of validation and verification is required to ensure that the architecture definition satisfies the requirements and constraints, by a correct and complete representation of architectural characteristics. Validation is the set of activities ensuring and gaining confidence that a system is able to accomplish its intended use, goals, and objectives (i.e., meet stakeholder requirements or top-level functions) in the intended operational environment [35]. Several methods can support the activity of validation, including traceability, analysis, modeling, test, similarity and engineering review. For example, modeling and simulation used during architecture definition can significantly verify the design items and reduces the risk of failure in satisfying the system mission and performance requirements. Wheatcraf [46] defines that verification refers to the basics (structure) of the item, making sure it meets requirements that drive the creation of the item, standards and best practices (external and internal) on the design, or requirements on the system. General verification methods consist of inspection or review, analysis, modeling, test or demonstration, and service experience. The objectives of validation and verification in the architectures definition process are identified as follows [46]:

a). Confirm that the intended functions have been correctly and completely structured in functional architecture.

b). Examine the behaviors and the transmission of the states of a system.

c). Check the compliance of the defined elements and interfaces.

d). Confirm that the requirements (a group the requirements as a set of functions) have been satisfied.

e). Inspect the consistency during development.

Several papers have discussed the methods of validation and verification for complex systems [47–49]. Furthermore, some literature has discussed the state of the art regarding validation and verification issues in diagnostic, prognostic and health management research [50–52].

4.3. APPLICATION TOWARDS PHM SYSTEM ARCHITECTURE DEVELOPMENT

In this section, a generic PHM architecture is developed in accordance with the proposed methodology discussed in Section 4.2.

4.3.1. FRAMEWORK

A PHM system involves the specific processes for predicting future behavior and RUL of the monitored system, within the context of the current operating state, future operations and the scheduling of required maintenance actions to maintain systems health [36]. In this paper, a three-layer framework of PHM system is defined to effort aircraft maintenance (e.g. covering systems and components such as the engine(s) and landing gears) services, as shown in Figure 4.4. This framework is split into three layers: the onboard layer (aircraft systems, engines, and monitoring sensors), the communication layer (aircraft transmitted system and networks) and the ground layer (airline/manufacturers' ground mainframe computing system and PHM system).

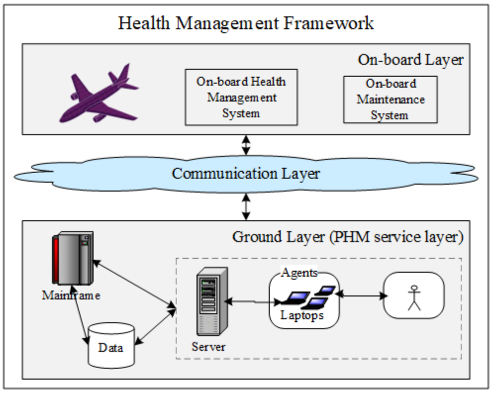

Figure 4.4: Conceptual design of the framework

4.3.2. SYSTEM FUNCTIONS

The system function is the intended behavior of a product according to a set of requirements regardless of implementation in the guidance of ARP4754A [53]. In accordance with the top-level objectives of PHM systems, this paper recommends the top-level functions of the PHM system consist of:

- F1-Data Acquisition (DA)
- F2-Data Processing (DP)
- F3-Fault Diagnostic Assessment (FDA)
- F4-Prognostic Assessment (PA)
- F5-Health Management (HM)

As shown in Figure 4.5, the PHM system has the capability of data acquisition (DA) to collect a significant amount of information from the various in-flight systems (e.g. engine data, sensor data, fault reports, pilot reports) [27]. Once the information is obtained, a data processing (DP) function is able to transmit them to configured functions after necessary manipulations produced on the raw data. On one hand, when the data is transmitted to the fault diagnostic assessment (FDA) function, it has the capability to determine the state of a component or system. This is performed on the basis of fault detection, fault isolation and fault identification by dedicated algorithms [54]. On the other hand, the prognostic assessment (PA) function performs prognostic assessment which includes health state estimation, as well as predicting and determining the useful life of a component/system by modeling the degradation progression in accordance with the operational data [55]. Finally, the health management (HM) function has the capabilities to generate informed and appropriate maintenance advisor via analyzing the assessment information (e.g. state assessment, health assessment, environment and operations).

The top-level functions are systematically decomposed into sub-functions by functions hierarchy diagram which shows all the functions involved in the system in a hierarchical manner, as shown in Figure 4.5. Additionally, one hypothesis is that these functions have the characteristic of robust partitioning. The partitioning means that an architectural technique provides the necessary separation and independence of functions or applications to ensure that only the intended coupling occurs. The process of separating, usually with the express purpose of isolating one or more attributes of the software, prevents specific interactions and cross-coupling interference.

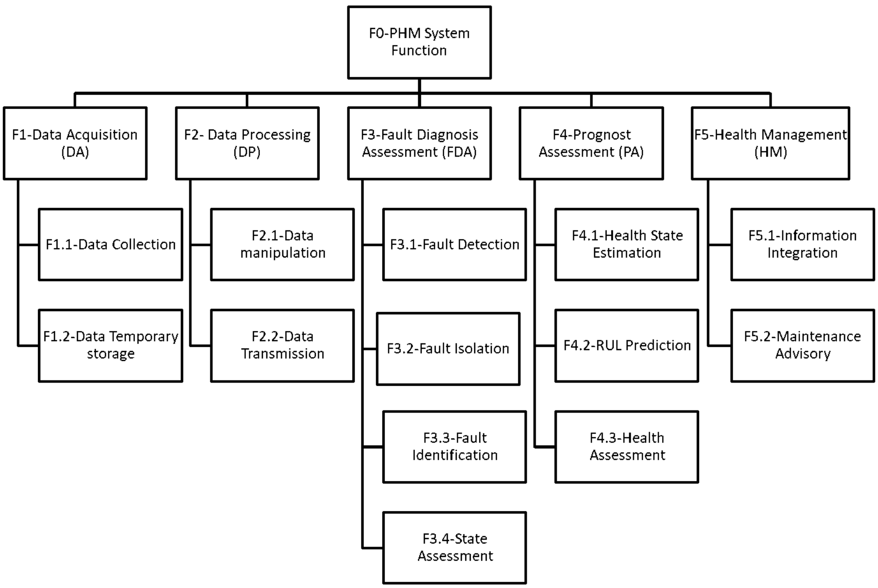

Figure 4.5: PHM function hierarchy diagram

4.3.3. FUNCTIONAL ARCHITECTURE

The health management system of aircraft is composed of onboard systems and ground-based systems, to sustain enhanced information for fault forecasting, troubleshooting, and maintenance history with the help of real-time flight data, so as to decrease scheduled maintenance on the ground and increase the maintenance efficiency.

PHM systems are typically, but not necessarily, defined as being a ground-based health management system (off-board PHM), which is the option pursued here. As a consequence, a generic functional architecture of PHM system is defined in Figure 4.6, in accordance with the advance research of literature [26, 27, 56]. This figure identifies the system boundary and the decomposed functional elements, as well as the internal interfaces among the elements and external interfaces with other systems.

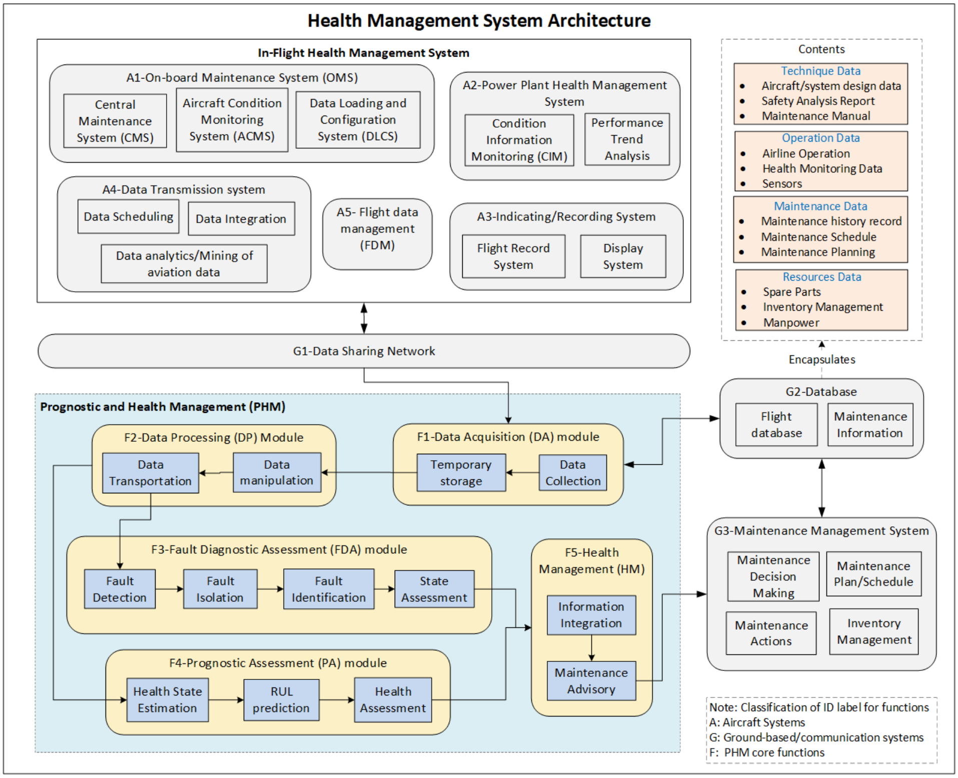

Figure 4.6: Functional architecture of PHM system

EXTERNAL SYSTEMS AND INTERFACES

The external systems include in-flight health management system (on-board layer), data sharing network (communication layer), as well as the database model and maintenance management system (ground layer).

a). In-flight health management system

The in-flight health management system is responsible for providing the in-flight data of the aircraft systems/components to ground systems, which primarily include sensors data, condition information, operation data, the various fault reports, maintenance information, historical data, real-time parameters, pilot reports, engine data, etc. As shown in Figure 4.6, the in-flight health management systems consist of indicating/recording system, onboard maintenance system (OMS), power plant health management system and data management system to collect flight information, and then all the collected data are transmitted to ground facilities through the aviation data-network system [55]. Furthermore, the flight data management (FDM), also referred to as flight operations quality assurance (FOQA), is the process of collecting and analyzing data form flights to improve safety and efficiency of flight operations, and aircraft design/maintenance [57]. Data recordings are done on a regular basis in order to reveal situations requiring corrective actions before problems occur.

b). G1-Data Sharing Network

The data sharing network provides the communication services between onboard system and ground-based systems, E.g. aircraft communications and reporting system (ACARS). A high-capacity wireless Gatelink system is another way of communication. Airlines are expected increasingly to use wireless datalink systems when they dock at airport gates to downlink aircraft diagnostic and operational data, and simultaneously uplink data to the aircraft's onboard computers, electronic flight bags, and other in-flight systems.

c). G2-Ground Database

The ground database stores the in-flight data and maintenance information data, as presented in Figure 4.6. It mainly provides the technical data (e.g. aircraft design data, safety report, manuals, etc.), operation data (e.g. airline operation, monitoring data and sensors data, etc.), maintenance data (maintenance schedule/plans and maintenance history records, etc.) and resources data (spare parts resource, inventory information and manpower resource). More specific, this database collects the operation data from the in-flight system via the data acquisition function, and it acquires the maintenance and resources data from the maintenance management system.

d). G3-Maintenance Management System

When advisories are generated, PHM system will communicate with maintenance services systems to perform the required maintenance actions and services for specific aircraft components or systems. The maintenance services system has the capabilities to update the maintenance schedule, manage inventory and logistics services, and manage maintenance actions.

PHM internal elements and interfaces

The internal elements and interfaces of PHM system, integrated to perform the configured functions, are identified in Figure 4.6. The internal elements with different functional characteristics include: data acquisition, data processing, fault diagnostic assessment, prognostic assessment and health management [55].

a). F1-Data Acquisition (DA)

The DA module has been generalized to represent the software module that provides the capability to collect the sensors and operational data from the in-flight systems through the data sharing network [58]. Then the collected data will be temporarily stored for further producing by data processing module. Therefore, this functional model has the capabilities of data collection and data temporary storage are identified in Figure 4.6.

b). F2-Data Processing (DP)

The DP module is responsible for manipulating the data to a desired form which characterizes specific descriptors (features) of interest in the machine condition monitoring and diagnostic process [58]. This function can be configured with algorithms to perform the signal transformation (e.g., Fast-Fourier Transforms (FFT), and digital filtering), synchronous and nonsynchronous averaging, computations and feature extraction. Afterward, the processed output data will be transmitted to both fault diagnostic assessment module and prognostic assessment module for further analysis.

c). F3-Fault Diagnostic Assessment (FDA)

In Figure 4.6, the FDA module implements the functions of fault detecting, fault isolation, and fault identification by software programming configuration. Then, the assessment results (health states) are sent to the health management module for decision making. When appropriate data is available, the state assessments are obtained based on operational context, sensitive to the current operational state or operational environment [58]. Moreover, it also identifies the current operation of the component or system and diagnoses existing fault conditions to determine the state of health and potential failures.

d). F4-Prognostic Assessment (PA)

As a crucial function, the PA module is embedded with a set of prognostic algorithms to perform the functions of health state estimation, RUL prediction and health assessment, as shown in Figure 4.6. In this sense, the configured algorithms can be model-based, data-driven or hybrid prognostic approaches for specific system/components (e.g. engine, landing gear, bearing, etc.). The PA function is able to determine the current health state on account of analyzing the features extracting from the selected sensors data. The objective of this function is to determine the current health state and estimate the further status, in order to predict the remaining useful life by modeling failure progression on the basis of the extracted features from the historical data. Lastly, it will publish the health assessment report to HM module for maintenance advisory generation.

e). F5-Health Management (HM)

The primary function of HM module is able to integrate the information from FDA and PA functions and consolidate with the constraints (safety, environmental, budgetary, etc.) to provide recommended maintenance advisories to an external maintenance management system. At this point, the PHM system has completed its mission. Afterward, the maintenance management system, outside the PHM boundary, is responsible for making the maintenance decisions with the consideration of resources (inventory, parts, and human resources) and maintenance plan/schedule, and managing the maintenance services.

4.3.4. PHYSICAL ARCHITECTURE

The physical architecture concretizes physical elements that can sustain functional, behavioral and temporal features along with the expected properties of the system deduced from non-functional system requirements (e.g. constraints, replacements, configuration, and/or continued product support) [43].

A set of system requirements and a functional architecture can drive more than one physical architecture candidate depending on the different technologies available for physical implementation. The preferred candidate is then selected based on the constraints of a specific project. For simplicity, this paper recommends one physical architecture candidate compliant with the functional architecture for a PHM system in Figure 4.7. In Figure 4.7, this generic physical architecture of ground-based PHM system incorporates three main modules for implementation, which are the cabinet, auxiliary power module and integrated computing module. In reality, these physical modules can be Commercial off-the-shelf (COTS) products satisfying the needs of a specific project. The integrated computing module is incorporated with hardware elements and software elements. The hardware elements (e.g. operating equipment and embedded sensors), can provide the computing capability, resources and operating environment. The embedded sensors cooperate with in-flight sensors, which are capturing critical data for processing and feeding user interfaces that present key metrics and intelligence to an operator/user so they are appropriately informed of changing health conditions. Additionally, the software elements, including the main computing functions and support functions as the core, enable to implement the required functions and provide the related services. For example, the software element can be configured with a set of diagnostic or/and prognostic algorithms to perform fault isolation, identification and RUL prediction for different aircraft components and systems. The cabinet is an enclosure with fitted, fixed or removable modular slots integrated with bus and power supply, which provides the data bus to connect with database and other ground mainframe systems.

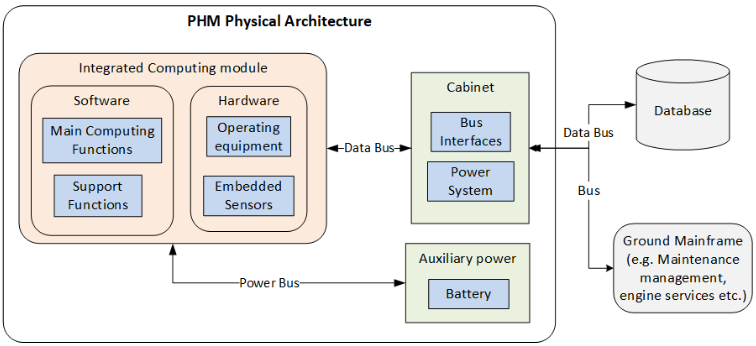

Figure 4.7: Physical Architecture of Ground-based PHM system

4.3.5. REQUIREMENTS DERIVATION AND ALLOCATION

In practice, system architecture development and the allocation of system requirements to item requirements are tightly coupled iterative processes. With each cycle, the identification and understanding of derived requirements increases and with it the rationale increases for the allocation of system requirements to functional elements and physical elements (hardware or software).

Upon definition of PHM generic architecture, the specific requirements or a group of requirements (function) should be allocated to the related architecture elements. Meanwhile, a set of derived requirements may be generated as a result of architectural design decisions, which represent the factors of elements, data flows, interfaces, behaviors and so on. In this case, the physical architecture generates some derived requirements in accordance with the implementation selection and design constraints. The following are some examples of possible derived requirements in this application:

- PHM-DR-1: The PHM system should provide at least 64 GB memory for temporary storage.
- PHM-DR-2: The PHM system should provide a redundant power supply.
- PHM-DR-3: The PHM system should be able to accommodate multiple prognostic algorithms.
- PHM-DR-4: The PHM system should be configured with a 64-bit data bus.
- PHM-DR-5: The PHM system should be able to call for a specific algorithm as defined in configuration files.

4.3.6. ARCHITECTURE VALIDATION AND VERIFICATION

As aforementioned, validation is the process of ensuring the architecture is correct and complete, and ensuring compliance with requirements or stakeholders expectations; besides, verification ensures that an item within architecture complies with all of its design options. In this research, when we obtain the PHM architecture, the validation and verification activities can ensure the confidence that the defined architecture is able to accomplish the intended functions of PHM system, and compare that the architecture against the required characteristics. To achieve these objectives in Subsection 4.2.2, the specific validation and verification method used in this case are presented in details through Table 4.1 and Table 4.2 .

Furthermore, Subsection 4.2.2 has discussed a set of validation and verification means respectively, from SE perspective. For example, analysis and modeling methods can be applied to verify the PHM architecture conducted in this section. The modeling of complex systems typically consists of a combination of computation analysis and tests; however, modeling deterministic systems behavior may also be entirely computational, and is usually able to examine the behaviors and states transmissions, as illustrated in Table 4.1. Moreover, an analysis method provides evidence of compliance by performing a detailed examination (e.g., functionality, performance, interfaces) of a system or element, as present in Table 4.2. Similarly, the methods of traceability and analysis can be

Table 4.1: Verification Matrix of SysML modeling method

Means		Items	Activity Description	Objective
4.4.1 Functional Structure Modeling	Block Definition Diagram (BDD)	Functional elements	Identify and check compliance of the functional elements with functions hierarchy.	Verification
	Internal Block Diagram (IBD)	Functional interfaces	Identify the internal connections between functional elements and the details of how elements are connected with each other.	Verification
4.4.2 Logical Behavior Modeling	4.4.2.1 State Diagram	State transition	Describes the discrete states of elements and the transition from one state to another, which is used to capture the operational scenarios of a system.	Verification
	4.4.2.2 Activity diagram	Activity	Identify and check the system activities, data flow, and control flow in sequence with the logical relationships.	Verification
4.4.3 Physical Structure Modeling	Block Definition Diagram (BDD)	Physical elements	Identify the physical elements of a system and check the consistency of requirements and functions.	Verification
		Physical interfaces	Check the correctness and completeness of the interfaces between the physical elements, and examine the consistency with system behaviors.	Verification

used for validation activity, as the described in Table 4.2, with the purpose of checking the compliance of defined elements and interfaces, as well as the consistency.

Firstly, the case study utilizes the SysML modeling method to check, analyze and exam the design elements and interfaces of the architecture from functional, logical and physical perspective views [59]. SysML is a modeling language for engineering systems which is able to build models for system specification, design, analysis, validation, and verification as expressed in the papers [60–63]. SysML can represent systems, components, and other entities as follows:

- Structural composition, interconnection, and classification;
- Function-based, message-based, and state-based behavior;
- Constraints on the physical and performance properties;
- Allocations between behavior, structure, and constraints (e.g., functions allocated to components);
- Requirements and their relationship to other requirements, design elements, and test cases.

In this paper, Table 4.1 shows the matrix of verification items by various modeling diagrams. These verification means are primarily applied in the case study of PHM architecture modeling, as further discussed in Section 4.4.

Furthermore, a set of various analysis means is used to validate and verify the generic PHM architecture for the items of functions, interfaces, traceability, and compliance with Table 4.2 [64]. In reality, one item is always validated and verified by more than one means in order to improve the confidence of validation and verification results. Accordingly, the means of functions analysis in Table 4.2 is a parallel activity with respect to structure modeling defined in Table 4.1, to validate and verify the same items (functional element and interface) in architecture definition. Similarly, the means of interfaces analysis is conducted in parallel with structure modeling to check the item of system interfaces. To conclude, these validation and verification means are applied in the case study of PHM architecture analysis, as presented in Section 4.5.

Table 4.2: Validation and Verification matrix including analysis methods

Means	Items	Activity Description	Objective
4.5.1 Functions Analysis	Functions decomposition, elements and interfaces	Check the functional elements in consequence, and the functions are organized and depicted by the order of execution.	Verification
4.5.2 Interface Analysis	Interfaces	Check the interface/interactions between each functional element and the external interfaces with other systems.	Verification
4.5.3 Traceability Analysis	Sources of the design items	Traceability matrix from functions/requirements to functional elements and physical elements ensure that the architecture is compliant with the high-level requirements.	Validation
4.5.4 Compliance Analysis	4.5.4.1Compliance with ISO-13374	Check the compliance between the PHM architecture and the standards of ISO-13374 to demonstrate its interoperability and compatibility with various systems.	Validation
	Compliance with IEEE Std 1856	Check the compliance with IEEE standard 1856 to demonstrate the effective applicability of the PHM architecture.	Validation

4.4. CASE STUDY 1: PHM ARCHITECTURE SYSML MODELING

In this section, a case study is conducted to validate and verify the design of the PHM system architecture based on Table 4.1. This case study establishes a modeling project for PHM system to model the PHM functional architecture, logical behavior and physical architecture using different diagrams via the tool of Enterprise Architecture [59].

4.4.1. FUNCTIONAL STRUCTURE MODELING

The block definition diagram (BDD) is a black-box structure of the system, with the connections between components and external interfaces, and the interfaces present a whole part or composition, or communication relationship between the blocks [65][65]. The functional elements related to PHM system are modeled in SysML and presented through the BDD diagram as given in Figure 4.8 . This modeling diagram is compliant with the elements addressed in Figure 4.6 . The PHM system is connected to the external systems, such as in-flight health management systems and the ground database [59]. It also connects with the related maintenance services system in order to perform the required maintenance services and actions. Further, it also identifies the partitioning of functional blocks within the PHM system boundary, including the blocks of data acquisition, data processing, fault diagnostic assessment, prognostic assessment and health management, as illustrated in Figure 4.8 . Additionally, each block has the functionality to configure the specific attributes, operations and ports information, which can be used for testing and simulation in further research.

The Internal Block diagram (IBD) can be used to define the internal connections between parts, and the details of how parts wired with each other. The IBD modeling diagram of PHM system, which provides more details regarding the specific nature of the relationship between blocks, has been addressed in previous research [55].

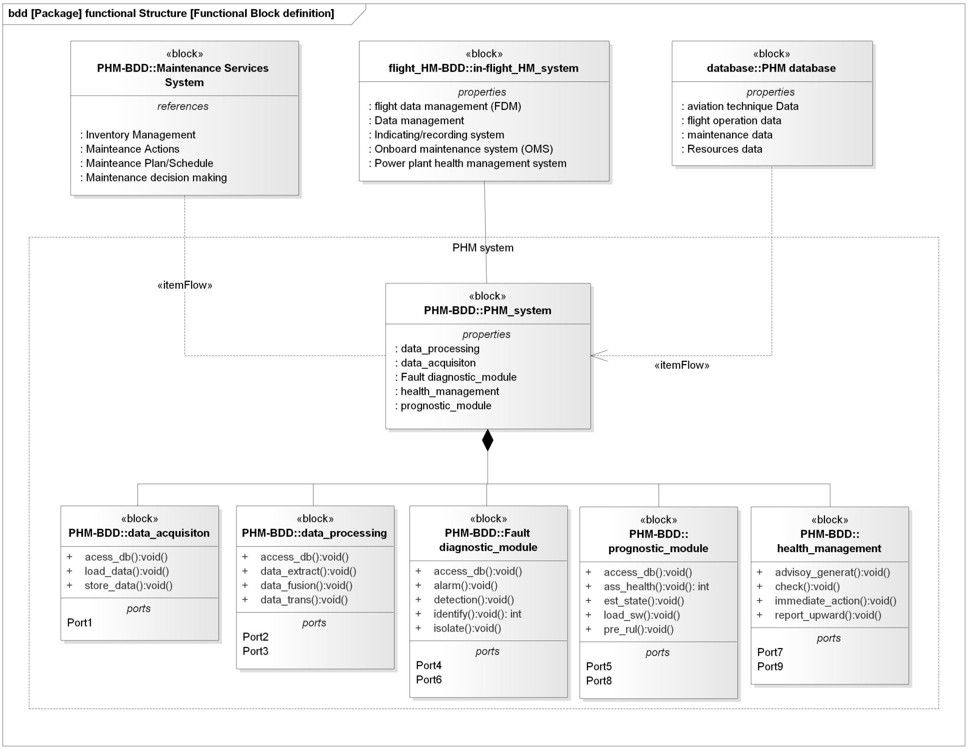

Figure 4.8: Block definition diagram of PHM system

4.4.2. LOGICAL BEHAVIOR MODELING

System logic modeling is able to describe the logical relationships and data-flows among the partitioning elements within the system boundary. This case study constructs the state machine diagrams and activity diagrams for logical behavior modeling in the following sub-sections, which are all compliant with the structure in Figure 4.6.

STATE DIAGRAM

A state machine diagram describes the discrete states of a block and the transition from one state to another, which presents a condition of a block. The transition between these states may be triggered by the receipt of a configured signal or behavior, such as a time-based event or customized event [65]. In this paper, the state diagrams for the functions of fault diagnostic assessment (FDA), prognostic assessment (PA), and health management (HM) are modelled as examples.

a). F3-Fault Diagnosis Assessment (FDA)

As aforementioned, the fault diagnostic assessment function is responsible for fault detection and isolation. Therefore, this function is configured with the states: Idle, diagnostic, fault processing and assessment, as shown in Figure 4.9. Initially, it is in the idle state, waiting for events and preparing to receive corresponding events to call the other operations. When it receives abnormal events, the diagnostic state is activated to implement the diagnostic procedures for detecting the faults [26]. Once any fault is detected, the fault processing state is activated, in which the system triggers the alarm, isolates and identifies the specific faults. It subsequently transmits to the assessment state to assess the operational status and send an assessment report to the health management function.

b). F4-Prognostic Assessment (PA)

Similarly, the prognostic function is responsible for prediction of future health status and estimation of the RUL for the target system. Thus, this function is configured with the states: idle, prognostic, rul_prediction and assessment, as illustrated in Figure 4.10. When the module initializes, it stays in the idle state, and then it will transit to prognostic state according to the time cycle interval. In the prognostic state, the prognostic procedure runs periodically to predict degradation trends via the designated algorithms. Subsequently, it performs procedures for estimating the RUL in the rul_prediction state. Ultimately, the assessment state will analyze the health status of the target system and forward the assessment report to health management function for maintenance advisory making [26].

c). F5-Health Management (HM)

The health management module has the capability to generate the maintenance advisories and manage the maintenance services, so it is configured with the states: idle, Gen_advisory, maintenance, as addressed in Figure 4.11. This function starts as the idle state when power is switched on. After initialization, it is in the idle state waiting for reception of the configured events of assessment reports, to activate the maintenance advisory state. Subsequently, it performs the procedures to analyze the health status reports and generate maintenance advisories. Once the maintenance advisories are generated, the maintenance state is activated to decide the transmission to external health services system for future maintenance decision making and required maintenance actions.

ACTIVITY DIAGRAM

An activity diagram transforms a set of inputs to outputs through a controlled sequence of actions. It means that the activity diagram describes how these activities perform the defined functions on account of certain sequences and logic decisions, which reflect the operational procedures to provide the services [65].

As a core element, Figure 4.12 presents the primary functionalities and activities flow of PHM functions. It identifies the fundamental control flow, decision nodes and related events and actions among the operational activities in a logical sequence, which also contributes to understanding the functions and operation process of PHM system [26]. For example, as shown in Figure 4.12, the fault diagnostic assessment function performs the activities of fault isolating and identifying, when any faults are detected. Once a catastrophic fault is detected, it immediately provides an alarm for an emergency event. In another example, the health management function can integrate all assessment information from both diagnostic and prognostics functions. Then, it integrates all the health

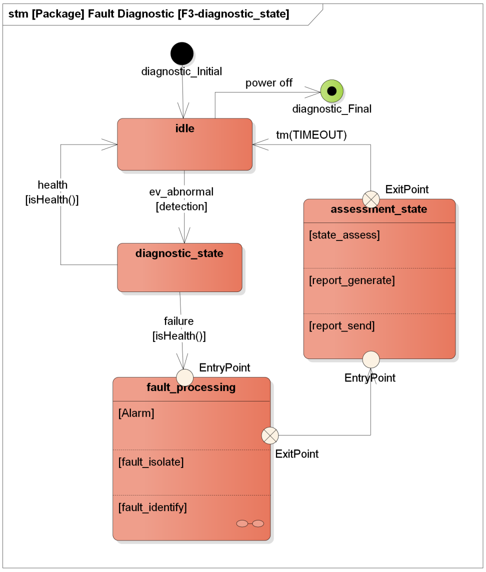

Figure 4.9: State machine diagram of FDA function

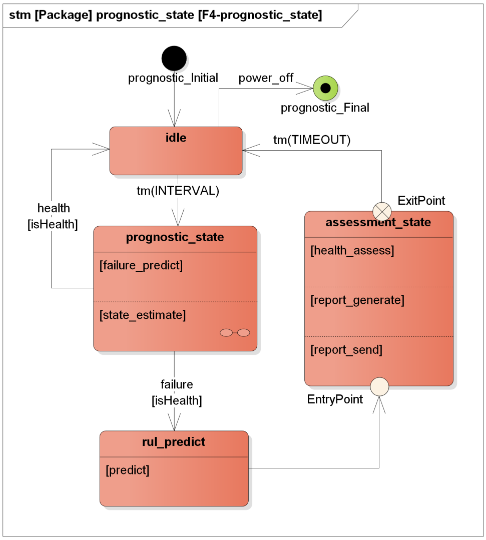

Figure 4.10: State machine diagram of PA function

information and provides a maintenance advisory. When the operation and maintenance advisory is generated, it will communicate with the external system which is responsible to support subsequent decision making and/or execution.

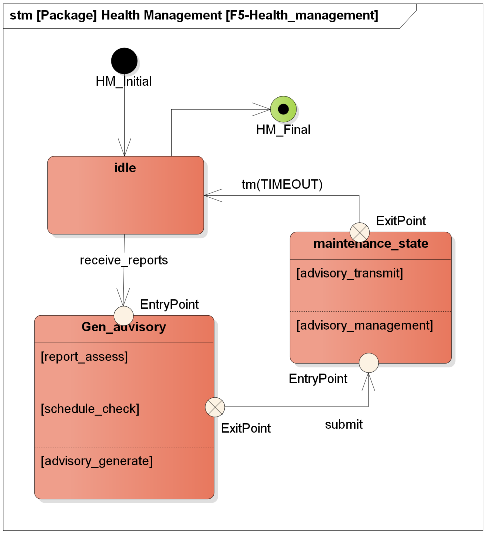

Figure 4.11: State machine diagram of HM function

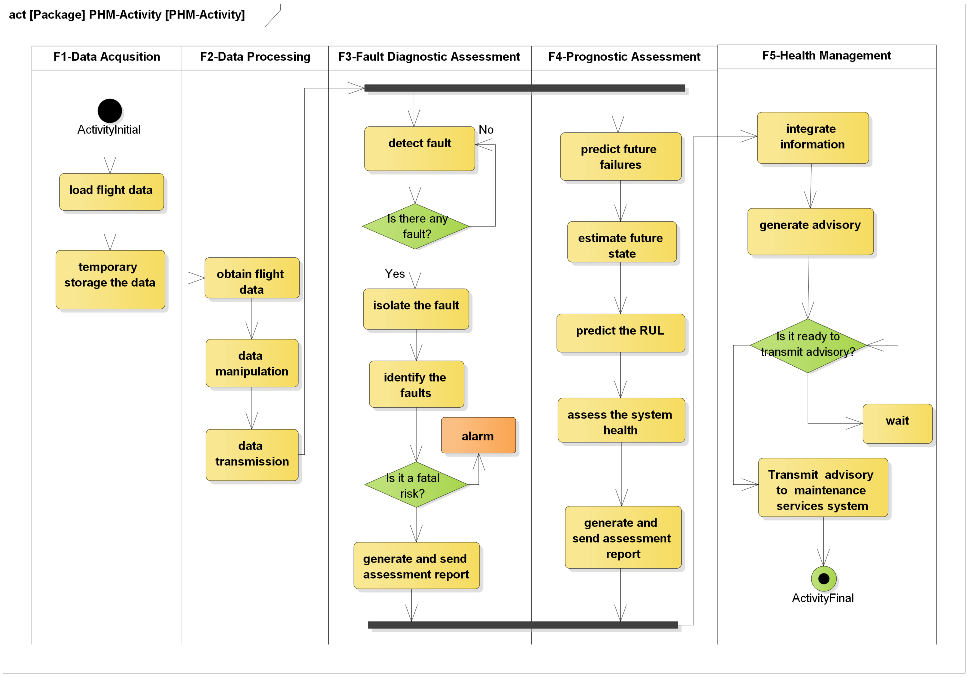

Figure 4.12: Activity diagram of PHM system

4.4.3. PHYSICAL STRUCTURE MODELING

Figure 4.13 is the BDD modeling diagram of the PHM physical architecture defined in Figure 4.7. This diagram identifies the decomposition of PHM system with the elements of a cabinet, auxiliary power modules, and integration computing modules. More specifically, the integrated computing module has the capability to load and install the configured software code to perform a set of algorithms through the devices of CPU and memory. Besides the battery module auxiliary power devices can provide the power to the computing module when the power supply is shut down in emergency cases. A cabinet is equipped with fixed power supply and data buses, as well as multiple computer racks for mounting integrated modular based on a configuration in a specific project. Furthermore, the relationship of how to implement the defined functions based on operating activities, identified in Figure 4.12, through the defined physical elements and interfaces are present in Table 4.3

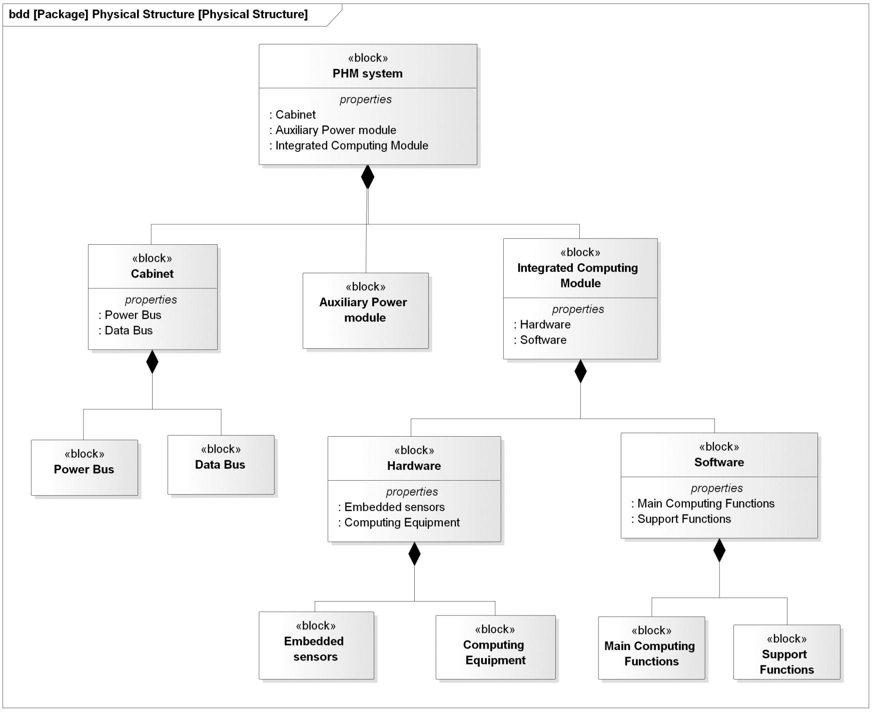

Figure 4.13: State machine diagram of PA function

4.5. CASE STUDY 2: PHM ARCHITECTURE ANALYSIS

Based on the matrix in Table 4.2, this section describes a case study to validate and verify the design of a generic PHM system architecture through various analysis methods, such as functions analysis, interfaces analysis, traceability analysis and compliance analysis.

4.5.1. FUNCTIONS ANALYSIS

Functional analysis is utilized to ensure that all functional elements of the system are described, recognized and defined. The functional flow block diagram (FFBD) is a time-sequenced and step-by-step diagram of the system's functional flow, with the detailed,

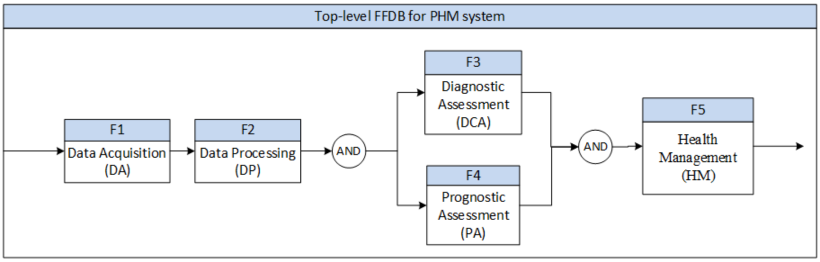

Figure 4.14: FFBD diagram of top-level functions for PHM system

operational and support sequences for the system. In other words, FFBD enables showing the sequential relationship of all functions that should be accomplished and identifies functional interfaces. In an FFDB diagram, the functions are arranged in a logical sequence so that any specified operational use of the system can be traced in an end-to-end path. For example, some functions may be performed in parallel or alternate paths.

Firstly, the top-level functions flow block diagram is defined in Figure 4.14. In this diagram, the top-level functions are organized and depicted by their logical order of execution, and each of them is represented with the logical relationship (e.g. Logic symbols represent, the sequential or parallel execution) to the execution and completion of other functions.

Furthermore, Figure 4.15 analyzes and identifies the low-level functional flow block diagrams for PHM system, which is compliant with the top-level functions flow in Figure 4.14 and the decomposition of PHM functions in Figure 4.5. Differently, this diagram emphasizes the end to end functional flow within the PHM system. For instance, the DA function firstly collects and stores the in-flight information data. Then the collected data is transmitted to both fault diagnostic and prognostic functions after the necessary procedures via the DP function. The FDA function detects a fault, and then it is able to isolate and identify when there is any abnormality. It then assesses the health status of the target system and consolidates a diagnostic assessment report to submit to the health management function. Meanwhile, the PA function is responsible for sequence predicting the failure, and predicting RUL for the monitored system. Besides, this function also provides the health assessment report to health management function. Finally, the HM function is responsible for generating maintenance advisory according to the integrated health state information.

4.5.2. INTERFACE ANALYSIS

During system design, it needs to be defined how the system is required to interact or to exchange material, energy, or information with external systems (external interface), or how system elements within the system, including human elements, interact with each other (internal interface) [38]. Generally, the interface definition is performed along with the architecture definition process and is refined during architecture iteration activities. This includes both internal interfaces between system elements (e.g. PA function connects to HM function within the boundary of PHM system), and the external interface with other systems (e.g. DA function interfaces to G1 function, which is external to the

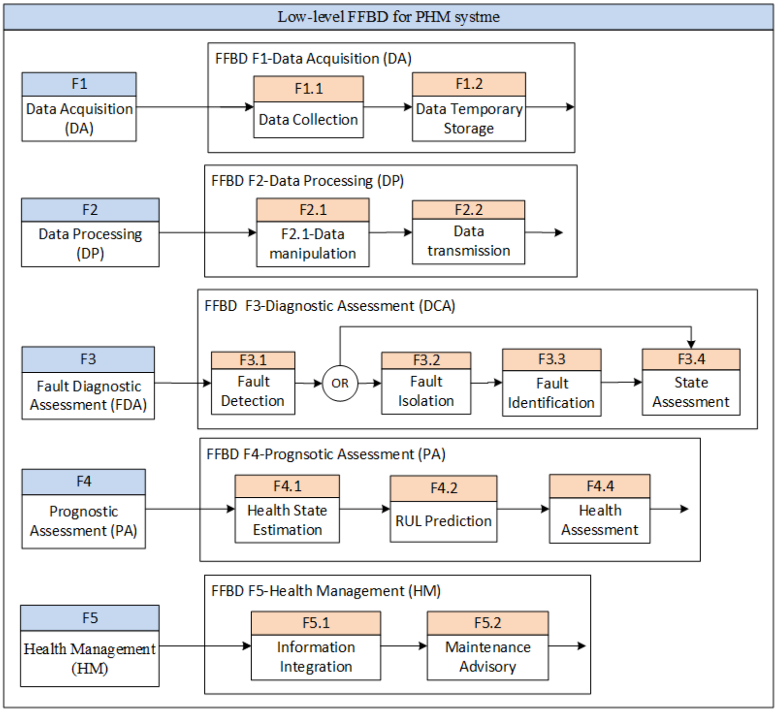

Figure 4.15: FFBD diagrams of low-level functions for PHM system

boundary of the PHM system). In practice, the system engineers team is responsible for system interfaces definition, with the support from technical specialists.

The interface analysis contributes to the activities of integration, validation, and verification during the development life-cycle for a complex system. Particularly, the activity of interface analysis enables checking the conformance of elements interfaces, and systematic coverage of relations and interfaces. Besides, interface analysis can perform semantic analysis, checking the description of the functionality of each element, and contracts among specifications; and perform behavioral analysis based on the behavior specification, including the activities of checking behavioral conformance and equivalence relations [38].

In this case, the internal and external interfaces among elements of the PHM system are identified in Table 4.3. It analyzes the interfaces of the PHM system using a three-layer framework incorporating the onboard layer, the communication layer, and the ground layer, and it also identifies the interactions between the elements within each layer. In terms of physical connection, communication among different modular parts is based on the data bus or power supply bus. Moreover, this interface mapping matrix visualizes the internal and external interfaces among the elements, which provide assistance to check the interfaces identified in Figure 4.6 in a consistent manner. Conversely, if they are not in conformance, it is also the result of verification.

Table 4.3: Interface Mapping for PHM system

		A1	A2	A3	A4	A5	G1	G2	G3	F1	F2	F3	F4	F5
On-board Maintenance System (OMS)	A1	A1	X	X	X	X								
Power plant health management system	A2	X	A2	X	X	X								
Indication/Recording system	A3	X	X	A3	X	X								
Aircraft data transmission	A4	X	X	X	A4	X	X							
Fight data management (FDM)	A5	X	X	X	X	A5								
Data sharing network	G1				X		G1							
Database	G2							G2	X	X				
Maintenance Management System	G3							X	G3					X
Data Acquisition (DA)	F1						X	X		F1				
Data Processing (DP)	F2									X	F2			
Fault Diagnostic Assessment (FDA)	F3										X	F3		
Prognostic Assessment (PA)	F4										X		F4	
Health Management (HM)	F5											X	X	F5

Table 4.4: Traceability Analysis Matrix

Function	Requirements	Functional Element	Logical Analysis	Physical Element
F1-DA	Related functional and performance requirements of data acquisition.	Data Acquisition module	Activity diagram to analysis	Integrated computing module
F2-DP	Related functional and performance requirements of data processing.	Data Processing Module	Activity diagram to analysis	Integrated computing module
F3-FDA	Related functional and performance requirements of diagnostic.	Fault Diagnostic Module	Activity diagram and state machine diagram to analysis	Integrated computing module
F4-PA	Related functional and performance requirements of prognostic.	Prognostic module	Activity diagram and state machine diagram to analysis	Integrated computing module
F5-HM	Related functional and performance requirements of health management.	Health Management Module	Activity diagram and state machine diagram to analysis	Integrated computing module

4.5.3. TRACEABILITY ANALYSIS

As discussed in Subsection 4.2.2, traceability is one of several available validation methods. Traceability is the recorded relationship established between two or more elements of the development process. For example, traceability can consider the bidirectional traceability of the architecture (e.g. functional elements, internal interfaces, and boundary) characteristics, and the design characteristics (partitioning functions and communication among functions). Therefore, the traceability method is able to ensure the consistency of design items during development.

In this case study, the development traceability starts from requirements (functions) to functional architecture (functional elements, interaction), logical architecture (consequence behavior), and then allocated to physical architecture (physical elements and interfaces), which are summarized in Table 4.4. This table sufficiently demonstrates that a lower design element or item satisfies a higher level requirement/stakeholders' expectation (functions) with regards to completeness. In the other words, it is used to make sure the sources of design elements at each development level.

Table 4.5: Compliance Matrix with OSA-CBM [55]

OSA-CBM Functional Blocks	PHM functions				
	F1-Data Acquisition	F2-Data Processing	F3-Fault Diagnostic Assessment	F4-Prongostic Assessment	F5-Health Management
Data Acquisition (DA)	X				
Data Manipulation (DM)		X			
State Detection (SD)			X		
Health Assessment (HA)			X		
Prognostic Assessment (PA)				X	
Advisory Generation (AG)					X

4.5.4. COMPLIANCE ANALYSIS

4

In general, compliance means has the characteristics of conforming to a rule, e.g. a specification, policy, standard or law, which is used to ensure the design quality of a complex system. This case study analyses the compliance between PHM architecture proposed in this paper, and the standards of ISO-13374 and IEEE standard 1856, according to Table 4.2. The analysis results are able to demonstrate the interoperability, compatibility, and applicability characteristic of PHM system.

OSA-CBM (ISO-13374)

The standard of ISO-13374-1 establishes the general guidelines for data processing, communication, and presentation of machine condition monitoring and diagnostic information [31]. This standard defines an open framework of PHM system, which consists the basic functional blocks organized in layers, including data acquisition (DA), data manipulation (DM), state detection (SD), health assessment (HA), prognostic assessment (PA), and advisory generation (AG), as list in Table 4.5. Standards provide designers/engineers with a basis for mutual understanding and are used as tools to facilitate communication, measurement, commerce, and manufacturing. If the proposed architecture is compliant with the standard, it provides confidence and credibility of the PHM design, and is likely more easily accepted by engineers, practitioners and/or end users.

The proposed generic PHM architecture is defined in Figure 4.6 in this paper. This architecture is compliant with the open framework of the PHM system defined in standard ISO-13374-1 (2003), and the results are illustrated in Table 4.5. Regarding the evaluation, the compliance matrix, in Table 4.5, ensures the credibility and compatibility of this architecture; what is more, it demonstrates the feasibility of integration and interoperability of the proposed PHM architecture with various other systems.

IEEE STANDARD 1856

The IEEE standard 1856 describes the information for the implementation of PHM for electronic systems [34]. It provides to manufacturers and end users for planning the appropriate prognostics and health management techniques to implement and the associated life cycle operations for the system of interest.

The related requirements of PHM framework in IEEE Standard 1856 are defined as follows [34]:

Table 4.6: Compliance with IEEE Standard 1856 [34]

IEEE Std 1856		Proposed Generic Architecture
1) Acquisition of object system data (e.g., by means of sensors),		F1-Data Acquisition
2) Data management, and		F2-Data Processing
3) Data processing algorithms and/or processes for:	Diagnostics, health state estimation, and prognostics	F3-Fault Diagnostic Assessment F4-Prognostic Assessment
	Health management	F5-Health Management

a). a) A prognostics and health management system shall consist of sub-systems and components with capabilities including:

1). Acquisition of object system data (e.g., by means of sensors),

2). Data management, and

3). Data processing algorithms and/or processes for:

- Diagnostics, health state estimation, and prognostics
- Health management

Due to the scope of this paper, this case study analyzes the compliance between the items of PHM framework in IEEE Standard 1856 and the proposed generic PHM architecture, as shown in Table 4.6. This standard [34], provides a standard framework that assists practitioners in the development of business cases and the selection of related techniques (e.g. approaches, methodologies, algorithms, procedures, etc.) for implementing PHM systems. Accordingly, the proposed PHM architecture has the characteristics of implementation and applicability.

4.6. CONCLUSIONS

This paper proposes a systematic methodology for PHM architecture definition, leveraging the concept of "RFLP" from system engineering and improving upon existing methodologies by providing a more complete and consistent representation of PHM architecture development from start to finish.

A detailed description of a generic PHM architecture is presented in a set of architecture views in accordance with partitioning elements and physical modularity; hence it has the architectural characteristics of functional/physical dimensions, modularity, and robustness. The robust partitioning system allows partitions with different criticality levels to execute in the same module without affecting one another spatially or temporally. The modularity in the design contributes to system reusability and mitigating the risk of duplicate work. These architecture views of a generic PHM system, as defined in Figure 4.6 and Figure 4.7, could be used as a practice case as to how to apply the proposed methodology.

A case study is conducted to verify and validate the proposed generic PHM architecture to ensure correctness and completeness. SysML modeling and various analysis means are employed to this end. More specifically, the SysML modeling diagrams show the start of the design elements, interfaces and the applied relevant techniques, such as the diagrams in Figure 4.8 and Figure 4.13. In addition, the operating functions and sequences of the PHM system are identified on the basis of the defined functional/physical elements (Figure 4.9 to Figure 4.12). To sum up, this case study confirms that the intended functions have been correctly and completely structured in functional architecture; examine the behaviors and the states transmission of a system, and confirms that the set of functions have been satisfied. Another case study analyses features of PHM architecture, expressing that the generic PHM architecture has the characteristics of interoperability, compatibility, and applicability allowing integration with a variety of systems through the means of interface, traceability and compliance analysis. Practical and important issues including functional flow, interfaces, implementations and standards are also covered as part of the required tasks. It also shows how a relatively small set of generic standardized interfaces can provide this interoperability and applicability. This case study ensures the compliance of the defined elements and interfaces, and the consistency of design elements during development.

In conclusion, this research contributes towards a systematic PHM system design and development methodology, including as its main elements:

- Providing guidance toward developing a PHM system, in particular the specification of a PHM architecture (and associated verification and validation thereof) in practice;
- Providing a generic functional and physical architecture of a PHM system using system engineering principles;
- Providing a reusable and practical approach;
- Addressing compliance, consistency, interoperability, and applicability of the proposed architecture.

Future studies on the current topic are concentrated on enhancing a comprehensive understanding of design methodology for a complex system involving requirements, architectures, and design solution and validation/verification items. From the current research, the following items are identified to be vital for contributing to an efficient PHM design:

- Apply and validate the proposed systematic design methodology for PHM architecture development towards industrial case studies;
- Improve the maturity of prognostic techniques in terms of robustness, reliability, and applicability;
- Select the appropriate prognostic approaches based on requirements and project constraints.

4

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5

PRACTICAL FRAMEWORK FOR DATA-DRIVEN PROGNOSTICS

This chapter presents a practical framework for data-driven prognostics approaches that can support the practices of prognostics. Existing literature lacks the method of determining specific techniques to implement RUL prediction, and the proposition of advanced prognostics techniques leads leads more complexity in practices. That constitutes a hurdle towards a successful design of PHM systems in industrial practice. This chapter develops a generic data-driven prognostics process, and a correspondingly practical framework, covering key characteristics of prognostics techniques. Moreover, comparative case studies are undertaken to validate and verify that framework. Thus, this practical framework can be used for the guidance of determining appropriate approaches for prognostics implementation. As a specific application case, this chapter primarily addresses the task of the design solution. Combined with the outputs of system requirements (Chapter 3) and architecture (Chapter 4), it fills the gaps in PHM system design in practice.

This chapter is based on a submitted (under review) article:

Li, R., Verhagen, W.J. and Curran, R., 2020. A Practical Framework for Data-Driven Prognostic Approaches in Remaining Useful Life Prediction. Journal of Aerospace Science and Technology

Prognostic and Health Management (PHM) enables the prediction of failures in aircraft systems/components resulting in reduced airline maintenance costs and increased availability of assets. The academic state of the art features a multitude of methods, techniques, and applications for the aircraft-specific system remaining useful life (RUL) prediction. However, the proposition of increasingly advanced techniques leads to challenges in practical uptake of prognostics. Redefining observations into more meaningful and comprehensive health assessment, providing crucial information for industrial practitioners, may address this challenge. Yet, it is difficult to make a prior determination of practical techniques to construct an accurate prediction for new prognostic applications. Along with this, comprehension and mastery of the essential characteristics of data-driven prognostics are lacking. In response, this paper develops a practical framework of data-driven prognostics for RUL prediction. This framework covers the critical characteristics of prognostics and relevant technical options of selected statistical models and machine learning (ML) models. Through a set of comparison experimental studies, the results compare the performance of various prognostics techniques in implementation and also express the applicability of the proposed framework. Therefore, this research enhances a comprehensive understanding of data-driven prognostics and provides a practical framework to support the techniques determination of prognostics applications in practice.

5

5.1. INTRODUCTION

With the rapid development of aeronautical technology, aircraft systems (e.g. engine, gear, and avionics) become more complex and require increasing reliability. The purpose of aircraft maintenance is to keep aircraft in a serviceable and reliable condition to generate revenue while maintaining the current and future value of the aircraft by minimizing the physical deterioration throughout its life [1]. Prognostic and health management (PHM) provides a set of capabilities that enable diagnostics, prognostics and health management integrated to achieve condition-based maintenance (CBM) for effective and efficient aircraft maintenance and operation [2]. Particularly, prognostics is a promising technology that can assess the health level and predict remaining useful life (RUL), usually under the assumption that the operating conditions are not changed [3]. It relies on its capacity to anticipate the evolution of anomalous conditions.

Recently, a significant amount of studies propose various prognostic approaches applying to different components or systems in the PHM field. These approaches employ a substantial number of advanced prognostic techniques as alternatives for implementation. For example, Javed et al. [4], review the taxonomy of prognostics approaches and their application perspectives based on a classification into physical-based, data-driven, and hybrid models. The authors also present a thorough survey on the state of the art of prognostics, including a brief discussion on the technology readiness level (TRL) for various prognostics algorithms. Atamuradov et al. [5], present a fundamental view of a PHM system and its steps to provide prior knowledge for users of the different approaches, such as model-based, data-driven, and hybrid models. The authors also address the typical merits of prognostics and a set of relevant drawbacks in current PHM research.

As identified in the previously mentioned review papers, prognostic approaches are usually divided into three categories: model-based, data-driven, and hybrid approaches, in which the data-driven approaches are more widely applied [6]. Data-driven approaches utilize the useful features from observations for identifying the characteristics of current system conditions and predicting future health trends with the assumption that the operational environment is consistent. Acknowledging that there are various data-driven prognostic approaches, Cristaldi et al. [7] present a comparison of two data-driven algorithms, based on a statistical approach and a neural network. The results show that both approaches are characterized by reliable prediction performances on RUL prediction, thus resulting in potential tools for the application of PHM.

With the rapid development of prognostics approaches in academics, a gap is increasingly exposed between advanced models and techniques and their application in practice [8]. The gap between research and practical uptake of PHM has resulted in the fact that although many prognostic techniques rely on various specific assumptions for their proper applications, these are not normally discriminated by practitioners according to the real operating conditions of their systems or components. To fill the shortcoming, this paper focuses on a practical framework of data-driven prognostic approaches regarding both statistical and machine learning (ML) models to guide the determination of appropriate techniques. Relevant comparison studies illustrate and summarize the practical technical options and their effect on the accuracy of RUL prediction.

The rest of the paper is organized as follows. Section 5.2 reviews the state of the art of data-driven prognostic approaches, methodologies of model selection as well as relevant practical techniques. Section 5.3 presents a generic process and a practical framework for data-driven prognostic implementation with the aspect of proper practical options. In Section 5.4, a set of typical practical techniques are introduced based on the proposed practical framework. Afterward, Section 5.5 produces the experimental study to compare the relevant technical options according to the framework, as a representative comparison study. A conclusion is given in Section 5.6 along with a discussion of research opportunities in the PHM field.

5.2. State of the Art

The rapid development of PHM techniques and applications is leading to the perception of PHM as an engineering discipline which depends on the use of in situ monitoring and advanced methods for assessing degradation trends [9]. As the most popular model, it is necessary to present relevant background about data-driven prognostics approaches and related methodologies to support the selection of a suitable (set of) approach(es). Thus, it introduces a brief review of the current state of the art via the following three axes of knowledge:

1). **Data-driven Prognostics**

The data-driven approaches deduce asset degradation/state behavior directly via available historical data [10]. Since the data-driven approaches depend on the trend of data, which often show a distinct characteristic near the end of life, they are powerful in predicting near-failure behaviors toward the end of life [11]. The data-driven approaches generally consist of two groups: (1) statistical models, e.g. Gaussian process regression [12], support/relevance vector machine (SVM/RVM) [13, 14], gamma/wiener process [15–17], etc.; and (2) ML models, e.g. deep neural networks (DNN) [18, 19], recurrent neural networks (RNN) [20, 21], long short-term memory (LSTM) [22], convolution neural network (CNN) [23–25], etc.

Particularly, the statistical models rely on available historical observational data and statistical techniques, e.g. statistical principles, stochastic processes, and mathematical regression, for nonlinear system prediction. Si et al. [26], systematically review the statistical-based approaches, which depend on available past observed data and statistical models. On the other hand, the ML models produce the predictions following the acquired data (e.g. health and failure data) by converting the gathered data into useful information used in conjunction with sensor data to provide future predictions [27]. In research [19], Zhao et al. review and summarize the emerging research of advance deep learning on complex system health monitoring with the introduction of relevant learning techniques and applications. Besides, the authors provide some new trends of deep learning-based prognostic approaches for further research. Khan and Yairi [18] present a systematic review of ML-based system health management with an emphasis on recent trends of deep learning techniques within the field. Various structures and principles are addressed to clarify its potential contributions and advantages to deal with the problem of RUL prediction. However, these researches focus on the review of popular and novelty prognostic approaches, and the prognostic process and practical options lack in discussing.

5

2). **Model Selection**

The degradation process is usually considered as a random phenomenon presented by time-continuous trajectories the criteria considered for model selection need to take into account the characteristics of the degradation process. The problem is posed on the choice of the suitable techniques and models among a class of available candidates according to the varying purposes. The literature review of prognostic approaches selection contributes to achieving a consistent identification of data-driven prognostic process and corresponding practical framework. The issue is to select a model which describes the underlying degradation behaviours in an excellent way depending on available data and knowledge. For instance, a framework of model determination to represent the failure process for a component/system is introduced according to a result of available trend tests by Louit et al [28]. In that study, the proposed selection framework is towards the difference between the use of statistical distributions to represent the time to failure; and the use of stochastic point processes, when there may be the presence of system aging or reliability growth [28]. Aizpurua et al. (2015) state a decision framework toward a prognostic algorithm through a cause-effect flowchart, for failure modes, application characteristics, and qualitative and quantitative metrics [29]. That framework determines the prognostic approach based on cause-effect and failure analysis, but not on the basis of the prognostic process and practical steps. Nguyen et al. (2018) discuss the selection criteria for degradation models with the groups of classical statistical criteria and prognostic criteria regarding statistical models [30]. Yet, this paper takes account of the errors in parameter estimation, but not characteristic features of the observations.

The degradation process is usually considered as a random phenomenon presented by time-continuous trajectories.The criteria considered for model selection need to take into account the characteristics of the degradation process. The problem is posed on the choice of the suitable techniques and models among a class of available candidates according to the varying purposes. The literature review of prognostic approaches selection contributes to achieving a consistent identification of data-driven prognostics processes and corresponding practical framework. The issue is to select a model that accurately describes the underlying degradation behaviours depending on available data and knowledge. For instance, a framework of model determination to represent the failure process for a component/system is introduced according to a result of available trend tests by Louit et al [28]. In that study, the proposed selection framework is geared towards the difference between the use of statistical distributions to represent the time to failure and the use of stochastic point processes, when there may be the presence of system aging or reliability growth [28]. Aizpurua et al. [29], propose a decision framework toward a prognostic algorithm through a cause-effect flowchart, for failure modes, application characteristics, and qualitative and quantitative metrics. That framework determines the prognostic approach based on cause-effect and failure analysis, but not on the basis of the prognostic process and practical steps. Nguyen et al. [30], discuss the selection criteria for degradation models with the groups of classical statistical criteria and prognostic criteria regarding statistical models. Yet, this paper takes account of the errors in parameter estimation, but not characteristic features of the observations.

3). **Practical Techniques**

A massive amount of techniques and models has been emerged in the light of the advances of data analysis, allowing to have accurate RUL prediction. The advances are identified as outcomes of an innovative discipline, nowadays discussed under data-driven prognostics. When developing data-driven solutions for RUL estimation, the approaches often use sensor and operational time series data from multiple instances to train degradation models [31]. It assumes that there are correlations among the observations from the same instance. Moreover, there exist random variations across the sensor time series as a result of the uncertainty elements, e.g. sensors, measurement, environment, etc. In practice, it is crucial to take into account both correlations and uncertainty in RUL estimation. Baptista et al. [32], describe the data-driven prognostics depend on the type of messages can be better suited to maintenance than time-based approaches. The result is demonstrated through the comparison with an industrial case study involving the removal times of a bleed valve from the aircraft air management system. In the research of Son et al. [33], a stochastic process (Wiener process) combined with a data analysis method (principal component analysis (PCA)) is proposed to model the deterioration phenomenon and estimate the RUL. It points out the advantages of the proposed approach by comparison with other approaches.

The research of prognostics approaches has achieved a certain success in varying critical systems/components. However, it is still usually not possible to precisely predict impending failures, which requires a thorough understanding to encounter different sources of uncertainty that affect prognostics. Hence, the drawback to be faced in this research concerns the issue that existing literature lacks a suitable method of determining specific techniques to implement RUL prediction, and the proposition of advanced prognostic techniques impedes practical uptake of prognostics, as implementation and interpretability are increasingly difficult. This constitutes a hurdle towards successful design of a PHM system in industrial practice.

5.3. METHODOLOGY

To overcome the drawback, this paper presents a comprehensive solution from two aspects. Firstly, this section introduces a practical framework of selecting technical options for data-driven prognostics from a methodological perspective, which concerns the main technical steps for RUL prediction. Furthermore, this paper dissects a typical group of technical options according to the practical framework proposed in Section 5.3, to comprehensively compare the applicability of selected statistical and ML models. This aspect is addressed in more detail in Section 5.4.

5.3.1. OVERVIEW

A generic data-driven prognostic process is proposed as presented in Figure 5.1, which is composed of five technical steps: data acquisition, data processing, degradation prognostics, RUL prediction, and evaluation. Firstly, the measured data (e.g. vibration signals, temperature, pressure, etc.) are acquired from sensors to monitor the health condition of component/systems. Then, it applies a set of data processing options to transform the observation data into an understandable format that can be consumed by a filtering process. Afterward, the extracted features are used to assess the system health status and represent varying degradation phenomenon in a fixed operational environment, as the trained degradation models. Thus, it can predict the RUL of testing instances according to the constructed degradation models. Finally, the evaluation metrics can evaluate the estimated RULs to evaluate prognostic performance.

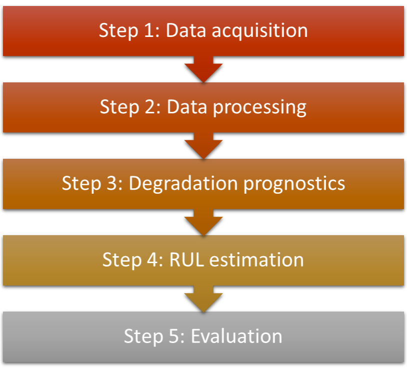

Figure 5.1: Data-driven prognostic process

According to the literature review, the data-driven prognostic process can be summarized with five technical steps: data acquisition, data processing, degradation prognostics, RUL prediction, and evaluation, as presented in Figure 5.1 [6]. Firstly, the measured data (e.g. vibration signals, temperature, pressure, etc.) are acquired from sensors to monitor the health condition of components/systems. Then, it applies a set of data processing options to transform the observation data into an understandable format that can be consumed by a filtering process. Afterward, the extracted features are used to assess the system health status and represent varying degradation phenomenon in a fixed operational environment, as the trained degradation models. Thus, it can predict the RUL of testing instances according to the constructed degradation models. Finally, the evaluation metrics can be applied towards the estimated RULs to evaluate prognostic performance.

5.3.2. PRACTICAL FRAMEWORK OF PROGNOSTIC

In this context, it is still difficult to implement a data-driven prognostic approach only with the knowledge of the prognostic process, and it also requires a practical framework regarding the proper technical options for RUL prediction. To support practice, this section describes a framework in detail to represent the practical methodology of data-driven approaches, as illustrated in Figure 5.2 . It identifies the specific activities corresponding to each step of the generic prognostic process regarding both statistical models and ML models. The specific aspects of the proposed framework are discussed next.

1). **Data Acquisition**

The literature addresses that all statistical methodologies are limited when done based on small data sets since the amount of information contained by such sets is by nature small [34]. Furthermore, empirical evidence indicates that sets of failure times typically contain fewer observations, which emphasize the need to develop methods to deal adequately with small data sets. Hence, acquiring available condition monitoring data from the target systems is important before predicting.

Data acquisition is a process to capture and store a set of monitoring data from various sensors (e.g. mechanical sensors, optical sensors, etc.) installed on the monitored equipment. Various sensors are embedded to collect diverse formats of observations data (e.g. vibration signals, temperature, or pressure). Such observations can reflect the information about the degradation of the individual components/systems to monitor the health condition [35]. In the research field, the datasets are usually divided into subsets of training datasets for learning the degradation phenomenon, validation datasets for validating the parameters in degradation models, and testing datasets for predicting the RULs, as shown in Figure 5.2.

2). **Data Processing**

Data processing is performed to transform raw observation data into an understandable format or extracting some useful features. Proper data processing enables the improvement of prognostic performance, otherwise, the prognostic approach applies to poorly partitioned data that could produce misleading outcomes. It means that the application of appropriate data processing can obtain accurate results and effective performance. With the development of technology, many advanced data processing techniques are available to be applied in prognostics implementation. This paper will intro-

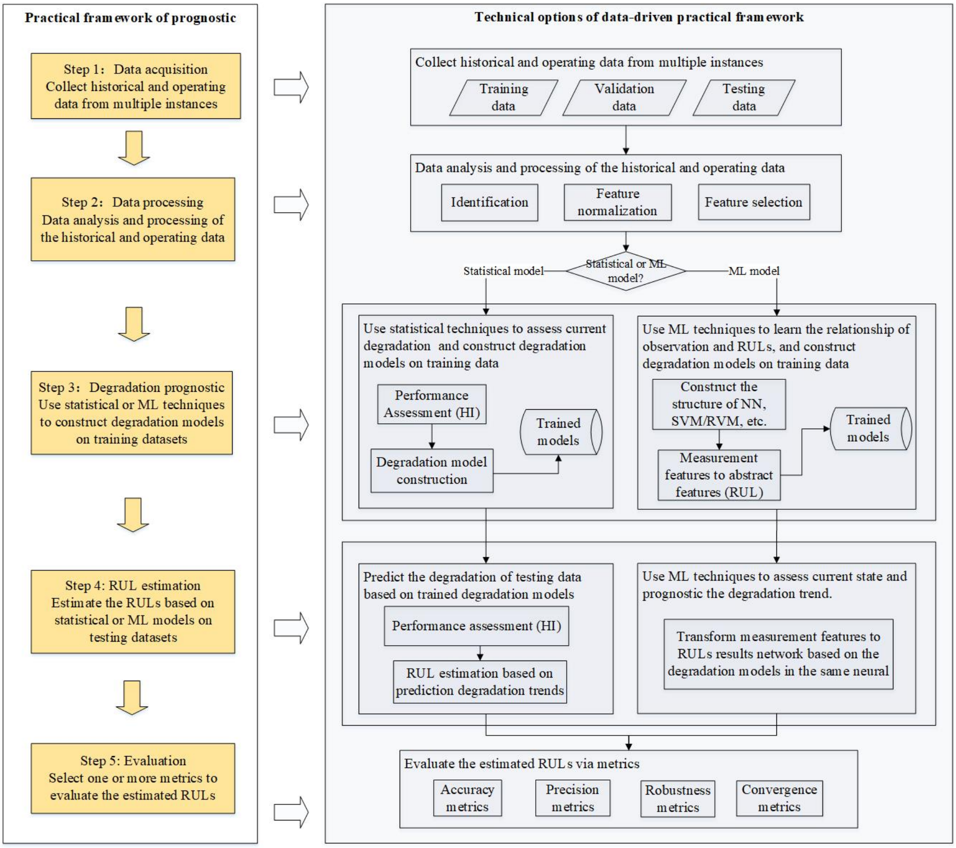

Figure 5.2: Practical framework of Data-Driven Prognostics

duce the typical data processing options for data identification, normalization, and feature selection, which can be produced in data-driven prognostics approaches for comparison. For instance, the techniques of normalization are generally utilized in ML models but rarely in statistical models. Sensor selection is mostly relevant to the application, and it aims at reducing the unnecessary redundancy while maximizing the relevance in the sensor subset. According to the characteristics of the collected data, the sensor selection scheme consists of operation condition division, empirical observation, and correlation analysis.

3). **Degradation Prognostic**

After adopting the useful features from observations, the framework takes into account the suitable techniques to identify the health conditions and to further describe the trends of the degradation phenomenon [36]. The data-driven approaches can figure this out from observations through the statistical and/or ML models. Hence, one issue is how to determine the suitable and useable statistical models or ML models, as shown in Figure 5.2. Statistical models primarily rely on available and statistical techniques (e.g. statistical principles, stochastic processes, and mathematical regression, etc.) to describe the nonlinear degradation phenomenon. Differently, the ML models make full use of training data to learn the outputs with the representation of degradation characteristics (e.g. health indicators, RULs, etc.). The key is to extract useful features from the observation data. In this case, the practical techniques for RUL estimation depend on the selected prognostic model. Generally, this determination of specific model depends on the available data (multiple run-to-failure data), knowledge (reliability model) and techniques (based on regression or black-box analysis). Sometimes, the selection of specific technical options also depends on the stakeholders' requirements and project constraints.

As identified in Figure 5.2, statistical models employ statistical techniques to assess system current status through extracting the corresponding health indicators (HIs) from the observations data [37, 38]. Then, it is to establish the degradation models by fitting a degradation trend with HIs under a probabilistic method, e.g. statistical principles, stochastic processes, or mathematical formulation regression [26]. Thereby, the training datasets support to construct the degradation models. In comparison, ML models take advantage of artificial learning techniques to abstract the measurement features into the RULs by iterative learning produces [8]. For an example of artificial neural network (ANN) models, the efficiency and results of RUL prediction sometimes rely on the constructed structure of the neural networks and the learning techniques. In this case, the validation datasets are properly used for the validation of relevant parameters.

4). **RUL estimation**

Afterward, the process of RUL estimation operates the corresponding techniques to estimate the RULs based on the results from the process of degradation prognostic. For instance, statistical models produce performance assessment intending to extract the health features from observations into health indicators on testing data. Hence, it predicts the RULs though statistical technical options according to trained degradation models. Differently, ML models learn the features of the test dataset according to the constructed degradation models with the optimized parameters and learning techniques by iterating pre-defined epochs. After learning iterations, the corresponding RULs of the testing datasets are obtained.

5). **Evaluation**

Along with developing the fundamentals of RUL prediction, the results require a stringent performance evaluation, so that the significance of the concept can be fully exploited [39]. Yet, it is rather difficult to compare various efforts and select a more suitable approach from several prognostic algorithms, especially for safety-critical applications. Research efforts more major emphasis on developing algorithms that can provide an RUL estimate, generate confidence bound around the predictions and integrate with existing diagnostic/health management systems. Depending on the use of prognostic information, the popular evaluation metrics include the categories of accuracy, precision, robustness, and convergence, etc. As the most widely used, the accuracy based prediction metrics aim to quantify any bias from sample data and a smaller spread is desired, which is minimized through typical methods for standard error minimization [40].

5.4. TECHNICAL OPTIONS OF PROGNOSTIC FRAMEWORK

As considered previously, this section discusses a typical group of technical options according to the practical framework, to comprehensively compare a selection of statistical and ML models. Particularly, this section introduces a typical group of technical options according to the practical framework in Figure 5.2. It concerns the aspects of data acquisition (Subsection 5.4.1), data processing (Subsection 5.4.2), degradation and RUL estimation (Subsection 5.4.3), as well as evaluation (Subsection 5.4.4). Therefore, Figure 5.3 identifies the technical options of the data-driven practical framework, with the relevant techniques.

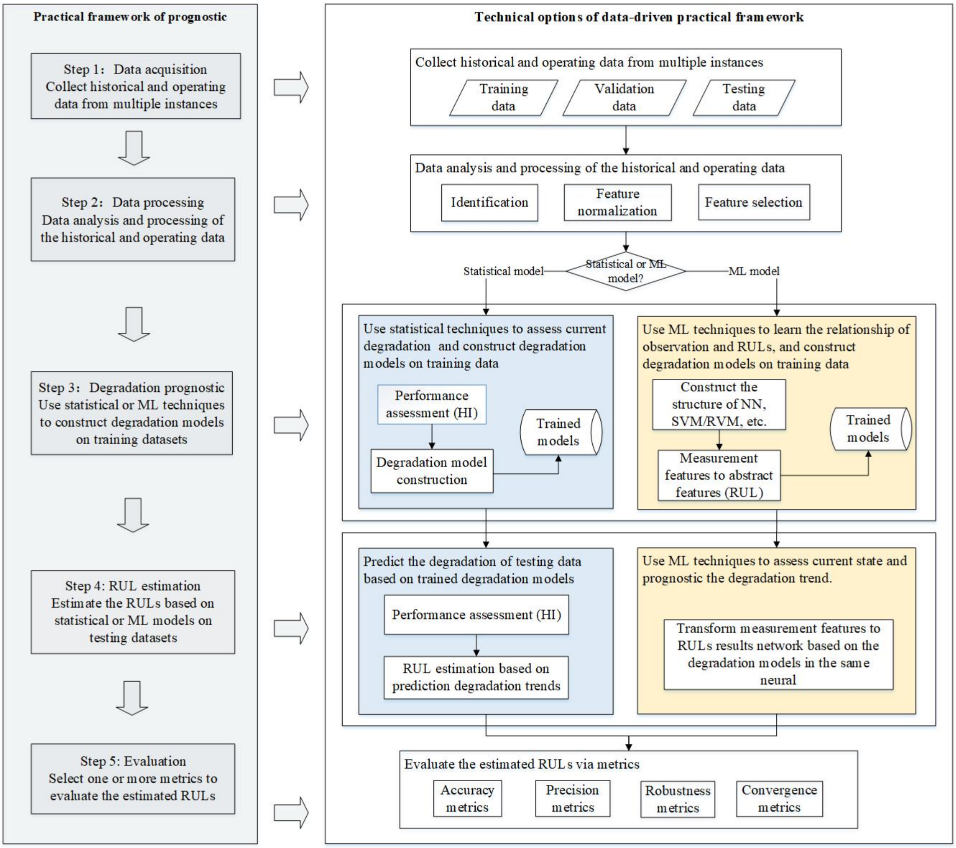

Figure 5.3: Technical Options of data-driven practical framework

5.4.1. DATA ACQUISITION

Generally, the acquired data are from the embedded sensors or on-board monitoring systems to reflect the health status and degradation phenomenon of the monitored systems/components (e.g. engine, bearing, milling, etc.). A data acquisition system, on-board or ground-based, is composed of sensors, data transmission devices, and data storage devices. With the purpose of research, the most open datasets developed for prognostics are always acquired from accelerated degradation testbeds instead of real industrial equipment.

To facilitate the development of prognostics, the Prognostic Center of Excellence of National Aeronautics and Space Administration (NASA) has established a prognostic data repository [41], which collects several open datasets specially generated for demonstration of prognostic approaches. For example, the most popular datasets are turbofan engine degradation simulation data sets and PHM08 Challenge data set, which are produced using the tool of C-MAPSS [42, 43]. Besides, the battery data sets are the experiments results on Li-Ion batteries charging and discharging at different temperatures, which are used in a series of studies [44]. The milling data set records the wear of the milling insert depends on experiments results on a milling machine for different speeds, feeds, and depth of cut [45].

5.4.2. DATA PROCESSING

Sufficient historical data and the relevant degradation observations (e.g. run-to-failure data) are the prerequisite requirements for data-driven prognostics approaches. Even though a large number of training data usually benefits for advancing the prediction results, it is not always effective because of the increased computational cost [46]. Whereas, the prediction performance sometimes depends on the quality of datasets, such as the factors of uncertainty, noise, along with the amount of failure data or the data close to failure. Thereupon, the data-processing techniques (such as data identification, normalization, and feature selection, as shown in Figure 5.3), can improve the prediction performance in most cases.

IDENTIFICATION

Sometimes, the acquired datasets consist of various operating conditions (various operating modes or operating status) of the target system. The prediction should consider those conditions separately and establish independent partitioning performance assessment models because the different operating conditions lead to different failures/faults. Thus, the identification of operating regimes partitioning in all trajectories is necessary as the first step in data-processing [47].

NORMALIZATION

A normalization method can carry out adjustments by returning raw values into a common scale. For instance, the z-score is a dimensionless quantity that results from subtracting the population mean of each regime from an individual raw sensor value and then dividing the difference by the population standard deviation [46]. Similarly, the method of min-max normalization can reduce the collected measurement data scale, transformed them within the range between -1 to 1. In this paper, we mainly apply these two normalization methods in the data-driven prognostics approaches.

FEATURE SELECTION

Furthermore, the method of feature selection aims at reducing the unnecessary redundancy while maximizing the relevance in the sensor subset. Before building the degradation models, it is necessary to gain insight relative to the features and attributes of the collected monitoring data from embedded sensors. However, not all sensor data contributes to health performance, or not all sensor data is meaningful for condition monitoring and prediction. Hence it is necessary to devise a systematic sensor selection process that offers guidance on choosing the most representative sensors for prognostics. The sensor selection scheme consists of operation condition division, empirical observation, data fusion, and grey correlation analysis.

This research applies a three-parametric method with the measures of monotonicity, prognosability, and trendability to evaluate the meaningful sensors [46]. Particularly, monotonicity is a measure of data complexity underlying the positive or negative trend of the sensors. This measurement is calculated by the average difference of the faction of positive and negative derivatives for each path [46]. The value outcomes close to 1 indicates that the sensor is monotonic and useful for RUL estimation, whereas the opposite result is difficult to reflect degradation phenomena. Moreover, prognosability evaluates the deviation of the failure cycle for each path divided by the average variation of the sensor during its entire lifetime, weighted in the scale of 0 to 1 [46]. If the value is more close to 1, it indicates that the failure thresholds are much similar. Otherwise, it means that the failure points are different from each other and the sensors are incapable of the prognostics. Differently, trendability can measure the consistency of sensors in all instances, which is defined as the minimum correlation computed among all the training trajectories [46]. In brief, the observations of sensors can be evaluated by a fitness function as a sum of these three-prognostic parameters to select useful and suitable sensors for prognostics.

5.4.3. DEGRADATION PROGNOSTICS AND RUL ESTIMATION

The following section addresses typical techniques of degradation prognostic and RUL prediction, respectively regarding statistical models and ML models, as shown in Figure 5.3.

STATISTICAL MODEL

Statistical data-driven approaches construct the RUL estimation models by fitting the model to available data under a probabilistic model without relying on any physics or engineering principle [26]. They have certain advantages over other methods in that some desirable mathematical properties can be analyzed regarding the estimated RUL. These models can describe degradation behaviors via statistical techniques, consisting of parametric models and non-parametric models. Generally, statistical prognostics models include the groups of regressive methods, stochastic methods, and reliability models. As shown in Figure 5.3, this section primarily addresses the steps of a) degradation prognostics; and b) RUL estimation. Meanwhile, Table 5.1 summarizes some typical examples of technical options applied to statistical models for RUL prediction.

a). Degradation Prognostics

The practical framework has identified that the statistical models generally consist of the steps of performance assessment and degradation model construction.

- Performance Assessment

To evaluate the current health state, it can make full use of health indicator (HI) for the step of performance assessment. As one of the most popular dimension reduction techniques, principal component analysis (PCA) is often applied for systems' HI construction. PCA is a statistical procedure to convert the multi-dimensional sensor data into a set of lower-dimensional principal components, which is mostly used for exploratory data analysis for HI and predictive models [34]. Widodo et al. [48], use PCA to reduce the dimension of feature sets and calculated the deviations between unknown states and the healthy state as a HI. Benkedjouh et al. [49], apply the advanced PCA combined with isometric feature mapping to construct a final HI for cutting tools. Some researchers have employed a linear data transformation method to construct a HI by fusing multiple features. This article compares the technical options of PCA and linear regression to construct HIs as shown in Table 5.1.

- Degradation Model Construction

Once the results of performance assessment are obtained, it is possible to describe the degradation phenomenon through statistical technical options, e.g. statistical principles, stochastic process, and mathematical regression for non-linear system prediction. In literature [26], the authors have reviewed a set of statistical data-driven approaches. Particularly, Wang et al. [47], propose a similarity-based model based on training data and apply to test data to calculate the RUL of components. These above non-probabilistic methods are popularly used in prognostic applications. Besides, some researchers utilize the Wiener process and Gamma process to regress the degradation trends for RUL predictions. A Wiener process is a time-homogeneous process, while not all degradation processes have this property. That process only employs the information contained in the current degradation, rather than the information of the entire sequence of observations [50]. The Gamma process is a positive stochastic process with independent increments, which can excellently describe the deterioration caused by the accumulation of wear. Representatively, this paper involves the typical statistical options of Weibull distribution, Similarity-based, Wiener process, and Gamma process for comparison, and the attributes of these methods are summarized in Table 5.1.

b). RUL estimation

The step of RUL estimation is responsible for predicting the degradation trend of testing data after the last observation, and further estimating the RUL with the trained degradation models. Similar to the training process, it is to assess the current health status of testing datasets through constructing the corresponding HIs using the same technique. Then, according to the information from the trained degradation models, estimate the RULs via the statistical techniques. Table 5.1 summarizes some typical examples of technical options in specific prognostics approaches.

Table 5.1: Examples of technical options for statistical model

Approach	Performance Assessment	Degradation Model Construction	RUL Estimation	Ref.
Weibull	Statistics failure cycles	Weibull distribution regression.	The mean residual life of Weibull reliability function.	[35]
Similarity -based with Regression	Linear regression method	Regress HIs into an exponential regression to fit the degradation curve for each training instance.	Estimate the RUL on the most similarity degradation models for each testing instance.	[35, 47]
Wiener Process with PCA	Convert observations to HIs using PCA.	Regress HIs into a three parameters Wiener process as the degradation model.	The RUL is estimated as the empirical mean reminding cycle of the Wiener process paths by Monte-Carlo method.	[35, 51]
Similarity-based with PCA	Convert observations to HIs using PCA.	Regress HIs into an exponential regression to fit the degradation curve for each training instance.	Estimate the RUL on the most similarity degradation models for each testing instance.	[51]
Gamma Process with PCA	Convert observations to HIs using PCA.	Approximate states are extracted from noisy HIs by Gibbs technique and then regressed into gamma process as degradation model.	The RUL is estimated from the trained Gamma process for testing instance.	[15]

5

ML MODEL

The ML techniques have attracted a great amount of research and industrial interests due to the wide applications in prognostics. The advanced machine learning approaches can produce predictions by converting the gathered data into useful information used in conjunction with sensor data to provide future predictions. Existing literature addresses that an artificial neural network (ANN) is one of the most popular machine learning approaches. In such models, the neural networks abstract the desired level of degradation or RUL via the observations measurements. This paper discusses the technical options of ML models with the steps a) degradation prognostics; and b) RUL estimation, as identified in Figure 5.3.

a). Degradation Prognostics

To obtain the trained degradation models, we need to regard the aspects of structure construction and learning techniques application, as defined inFigure 5.3. Firstly, the configuration of the neural network structure means the number of layers (input layer, hidden layer, output layer), and the nodes in each layer [29]. Although there are no common criteria for layers and nodes selecting, it can determent the structure via one or multi-objective functions (e.g. mean square errors). In practice, the number of layers and nodes determine the complexity of parameters, and a more complex network structure ends up with more unknown parameters, requiring more training data.

On the other hand, the techniques to find the weight parameters from measurement features (input) to abstract features (output). To illustrate, a typical architecture is a basic deep neural network (DNN) in which the weight parameter is determined through a learning algorithm by the backward propagation of errors between the training data and the output. In a basic DNN model, it is possible to learn the relationship by augmenting the neural network structure. However, the more hidden layers of the structure require more training data and consuming more time. For comparison, the convolution neural network (CNN) approach is also widely used in prediction because the convolution operation can extract high-level features from raw data. The convolutional layers can convolve multiple filters with raw input data and generate features, and the following pooling layers can extract the most significant local features afterward [52]. The input data are utilized to learn abstract spatial features by alternating and stacking convolutional kernels and pooling operation. Therefore, the degradation models with the aspects of the structure of the network, defined parameters, required learning parameters and, etc., are constructed based on the observations in training datasets.

b). RUL estimation

Likewise, the observations of testing data are transformed to the corresponding RULs through the same neural network with requiring calculation. The relevant parameters of such calculations are extracted from degradation models by iteration learning techniques. In this paper, we employ the DNN and CNN prognostics approach for the comparison study, to validate the practical framework proposed in Figure 5.3.Table 5.2 presents the configurations of the experimental study in this paper.

Table 5.2: Examples of practical technical options for ML model values in bold

Approach	Network Structure	Learning Techniques	Ref.
DNN	1 input layer and 1 output laver; 3 hidden layers with the nuerons: 75, 100, 50.	Feed-forward and backward propagation learning	[53]
CNN	1 input layer and 1 output layer; 4 convolution layers with 10 convolution filters (size: 10*1); 1 convolution layer with 1 filter (size: 3*1); Fully-connected layer with 100 neurons.	Convolution operation of features learning	[52]

5.4.4. EVALUATION

Prognostics aim to avoid catastrophic eventualities in critical systems through warnings (e.g. RUL). However, it is difficult to evaluate the performance of the warnings. This imposes a strict validation requirement on prognostics methods to be proven and established through a rigorous performance evaluation for the estimated RULs. With the continuously evolving and efforts, it undertakes a set of performance metrics towards presenting a sufficient degree of confidence to the algorithms and allowing their application in real in-situ environments.

The literature investigates a taxonomy of performance measures for RUL estimation [39, 40]. The main categories of prognostic metrics are accuracy-based, precision-based, robustness-based, convergence-based, etc., and some measures dedicated specifically to prognostics (PHM metrics). Due to that the prognostic process involves predictions on multiple instances, it is expected that the majority of publications would use error based accuracy and precision metrics.

5.5. EXPERIMENTAL STUDY

The experimental study addressed in this section sustains the determination of the appropriate technical options for prognostics, according to the practical framework presented in Section 5.3. Besides, the relevant techniques employed in prognostics approaches have been discussed in Section 5.4. Thus, the experimental study consists of two cases: 1) Regard and compare the technical options of data processing (Subsection 5.5.2); 2) Compare the typical statistical models and ML models with various technologies for RUL prediction, respectively (Subsection 5.5.3).

Particularly, the compassion studies produce the RUL predictions according to the flow-char in Figure 5.4, which expresses the relevant technical options determination, covering the statistical models and ML models. The flow-charts identify a set of technical options as the applications of the proposed practical framework. Ensuring the reasonableness of comparison, it hypothesizes that the applied datasets and the evaluation metric are fixed to all prognostic approaches.

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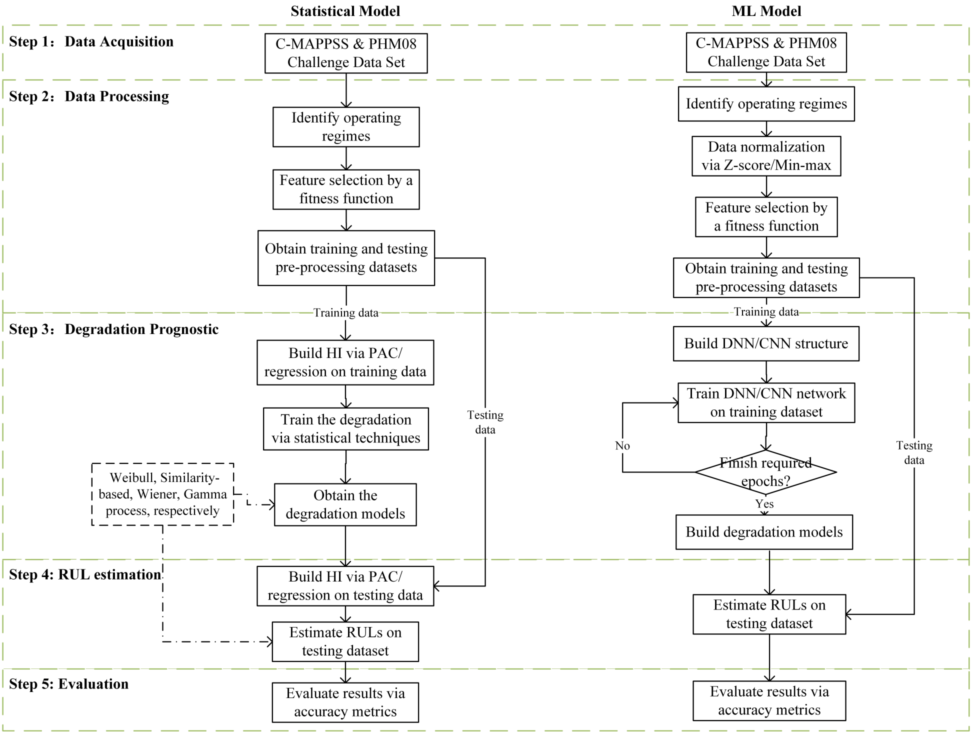

Figure 5.4: Technical Options of data-driven practical framework

5.5.1. EXPERIMENTAL DATA

This case study makes the use of C-MAPSS datasets (FD001 FD004) and PHM08 Challenge Data Set for prognostic implementation and comparison. These datasets are aircraft engine degradation simulation data under different combinations of operational conditions and fault modes, which are generated through the tool of C-MAPSS [42, 43]. Each dataset consists of multivariate time series that are from identical and independent instances of a turbofan engine. Further, each instance has the format of 3 operational settings and 21 sensors measurements.

Table 5.3 identifies the formats of these datasets with the aspects of units, operation conditions and fault models [54]. The selected sensors in this case study are #2, #3, #4, #7, #11, #12, and #15. Whereas, the final results were evaluated by the metrics (e.g. PHM'08 estimation metric, root squared error (RSE), mean squared error (MSE) reflecting the accuracy, meaning that lower scores indicate better performance [39].

Table 5.3: Datasets for experimental study

Data Sets	C-MAPSS Datasets				PHM08 Challenge Data Set
	FD001	FD002	FD003	FD004	
Train Units	100	260	100	249	218
Test Units	100	259	100	248	218/435
Operating Conditions	1	6	1	6	6
Fault Models	1	1	2	2	1

5.5.2. DATA PROCESSING

As defined in Figure 5.3, the typical technical options of data processing include data identification, data normalization, and feature selection. Then, this section presents the study results for the comparison of the data processing technical options.

IDENTIFICATION

The trajectories of the sensors data differ from each other because these data are under various combinations of operational conditions, regimes and fault modes. In this case, the dataset contains three operational settings, such as altitude, Mach number, and sea-level temperature (TRA) that indicate variations of operational regimes. Whereby, it is necessary to identify the operational regimes to apply the technical options separately within each partitioning performing mode. Generally, the number of regimes depends on the number of clusters in operational settings. Based on experimental results, the observations of the PHM08 Challenge dataset are concentrated into six different clusters, pointing out six operating regimes as shown Figure 5.5. That is compliant with the aspect of operating conditions in Table 5.3. For comparison, Figure 5.6 shows the operating regimes of C-MAPPS datasets, in which the regime's number of the datasets FD001, FD002, FD003, and FD004 are 1, 6, 1, and 6 respectively. Particularly, the operating settings of FD001 and FD003 are clustered in 2D, so that there is only one partition regime in these datasets.

NORMALIZATION

Subsequently, the study applies the technical options of data normalization on the PHM08 Challenge dataset. The application of data normalization can transform the standardized sensors data reassembled to form the normalized dataset, enhancing the features

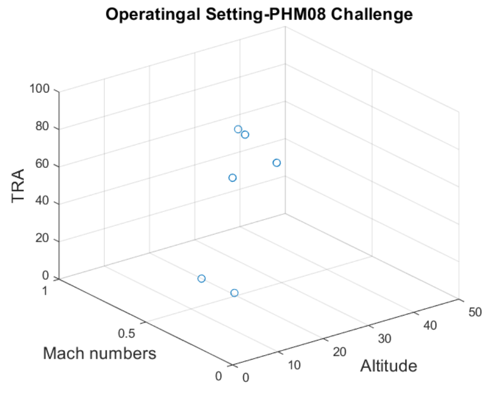

Figure 5.5: Operating Regimes of PHM08 Challenge Data

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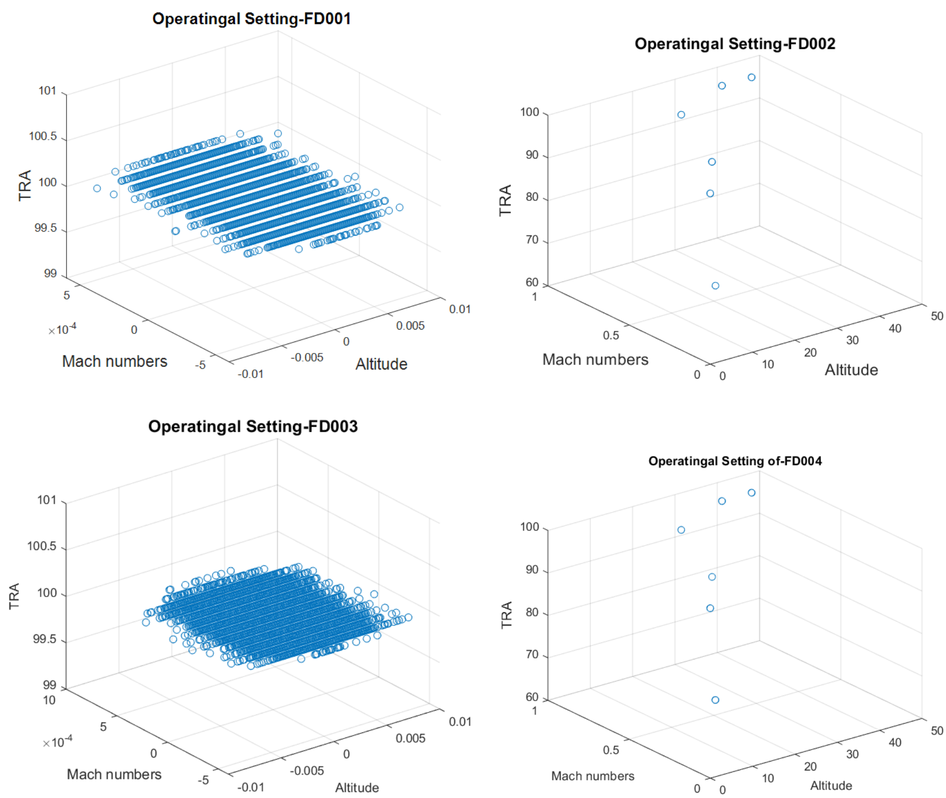

Figure 5.6: Operating Regimes of C-MAPPS datasets

of sensors data. For example, Figure 5.7 shows the measurements of raw sensors data of unit 1 in PHM08 Challenge dataset. Whereas, the corresponding normalization results are presented in Figure 5.8, comparing the options of z-score and min-max normalization techniques. As a result, the raw data are mapping into a fixed scale with high dimension quantity, which improves the quantity for features extracting and comparison. The normalization options benefit to prognostic performance because of the high quantity of data characteristics, and such results are presented in validation section.

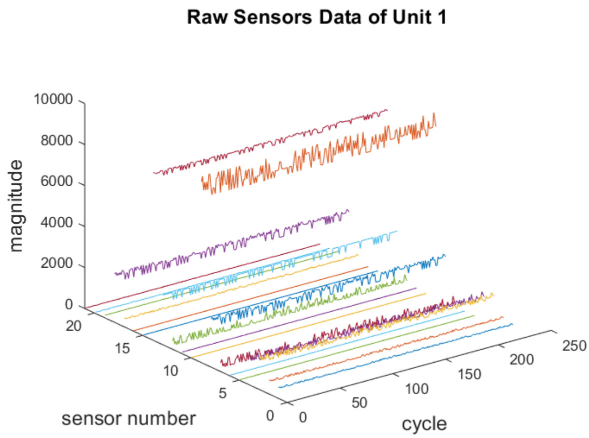

Figure 5.7: Raw Sensors Data

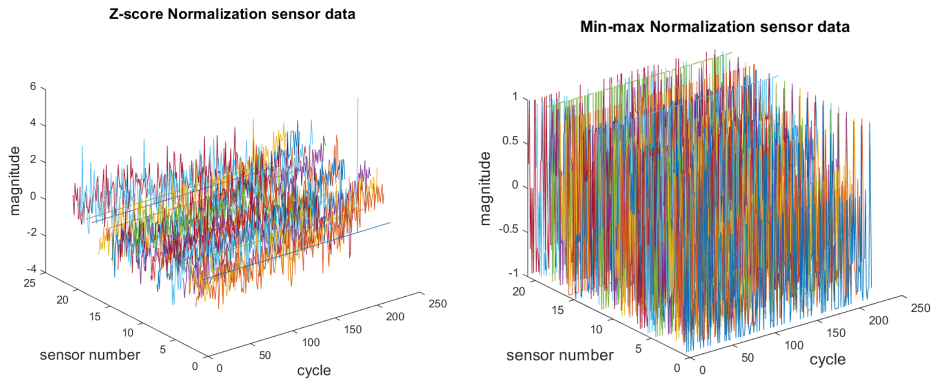

Figure 5.8: Normalization of sensors data

FEATURE SELECTION

In prognostic approaches, feature selection is an important option to improve the prediction results because of reducing the unnecessary redundancy and noise in the measurements. Not all observation sensors of the dataset provide degradation information, even it provides, the degrees of degradation information is varying from different sensors. Whereby, the evaluated degree of the sensors correlate with the degradation pattern is the metric for feature selection. As aforementioned, a functions with the parameters of trendability, monotonicity, and prognosability can evaluate the observation sensors. The sum of these there parameters can measure whether the candidate sensors are useful for individual-based prognosis [45].

Figure 5.9 demonstrates the evaluation results of all 21 sensors of PHM08 Challenge dataset, including the values of three parameters and the final fitness functions, in which more value means more advisable for prognostics. Accordingly, the sorting results of fitness function measures (values form more to less) are: #11, #4, #15, #2, #17, #3, #7, #12, #20, #21, #6, #8, #13, #9, #14, #10, and #16. Whereas the sensors of #1, #5, #18, #19 are not suitable for prognostic due to the non-monotonic. Figure 5.10 shows the evaluation results of C-MAPPS datasets (FD001 and FD003) for comparison. The results demonstrate that the evaluations are different in various datasets even though the sensors are the same that is due to the data amounts in varying datasets and the uncertain noise during data acquisition. However, the fitness features still have a significant performance of the sensors #2, #3, #4, #11, #15, #17, #20 and #21, when comparing with other sensors.

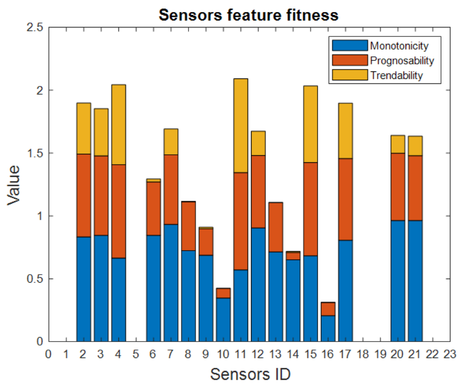

Figure 5.9: Evaluation results of sensors

VALIDATION

PHM08 Challenge Data Set exhibits multiple operational regimes that may cause prognostic models without a detailed data processing step to have a risk of excessive error rates. The above experimental results are unable to directly demonstrate the improvement of RUL accuracy prediction results. Thus, this section validates the prognostics performance through the studies with/without the solution of data processing techniques and feature selection.

Regarding data normalization, Table 5.4 illustrates the evaluation results of DNN and CNN prognostic approaches in the cases of applied or not applied the normalization technical options for comparing. Besides, Figure 5.11 figures out these results in a visualized view. In conclusion, the results demonstrate that the most striking observation to emerge from the data comparison is that the technical option of normalization can

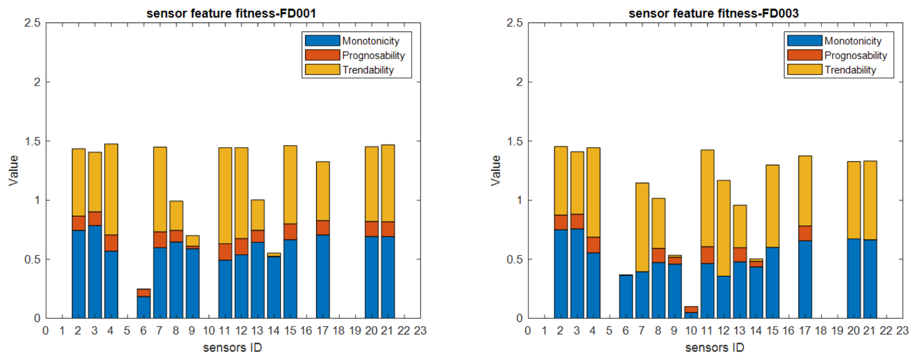

Figure 5.10: Evaluation results of FD001 and FD003

improve the accuracy performance in both DNN and CNN prognostics models. Further, CNN prognostic approach generally has a better result compared with the DNN approach owing to the effective feature extraction of convolution learning.

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Table 5.4: Evaluation Results of Normalization

Approach	PHM08 Evaluation	RSE	MSE	RMSE	MAE
DNN without normalization	1077	223.8772	737.0735	27.5801	27.0441
DNN with normalization	293.6918	130.4301	250.1765	16.861	14.7941
CNN without normalization	338.9281	139.0396	284.2941	16.861	14.7941
CNN with normalization	219.8198	107.7404	170.7059	13.0654	10.6765
PHM08 Challenge Data Set: 150 training instances and 68 testing instances in training dataset; The selected sensors are : #2, #3, #4, #7, #11, #12, #15 (7 sensors).					

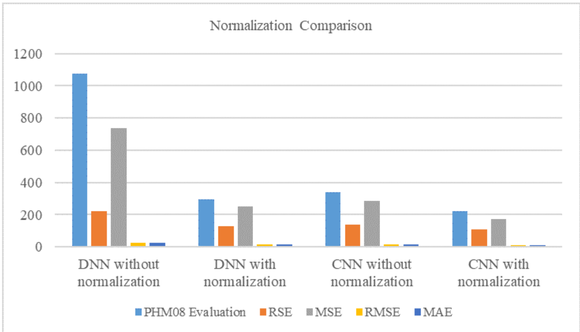

Figure 5.11: Evaluation Results for Normalization

For feature selection, this case study undertakes the typical data-driven prognostic approaches with 4 different sensors groups for producing. Table 5.5 represents the evaluation results of the CNN approach with 4 selected sensors groups for comparing. As a result, group #3 (7 sensors) has the best prediction performance, closed to the result of group #4 (6 sensors). Whereas group #1 (21 sensors) gives the worst results because of more redundancy information from sensors. Figure 5.12 shows not only the evaluation result but the elapsed time, which is improving with less number of sensors. In this case, it is effective to select the sensors group #3 (sensors: #2, #3,#4, #7, #11, #12, #15) to optimize RUL prediction. It validates the three-parametric method to evaluate the usefulness measurement of sensors.

Table 5.6 expresses that group #3 and #4 have better performance when compared with group #1 and #2 in similarity with PCA prognostic approach (statistical model). It demonstrates that the sensors selection option can determine the more meaningful sensors to advance RUL prediction performance. However, different from the CNN approach, there is no significant improvement of the elapsed time, when deploying the different groups of sensors in similarity with the PCA approach, as shown in Figure 5.13. To conclude, this comparison case study can reinforce the results of feature selection in Figure 5.9, and it also demonstrates that the option of sensors selection can improve the accuracy for RUL estimation.

Table 5.5: Sensor selection results of CNN approach

ID	Sensor	No.	Evaluation					Elapsed time
			PHM08 Evaluation	RSE	MSE	RMSE	MAE	
1	All sensors	21	425.4448	141.4532	294.25	17.1537	13.9625	11105.9911
2	#2,3,4,7,8,9,11,12,13 ,14,15,17, 20,21 [[52]]	14	359.8404	139.4346	285.9118	16.9089	14.1176	2406.9057
3	#2,3,4,7,11,12,15 [[15, 33, 35]]	7	219.8198	107.7404	170.7059	13.0654	10.6765	1034.2088
4	#11,4,15,2,17,3 [[46]]	6	236.1943	115.5984	196.5147	14.0184	11.4559	916.6368
PHM08 Challenge Data Set: 150 training instances and 68 testing instances in training dataset								

Table 5.6: Sensor selection results of similarity with PCA approach

ID	Sensor	No.	Evaluation					Elapsed time
			PHM08	RSE	MSE	RMSE	MAE	
1	All sensors	21	1363.2	313.423	1444.6	38.0081	37.1471	18.0476
2	#2,3,4,7,8,9,11,12,13, 14,15,17, 20,21 [[52]]	14	452.6103	213.4737	670.1618	25.8875	25.3088	20.0417
3	#2,3,4,7,11,12,15 [[15, 33, 35]]	7	305.0142	179.8027	475.4265	20.5314	18.9118	23.1331
4	#11,4,15,2,17,3 [[46]]	6	207.8055	148.59	324.6912	18.0192	17.5441	22.4389
PHM08 Challenge Data Set: 150 training instances and 68 testing instances in training dataset								

5.5.3. PROGNOSTIC MODELS

This section presents the evaluation results of several typical statistical models and ML models for RUL prediction, as the experimental study based on the flow-charts in Figure 5.4.

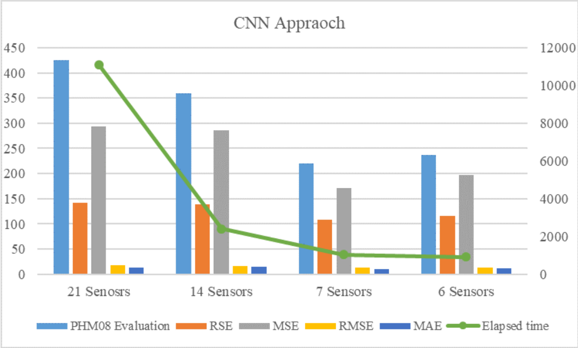

Figure 5.12: Evaluation Results for Normalization

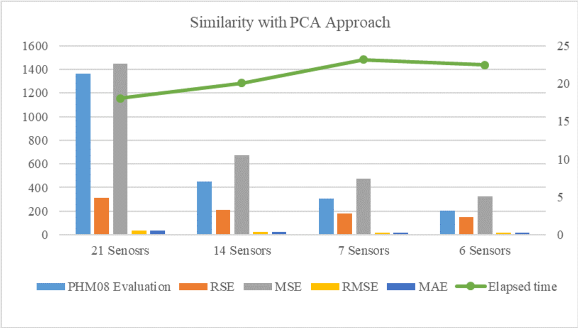

Figure 5.13: Evaluation Results for Normalization

STATISTICAL MODELS

Afterward, the study performs several popular statistical approaches on the datasets of HM08 Challenge Data Set. Table 5.7 summarizes the evaluation results of prediction performance with a set of statistical prognostics approaches based on the literature review. According to the results, it expresses that the gamma process improves the evaluation scores when comparing with the Wiener process and similarity-based prognostics methods with the same technique for performance assessment (e.g. PCA). The results in Table 5.7 also demonstrates that the linear regression technique provides better accuracy performance comparing with the PCA techniques if it employs the similarity approach. To conclude, these results justify the accuracy of statistical models and demonstrate that such probabilistic approaches can describe the degradation phenomenon and predict the RUL through statistical principles.

ML MODELS

This section performs the experimental study of several ML prognostics approaches. Table 5.8 and Figure 5.14 show the results of the CNN prognostic approach with different configuration number of convolution layers in its neural network. Generally, the more hidden convolution layers lead to better accuracy values due to the fact that the deep

Table 5.7: Evaluation of Statistical Models

ID	Approach	PHM08 Evaluation	RSE	MSE	Ref
1	Weibull prognostic	9450	x	1011	[33]
2	Similarity-based with regression	5636	x	x	[47]
3	Wiener process with PCA	5575	423	823	[33]
4	Similarity-based with PCA	6690	420	809	[33]
5	Gamma process with PCA	4107	x	864	[15]

architecture can capture more useful information than the shallow ones. Although the higher prognostic accuracy can be obtained by a deeper structure, the computing time for the training process increases almost linearly with the hidden layer number. Figure 5.14 indicates that the network with 5 convolution layers can provide better performance with a medium computing burden. In conclusion, the CNN prognostics approach is configured with 5 convolution layer, when comparing with other ML prognostic approaches.

Table 5.8: Effective convolution layers of CNN model

ID	No. of layers	Evaluation					Elapsed time
		PHM08 Evaluation	RSE	MSE	RMSE	MAE	
1	1 Conv layers	1020.8	193.3805	549.9412	23.4508	20.3529	209.8019
2	3 Conv layers	457.0775	157.8322	366.3382	19.14	17.2794	1604.6216
3	5 Conv layers	219.8198	107.7404	170.7059	13.0654	10.6765	2072.931
4	7 Conv layers	235.7336	113.1813	188.3824	13.7252	11.4118	5528.2546
Note: PHM08 Challenge Data Set: 150 training instances and 68 testing instances in training dataset; The selected sensors are : #2, #3, #4, #7, #11, #12, #15 (7 sensors).							

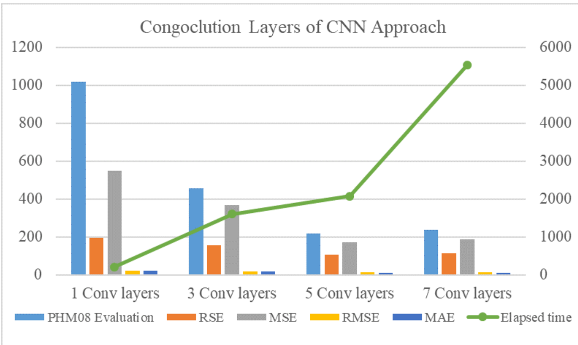

Figure 5.14: Effective Convolution Layers of CNN model

The comprehensive comparison result of some typical ML approaches is presented in Table 5.9 [52]. The results indicate that the CNN method is more suited for the C-

MAPSS datasets, comparing with the others. The convolution layers contribute to learning capability by effectively extracting more useful features. The RNN structure is the second-best using the recurrent information flow. Whereas LSTM is a more advanced variant of RNN, its performance is not as good as RNN in this case study. The basic neural network method DNN is still competitive in faster producing, sample preparations with raw data.

Table 5.9: Evaluation of ML models [52]

Approach	PHM08 Evaluation				RMSE				Ref.
	FD001	FD002	FD003	FD004	FD001	FD002	FD003	FD004	
DNN	348.3	15622	364.3	16223	13.56	24.61	13.93	24.31	[55]
RNN	339.2	14252	315.7	13931	13.44	24.03	13.36	24.02	[52]
LSTM	431.7	14459	347.3	14322	13.52	24.42	13.54	24.21	[56]
CNN	273.7	10412	284.1	12466	12.61	22.36	12.64	23.31	[52]

5.5.4. DISCUSSION

Table 5.10 summarizes the advantages and disadvantages of a typical set of data-driven prognostic approaches based on the experimental study. It provides useful information and a recommendation to determine the appropriate technical options taking into account the relevant processes.

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Table 5.10: Applicability of Prognostic Approaches

Approach	Advantages	Disadvantage
Weibull	Low cost; Simplest technique to apply and explain.	Do not consider operating conditions; Requires a significant amount of data.
Similarity-based with Regression	Non-linear system can by model; Multiple failure modes; the probability density function of RUL is expontial function.	Reqires run-to-failure data; Limitation of noise; Highly depends on the trends of observation data.
Wiener Process with PCA	The Multi-dimensional, non-linear, non-monotonic system can by model; Multiple failure modes; Higher accuracy; Uncertainty consideration.	Different to calculate the probability density function of RUL; Requires too much computation cost.
Similarity-based with PCA	The multi-dimensional, non-linear system can by model; Multiple failure modes; Computationally efficient; Accurate results for short-term prediction.	Limitation of noise; Unable to re-use to other operations.
Gamma process with PCA	The mathematical calculations are easy to be understood.	The process is adequate for monotonic processes; High time complexity; Limitations of noise.
DNN	Model complex, multi-dimensional, unstable or non-linear system; More capable of capturing and modeling complex phenomena without a priori knowledge.	Requires a significant amount of data for training data; Data processing is required to limit the number of input and reduce model complexity; Unable to re-use to other components/systems
CNN	Model complex, multi-dimensional, unstable or non-linear system; More capable of capturing and modeling complex phenomena without a priori knowledge; Convolution operation can extract high-level features from raw data.	Requires a significant amount of data for training data; Data processing is required to limit the number of input and reduce model complexity; High time complexity; Unable to re-use to other operations.

5.6. CONCLUSION AND FUTURE WORK

The paper aims to fill the gaps between state of the art research and the actual practice of implementing and adopting prognostics using various advanced techniques. Therefore, this article develops a practical framework for data-driven prognostic approaches for RUL prediction. This framework not only address the main steps of practical adoption, but also identifies the critical characteristics of prognostics and relevant technical options of statistical models and machine learning (ML) models, as shown in Figure 5.2 and Figure 5.3. To synthesize the underlying knowledge, relevant statistical and ML techniques are discussed in Section 5.4 to demonstrate application of the framework from a practical perspective. Regarding the application of the framework, the comparative studies illustrate the typical practical techniques for prognostics and compare their effects on the accuracy of RUL prediction. The experimental results produced on PHM08 Challenge Dataset and C-MAPSS datasets reflect the accuracy evaluation for comparison and validating the framework for determining suitable options for selection of techniques.

This study has contributed to the data-driven prognostic techniques implementation from a methodological perspective. With the existing development of prognostics approaches, this article also contributes more depth and comprehensive cognition. Synthesizing these content can constitute a booster towards successfully design a PHM system in industrial practice. However, the underlying limitations and applicability of this research are comprehensively concluded as follows. The main limitations in this research are as follows:

- The first limitation is that the experimental datasets are simulations data (C-MAPSS datasets and PHM08 Challenge Data Set), but not real-life data. These datasets the run-to-failure simulation data of turbofan engines carried out through C-MAPSS. Hundred engine's run-to-failure time series trajectories are addressed in this paper, which can be squared up to be from a fleet of engines of the same type. The observation data on the health of a system are noisy due to the presence of different sensors or measurement errors. However, these simulation datasets use the approximate model combined with a random noise into the observations instead of the real noise from measurement and environment.

- The second limitation is that this chapter focuses on providing a practical framework of technical options for data-driven prognostics, but does not contributing to the novelty of advanced techniques or prognostic approaches. Therefore, it is unable to cover all technical options and prognostic approaches to validate the framework. From a methodological perspective, the research has made full use of several popular technical options (e.g. fitness function, z-normalization, etc.) or prognostic approaches (Wiener process, gamma process, similarity, CNN, etc.) in a comparative study to demonstrate the applicability of the proposed methodology.

To address these limitations, a smart determination of prognostic approaches can produce a library of synthetic output models and the best-matching degradation model can be selected for the raw test data. Future studies should provide efforts on a comprehensive understanding of prognostic approaches determination under the consideration of requirements, to improve the effective implementation of prognostics systems. Existing research also calls for more efforts on developing up a decision framework to guide the designer toward a prognostic algorithm or some practical options selection based on analysis of failure modes and safety analysis for the monitored system, and/or the available dataset. Concerning the system/component (e.g. engines, landing gear, bearing), it improves the information carried in the complex systems and minimise uncertainty. As a result, a novel framework can achieve a consistent understanding of the practical options and criteria for selection.

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6

CONCLUSION

This chapter concludes the thesis with observations and findings obtained during this research development. Firstly, it reviews the research questions and objectives defined in Chapter 1. Then the contributions and novelties gained from this research are summarized. Finally, limitations and challenges are stated and recommendations for future work are discussed.

6.1. REVIEW OF OBJECTIVES

This dissertation has focused on enhancing the design methodology for PHM systems to support airline predictive maintenance. The introduction chapter has addressed the relevant research questions and motivations. To fulfill the gaps, the main research goal was summarized as:

> **To develop a systematic design methodology toward the design of a PHM system in a comprehensive manner to support aircraft predictive maintenance.**

To achieve this goal, five research objectives were also raised in Chapter 1.

1). To develop a systematic and comprehensive methodology for the PHM system, emphasizing the method of stakeholders' expectation definition

Chapter 2 proposes a stakeholder-oriented methodology that formulates all elements of designing and engineering a PHM system. Further, it emphasizes the process and deployment of Task 1 (stakeholder expectations definition) in detail, involving in the steps of identifying stakeholders, capture stakeholder expectations/requirements, as well as stakeholder and requirement analysis. In practice, two case studies verify the stakeholder expectation definition process, including a generic project of PHM system design, and an application case for the ReMAP research project. Summaries of the case studies demonstrate that the stakeholder-oriented methodology has the applicability to be applied in a group of similar projects. Moreover, the established stakeholders' expectations and requirements of a generic PHM system have the aspects of traceability, consistency, and reusability. Hence, this chapter has developed a stakeholders-oriented methodology for the PHM system, with a detailed description of stakeholders' expectations, which is compliant with this research objective.

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2). To develop a requirement definition methodology that describes the practicable steps in detail.

InChapter 3, a systematic design methodology of requirements definition for PHM systems is developed. This methodology focuses on the processes and requirement definition, as well as how each category of requirements can be derived through appropriate analyses. Furthermore, it has identified the sequence of interoperability requirements categories and the solution of requirements flow-down with step-by-step description. Requirement definition activities can continue within the system design process recursive loop until a preferred system solution has been fully delimited. The associated case study captured a set of requirements for the PHM system according to the stakeholders' expectations and the analysis results of FA and ConOps. To ensure the design quality, relevant validation activities were performed. In summary, a comprehensive requirements definition methodology has been developed and the practicable steps are described in detail, thereby achieving the research objective.

3). To propose a methodology for PHM architecture definition that can guide the design of architecture.

Chapter 4 presents a systematic methodology for PHM architecture definition, leveraging the concept of "RFLP" (requirement, functional architecture, logical architecture, and physical architecture). A detailed description of a generic PHM architecture has been established in a set of architecture views by partitioning elements and physical modularity; hence it has the architectural characteristics of functional/physical dimensions, modularity, and robustness. Additionally, a case study is conducted to verify and validate the proposed PHM architecture to ensure correctness and completeness though SysML modeling. Another case study analyzes the relevant characteristics of PHM architecture ensure compliance and the consistency of design elements. Consequently, this chapter has proposed a methodology for PHM architecture definition, which improves upon existing methodologies by providing a more complete and consistent representation of PHM architecture development from start to finish.

4). To present a practical framework for data-driven prognostic approaches that can support the practices of prognostics.

To discuss the aspect of the design solution, Chapter 5 introduced a generic data-driven prognostic process, which is divided into five technical processes for the RUL prediction. Correspondingly, a practical framework of data-driven prognostics is presented, covering key characteristics of prognostic techniques with particular consideration of statistical and machine learning models. A comparison of statistical and machine learning prognostic models is performed based on C-MAPSS and PHM08 datasets. Summaries of case study results express the applicability of the generic prognostics process and the practical framework in RUL prediction. Therefore, this chapter enhanced a comprehensive understanding of prognostics and provided a practical framework to support the determination of prognostics approaches. In practice, the method of selecting a suitable prognostics approach plays an important role in the design and engineering PHM systems.

5). To address the validation and verification activities that can ensure the design quality.

According to the structure of this thesis, Chapter 2-Chapter 5 addressed the research objective of V&V from various perspectives. These chapters evaluate the sufficiency and quality of the design material and outputs. Particularly, this dissertation stated the V&V activities concerning the aspects of stakeholders' expectations (Chapter 2), system requirements (Chapter 3), system architecture (Chapter 4), and design solution of prognostics function (Chapter 5), respectively. Integrated, these relevant V&V activities demonstrated that the intended functions have been correctly and completely structured; examined whether the behaviors and the state's transmission of a system have been satisfied; and ensure the implementation of prognostics approaches. This dissertation has comprehensively addressed the V&V activities in the systematic design methodology. Accordingly, it has successfully achieved the objective to evaluate the design quality and ensure the aspects of traceability, consistency, and reusability during the design life-cycle under the proposed design methodology.

6.2. RESEARCH NOVELTY AND CONTRIBUTION

This dissertation has aimed to significantly advance the current design thinking relative to PHM systems. This research is set up to address the gaps in systematic design methodology for PHM systems to support predictive maintenance. Based on the literature review, there is no known work specifically underlining the lack of a comprehensive design methodology for the PHM system.

The novelty of the dissertation lies in developing a systematic design methodology for PHM systems. The main novelties and contributions are summarized as follows.

- We define a design methodology that identifies the stakeholder involvement and interest levels to lead towards more precise and better design information. It comprehensively covers the aspects of traceability, consistency, and reusability to capture stakeholders' expectations to aid in the successful design of PHM systems.
- The proposed methodology of defining requirements premeditates the practicable steps in detail and interprets requirements validation and requirements flowdown ensuring the consistent design. Meanwhile, we establish a generic case of requirements specification for the PHM system as guidance for engineers.
- Furthermore, we contribute a design methodology of architecture defining in compliance, consistency, interoperability, and applicability perspective, and also provide a generic architecture for PHM systems. Hence, we contribute guidance for PHM systems design, alongside with a reusable and practical generic architecture for the PHM system.
- This research contributes to a novel practical framework for data-driven prognostics approaches. This framework comprehensively presents the key technical steps in data-driven prognostics with the proper technical options, aiming to provide an informative tool for prognostics approaches selection.

To conclude, the main novelty of the dissertation is to develop a systematic design methodology toward the design of a PHM system in a comprehensive manner for the implementation of aircraft predictive maintenance. To progress from application-specific solutions towards structured, consistent and efficient PHM system implementations, it is essential to use an unambiguous, comprehensive and pragmatic design methodology proposed in this thesis. This research further contributes toward designers' guidance or principles conducting the design activities for engineering PHM systems. According to the outputs from the PHM system, e.g., estimated RULs and generated maintenance advise, the airline operators and MROs may make full use of them to support predictive maintenance and optimize maintenance operations.

6.3. LIMITATIONS AND RECOMMENDATIONS

This dissertation has provided significant contributions, yet there still are challenges related to the gap between theory and practice. In this context, the limitations and corresponding recommendations for future work are discussed in the following aspects:

1). Prognostics approaches selection

The prognostics algorithm selection plays a critical role to achieve consistency design. However, there is not yet a comprehensive method to support approaches determination in practice. Such determination requires a thorough understanding of the underlying data and/or physical processes to counter different sources of uncertainty that affect prognostics. Furthermore, the PHM systems in real-life operations are complex and have countless uncertainty factors that can affect their processes. Hence, the selection of suitable prognostic techniques should focus on the feasibility of advanced techniques without suppressing the information carried in the complex systems and with minimized uncertainty.

Principally, determining a suitable prognostic approach should satisfy the requirements, as the implementation of prognostics function is to integrate into the design of PHM systems. Satisfying solutions can take the form of using heuristic problem-solving techniques and is only useful if non-optimal solutions exist for a problem. A smart determination of prognostic approaches can produce a library of synthetic output models and the best-matching degradation model was selected for the raw test data. Future studies should provide more efforts on a comprehensive understanding of prognostic approaches, to conduct a more complete decision framework for design solutions (e.g., the selection of prognostics or diagnostics) based on analysis of failure modes and safety analysis and requirements. Therefore, researchers can invest in setting up a decision framework to guide the designer toward a prognostic algorithm or the practical options selection based on analysis of failure modes and safety analysis for the monitored system, and/or the available dataset. Considering the characteristics of specific systems/components (e.g. engines, landing gear, and bearing) can improve the information carried in the complex systems and minimize uncertainty.

2). V&V and evaluation

Although this thesis has covered the associated V&V activities in the proposed design methodology, another remaining challenge is about validation and verification. More specifically, it is difficult to perform validation and verification activities on a completely realistic PHM system due to the constraints of engineering. Therefore, results and evaluation of requirements verification and system verification of this generic PHM system and interrelated techniques are lacking. The existing prognostic techniques are not extensively applied in industries even though they can deal with model complexity because there are several limitations and assumptions of prognostics for complex systems (e.g. engines, gearbox, and avionics). While some prognostic techniques have been verified in a laboratory-controlled environment or simulation system. However, the verification performed in this way is not completely realistic as the results can be different from those in real operations. Thus, the verification results and evaluation of the methodology are lacking in existing research.

To face the gaps, future studies on the current topic are concentrated on enhancing a comprehensive understanding of design methodology, involving requirements, architectures, and design solutions and validation/verification items. Further research should be encouraged to validate and verify the design material and to develop elements (e.g. requirements specification, prognostics algorithms, embedded computing modules, framework, etc.) in the PHM field. Validation and verification should be performed while involving a multi-level design perspective. Furthermore, we should make an effort to develop an evaluation criterion of design methodology to provide confidence towards the successful engineering of a PHM system with high quality and satisfactory services and performance. On the other hand, it is also an opportunity to establish the best practices in both fields of academia and industry. More efforts are required in developing and engineering PHM systems and related functionalities, such as the approach selection, health management, performance evaluation, uncertainty treatment, application economics, as well as environmental issues, to build the best practices.

A

GLOSSARY

Terms	Definition
Analysis	Use of mathematical modeling and analytical techniques to predict the compliance of a design to its requirements based on calculated data or data derived from lower system structure end product validations.
Baseline	An agreed-to set of requirements, designs, or documents that will have changes controlled through a formal approval and monitoring process.
Block Definition Diagram	The block definition diagram (BDD) is a black-box structure of the system, with the connections between components and external interfaces, and the interfaces present a whole part or composition, or communication relationship between the block
Compliance	Successful performance of all mandatory activities; agreement between the expected or specified result and the actual result
Component	Any self-contained part, a combination of parts, subassemblies or units, that perform a distinctive function necessary to the operation of the system
Concept of operations (ConOps)	The ConOps describes how the system will be operated during the life-cycle phases to meet stakeholder expectations. It describes the system characteristics from an operational perspective and helps facilitate an understanding of the system goals. It stimulates the development of the requirements and architecture related to the user elements of the system. It serves as the basis for subsequent definition documents and provides the foundation for the long-range operational planning activie.
Functional Analysis	The process of identifying, describing, and relating the functions a system must perform to fulfill its goals and objectives.

A

Terms	Definition
Functional Decomposition	A subfunction under logical decomposition and design solution definition, it is the examination of a function to identify subfunctions necessary for the accomplishment of that function and functional relationships and interfaces
Functional Flow Block Diagram	A block diagram that defines system functions and the time sequence of functional events.
Interface Definition	The logical and physical aspects of internal interfaces (between the system elements composing the system) and external interfaces (between the system elements and the elements outside the system of interest)
Internal Block diagram	The internal Block diagram (IBD) can be used to define the internal connections between parts, and the details of how parts wired with each other.
Methodology	Methodology is the systematic, theoretical analysis of the methods applied to a field of study. It comprises the theoretical analysis of the body of methods and principles associated with a branch of knowledge. Typically, it encompasses concepts such as paradigm, theoretical model, phases and quantitative or qualitative techniques.
Mission	A major activity required to accomplish an Agency goal or to effectively pursue a scientific, technological, or engineering opportunity directly related to an Agency goal. Mission needs are independent of any particular system or technological solution.
Model	An abstract representation of a given set of aspects of a syste, function, item that is used for analysis, simulation and/or code generation and that has an unambiguous, well-defined syntax and semantics
Model-based systems engineering	Model-based systems engineering (MBSE) is a systems engineering methodology that focuses on creating and exploiting domain models as the primary means of information exchange between engineers, rather than on document-based information exchange.
Process	A set of activities used to convert inputs into desired outputs to generate expected outcomes and satisfy a purpose.
Product	A part of a system consisting of end products that perform operational functions and enabling products that perform life-cycle services related to the end product or a result of the technical efforts in the form of a work product (e.g., plan, baseline, or test result
Product-service systems	Product-service systems are business models that provide for cohesive delivery of products and services. PSS models are emerging as a means to enable collaborative consumption of both products and services, with the aim of pro-environmental outcomes

Terms	Definition
Project Constraints	Any constraints on the system arising from the technical management strategy including cost, schedule, and technical constraints
Redundancy	Multiple independent means incorporated to accomplish a given function.
Requirement	The agreed-upon need, desire, want, capability, capacity, or demand for personnel, equipment, facilities, or other resources or services by specified quantities for specific periods of time or at a specified time expressed as a shall statement. Acceptable form for a requirement statement is individually clear, correct, feasible to obtain, unambiguous in meaning, and can be validated at the level of the system structure at which stated. In pairs of requirement statements or as a set, collectively, they are not redundant, are adequately related with respect to terms used, and are not in conflict with one another
Requirements engineering	Requirements engineering refers to the process of defining, documenting and maintaining requirements in the engineering design process. It is a common role in systems engineering and software engineering.
Specification	A collection of requirements which, when taken together, constitute the criteria that define the functions and attributes of a system, component or item.
Stakeholder	A group or individual who is affected by or is in some way accountable for the outcome of an undertaking.
Stakeholder Expectations	A statement of needs, desires, capabilities, and wants that are not expressed as a requirement (not expressed as a shall statement) is to be referred to as an expectation Expectations can be stated in either qualitative (nonmeasurable) or quantitative (measurable) terms.
Stakeholder Requirements	Requirements form various stakeholders that will govern the project, including required system capabilities, functions, and/or services; quality standards; system constraints, and cost and schedule constraints.
System	(1) The combination of elements that function together to produce the capability to meet a need. The elements include all hardware, software, equipment, facilities, personnel, processes, and procedures needed for this purpose. (2) The end product (which performs operational functions) and enabling products (which provide life-cycle support services to the operational end products) that make-up a system

A

Terms	Definition
System Archiecnture desciription	Description of the selected system architecture, typically presented in a set of architectural views (e.g, views form architecture frameworks), models (e.g., logical and physical models, although there are other kinds of models that might be useful), and architecture characteristics (e.g., physical dimensions, environment resistance, execution efficiency, operability, reliability, maintainability, modularity, robustness, safeguard, understandability, etc).
System element	System elements implemented or supplied according to the acquisition agreement.
System requirements	What the system needs to do, how well, and under what conditions, are quiredto meet project and design constraints. Includes types of requirements such as functional, performance, interfaces, behavior (e.g. status and modes, stimulus responses, fault, and failure handling), operational conditions transportation, storage, physical constraints, realizations, integration, verification, validation, production, maintenance, disposal constrains and regulation.
Systems engineering	Systems engineering is an interdisciplinary field of engineering and engineering management that focuses on how to design and manage complex systems over their life cycles.
Systems Modeling Language	The Systems Modeling Language (SysML) is a general-purpose modeling language for systems engineering applications. It supports the specification, analysis, design, verification and validation of a broad range of systems and systems-of-systems.
Traceability	The recorded relationship established between two or more elements of the development process. For example, between a requirement and its source or between a verification method and its requirement.
Validation	Testing, possibly under simulated conditions, to ensure that a finished product works as required. The determination that the requirements for a product are correct and complete. [Are we building the right aircraft/ system/ function/ item?]
Verification	The process of proving or demonstrating that a finished product meets design specifications and requirements. The evaluation of an implementation of requirements to determine that they have been met. [Did we build the aircraft/ system/ function/ item right?]

CURRICULUM VITÆ

Rui LI

Rui Li was born in Nov. 1986 in Xi'an, China. She received her Bachelor's degree in artificial intelligence science and technology at Xidian University (China) in 2009. Then, she graduated from Xidian University in 2012, where she got a master's degree in Electronic Engineering.

After graduated, she moved to Shanghai to start her engineer career in the company of GE aviation (AVIAGE SYSTEM). From 2012 to 2015, she worked as a system engineer for the design of C919 narrow-body civil aircraft. She was responsible for design and developing the avionics system, and performing certification analysis for aircraft/engine projects. During these 4 years, she completed the programs Lean Six Sigma Green Belt Certification and project management program. In Sep. 2015, she worked as a senior consulting engineer in the Aviation Industry Corporation of China (AVIC). She participated in around10 projects for the design/certification process of commercial civil aviation, which included the products of civil aircraft, commercial engine systems, and avionics. She also completed the training programs of system engineering (INCOSE), certification (CAAC) and AS9100.

In Sep. 2016, she began her new career as a Ph.D. Candidate in the faculty of Aerospace Engineering at Delft University of Technology (TU Delft), Delft, The Netherlands. She joined the department of Air Transport and Operations (ATO) with the funding of the China Scholarship Council (CSC). Her Ph.D. research focused on the design methodology of Prognostic and Health Management (PHM) to support aircraft predictive maintenance, which benefits for airline maintenance cost-saving. She provided her contributions to a design methodology for the PHM system and system engineering, leading to several publications. She also provided several presentations at international conferences for academic social events. Alongside the research, she has undertaken educational tasks to supervise bachelor students the design synthesis exercise as the graduation thesis (Project: Middle of the market airliner). Major of her hobbies are traveling, gym, tennis, and cooking.

List of Publications

Journal papers:

4. **R. Li**, W. J. C. Verhagen, C. Curran, *A systematic methodology for Prognostic and Health Management system architecture definition*,Reliability Engineering & System Safety 2020;193:106598 (2020).

3. **R. Li**, W. J. C. Verhagen, R. Curran, *Stakeholder-oriented Systematic Design Methodology for Prognostic and Health Management System: Stakeholder Expectation Definition*, Advanced Engineering Informatics 43 (2020): 101041.

2. **R. Li**, W. J. C. Verhagen, R. Curran, *Toward a methodology of requirements definition for Prognostic and Health Management system to support aircraft predictive maintenance* Aerospace Science and Technology (2020): 105877.

1. **R. Li**, W. J. C. Verhagen,R. Curran, *A Practical Framework for Data-Driven Prognostic Approaches in Remaining Useful Life Prediction*, Journal of Aerospace Science and Technology [Unpublished-under review].

Peer-reviewed conference papers:

3. **R. Li**, W. J. C. Verhagen, R. Curran. Comparison of Data-driven Prognostics Models: A Process Perspective. In: European Safety and Reliability Conference, editor, 2019 European Safety and Reliability Association; 2019,p.978–81.doi:110.3850/978-981-11-2724-30503-cd.(2019)

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