CRANFIELD UNIVERSITY

PIOTR SYDOR

Optimal On-Board / Off-Board Partitioning of Integrated Vehicle Health Management System

SCHOOL OF ENGINEERING

PhD Thesis

Academic Year: 2013 - 2014

Supervisor: Professor Len M. Gelman

Co-Supervisor: Professor Antonios Tsourdos

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In partial fulfilment of the requirements for the degree of
Philosophiae Doctor (PhD)

Abstract

The research presented in this thesis is intended to investigate and develop method to address optimal on-board / off-board partitioning of Integrated Health Management (IVHM) System.

The problem of optimal on-board / off-board partitioning of IVHM System, with the main focus on, but not limited to, diagnostics and prognostics, has not yet been examined in the current literature. As a result, there exist no current solutions to tackle the on-board / off-board partitioning problem. The main objective of this work is to propose, investigate and develop a novel method for optimal on-board / off-board partitioning of an aircraft IVHM System.

The current (legacy) and future design aircraft system architectures have been critically reviewed, including analysis of technological limitations and barriers to implementation and integration of a partitioned IVHM System.

Based on the findings from the literature review a set of main drivers for IVHM System partitioning has been defined in relation to health monitoring of aircraft system. These main drivers constitute the basis for the framework of further investigation towards optimal partitioning presented in this work.

The novel criterion for optimal IVHM System partitioning has been investigated and developed in this work. The proposed criterion uses cost trade-off analysis with weighting coefficients related to a vehicle concept of operations (CONOPS). The criterion has been used to create the novel method for optimal on-board / off-board partitioning of IVHM System. New metrics to evaluate cost effectiveness of the partitioned IVHM System have been also developed. The computer program implementation and simulation study using synthetic data-set to test the proposed method is given here.

The proposed novel method contributes to the evolvement of the emerging field of IVHM System.

Hofstadter's Law: "It always takes longer than you expect, even when you take into account Hofstadter's Law."

-*Douglas R. Hofstadter*

Acknowledgements

I would first and foremost like to thank my Supervisor, Professor Len M. Gelman, for giving me the opportunity to work on this interesting and challenging project, for his support, encouragement, discussions and help throughout my study. It has been a ruminative journey through which I have learnt a lot.

I would also like to thank my co-supervisor, Professor Antonios Tsourdos, for guidance, constructive criticism and fruitful discussions. I am also grateful to Professor Jennions for his advice and guidance on professional and personal level.

A special thank you goes to my friends and colleagues from the Cranfield IVHM Centre & from the TES Centre, past and present, who have been a pleasure to work with. It has been a great time.

I would like to thank to all my friends and family for their support and patience.

Very special gratitude goes to Paula - my wife, my soulmate, my inspiration.

This work was funded by Integrated Vehicle Health Management Centre, Cranfield University, UK. I would like to thank the IVHM Centre's industrial partners: BAE Systems, Boeing, Meggitt, Rolls-Royce and Thales for giving numerous feedbacks and suggestions throughout the development of this work and also for helping in many other ways.

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Nomenclature

List of Abbreviations

ACARS	Airline Communication Addressing and Reporting System
AG	Advisory Generation (OSA-CBM)
AL	Automatic Logistics
ALIS	Automatic Logistics Information System
ATG	Air-to-ground
AUV	Autonomous Underwater Vehicle
BM	Base Maintenance
CBM	Condition-Based Maintenance
CONOPS	Concept of Operation
CMC	Central Maintenance Computer
CND	Can Not Duplicate
CPU	Central Processing Unit
DA	Data Acquisition (OSA-CBM)
DFDAU	Digital Flight Data Acquisition (Access) Unit
DM	Data Manipulation (OSA-CBM)
D/P	Diagnostics / Prognostics
ECS	Environmental Control System
EEC	Electronic Engine Controller
EHM	Engine Health Management
ER	Erroneous Removal
FTA	Finite Element Analysis
GBR	Ground Based Reasoner
HA	Health Assessment (OSA-CBM)
HIRS	HUMS In-Flight Reporting System
HM	Health Management
HUMS	Health and Usage Monitoring System
I/O	Input / Output

IHUMS	Integrated Health and Usage Monitoring System
IIVM	Intelligent Integrated Vehicle Management
IMA	Integrated Modular Avionics (architecture)
ISHM	Integrated System Health Management
IVHM	Integrated Vehicle Health Management
JSF	Joint Strike Fighter
KM	Knowledge Management
LLP	Life Limited Parts
LM	Line Maintenance
LOA	Level of Autonomy
LRU	Line-Replaceable Unit
MCS	Mission Control Station
MMEL	Minimal Manufacturer Equipment List
MMS	Mission Management System
NFF	No Fault Found
NPV	Net Present Value
NTR	Nothing to Report
OCD	Operational Concept Description
OEM	Original Equipment Manufacturer
OMP	Operational Maintenance Program
OSA-CBM	Open System Architecture for Condition Based Maintenance
PA	Prognostics Assessment (OSA-CBM)
PDSC	Pre-Departure Service Check
PHM	Prognostic Health Monitoring
PSS	Product-Service System
QAR	Quick Access Recorder
RCA	Root Cause Analysis
RETOK	Retest OK
RIU	Remote Interface Unit
RLV	Reusable Launch Vehicle
RUL	Remaining Useful Life
SD	State Detection (OSA-CBM)
SPMS	Sensory Prognostics and Management System
TAT	Turn-around Time
TS	Troubleshooting
UCAV	Unmanned Combat Air Vehicle
V&V	Verification and validation
VMS	Vehicle Management System

Definitions

Built-in-Test (BIT) an embedded diagnostic capability.

Diagnostics the process of determining the state or capability of a component / system to perform its function(s).

Health Management the capability to make appropriate decisions about maintenance actions based on diagnostics/prognostics information, available resources and operational demand.

Health Monitoring the process of monitoring the state or condition of a component / system.

Prognostics predictive diagnostics; determining the remaining life or time span of the proper operation of a component / system.

Trade-off decision-making actions that select from various requirements and alternative solutions on the basis of net benefit to the stakeholders.

Chapter 1

Introduction and Outline of Approach

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1.1 Introduction

With the advancement in aerospace technology the need for a complex and sophisticated approach to asset health management has arisen, especially in case of long in-service life high-value assets such as aircraft and spacecraft systems. In response to this, the management of vehicle / fleet health has been developing over the last decades, with significant progress being made in recent years. This can be correlated with the continuously increasing operational and maintenance costs: to ensure mission success and high availability of vehicle and fleets (see e.g. [1, 2]).

The shift in business models: from product to product-service system (PSS), i.e. providing combination of products and services rather than only physical products (with a leading example in aviation sector of the Rolls-Royce gas turbine power-by-the-hour Total Care type of contracts [3, 4, 5]), can be marked as a strong contributing factor to the increased interest and development of complex asset health management. The proposed solution to the described challenges is the Integrated Vehicle Health Management (IVHM) that emerged from the domain of condition-based maintenance (CBM), fault diagnostics (FD) and prognostic health management (PHM). IVHM can be described as set of health management (HM) systems capabilities which are integrated into a systems design [6].

The IVHM encapsulates diagnostic, prognostic, maintenance and logistics functions and provides a complete solution to both: complex engineering and business challenges. IVHM addresses not only the vehicle but the whole supporting infrastructure which is necessary for a vehicle to operate. This includes on-board and off-board (ground-based support) vehicle systems. The key challenge is the complexity of system configuration resulting from the partitioning of IVHM System between on-board and off-board vehicle systems.

The cost and weight driven approach to HM / IVHM System is to implement on-board only the systems which can directly contribute to the safety and success of a mission. The potential impact of IVHM on overall vehicle operation, including maintenance and logistics, changed the traditional view on IVHM System implementation: optimal capability and productivity of a vehicle requires an optimally partitioned IVHM System [7].

This work approaches the optimal on-board / off-board partitioning of an IVHM system for the first time in world-wide terms: no literature exists on this specific topic.

Research context

The concept of IVHM is discussed in many areas of application, including automotive, airspace, marine and land vehicles. Also the distinction is made between civil and military application of IVHM System. In this work the core application is a civil air vehicle, however various vehicle types are discussed to highlight the challenges and possible solutions for IVHM System implementation across different technology sectors.

1.2 Motivation

The research presented in this thesis has been carried out at Cranfield University and Cranfield IVHM Centre in close collaboration with the industrial partners from the aerospace sector. The core industrial collaborators were: Boeing, Rolls-Royce, BAE Systems, Meggitt, and Thales Group.

The premise of the IVHM System is widely accepted by aerospace industry as an important part of the future vehicle operation, including legacy and new design platforms [8, 9, 10].

At the initial phase of the work, described in this thesis, researchers conducted a survey among the industrial partners to investigate how the IVHM is perceived today and what are the future expectations. Results of the survey confirmed the importance of IVHM System across the aerospace companies, including the mainframe manufacturer, engine manufacturer and system / subsystem providers and integrators.

Optimal partitioning of IVHM System has been pointed as the essential milestone in the process of successful IVHM System implementation.

The industrial partners accepted Cranfield's proposition to investigate the problem of optimal partitioning of IVHM System as part of the research activities of Cranfield IVHM Centre and established an official industial project titled System Architecture: *“System Architecture Project: Optimal par-*

titioning (split) of IVHM Diagnostics and Prognostics". A set of project scientific-technical deliverables has been defined by the project core partners. The project has been led by Meggitt and Boeing, and the remaining industrial partners have played an active role throughout this research work providing feedback, guidance, data and technical knowledge. Therefore, partner encouraging feedback was an additional important motivation.

1.3 Problem statement

This thesis deals with optimal partitioning of IVHM System problem. The main focus is on Diagnostics and Prognostics (D / P) IVHM functionalities and its spatial partitioning between on-board and off-board systems. To avoid ambiguities, the following definitions of a partitioned IVHM System and the optimal partitioning are given here:

What does it mean *partitioned IVHM System*? The partitioned IVHM System refers to spatial partitioning of IVHM functionalities (e.g. data acquisition, processing, reasoning, decision making) between vehicle on-board and off-board systems. Taking into account these functionalities all IVHM systems are partitioned due to at least on-board data acquisition functionality. On-board / off-board partitioning of IVHM system is depicted in Figure 1.1.

What does it mean *Optimal*? Following the dictionary definition, optimal is best in relation to the selected criterion of optimality. Operational research (OR), which is an interdisciplinary branch of applied mathematics, uses various methods (e.g. mathematical modelling, statistics, and algorithms) to arrive at optimal or near-optimal (commonly called suboptimal) solutions to complex problems [11]. Therefore, when talking about the optimal solution to the on-board / off-board partitioning problem, it is necessary to realise that each obtained solution is optimal only for the local case

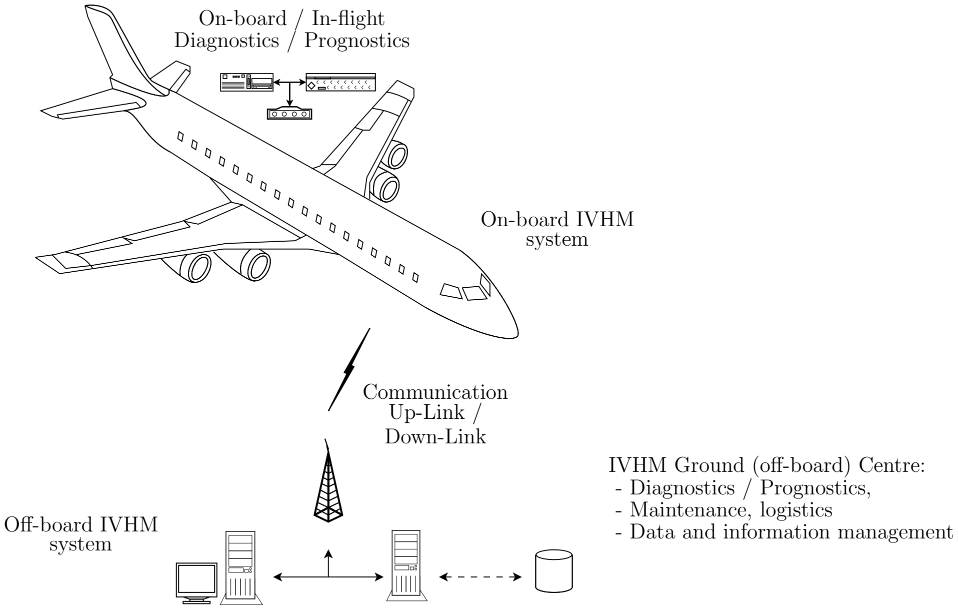

Figure 1.1: On-board / off-board partitioning of IVHM System: overview.

(e.g. given vehicle / fleet of vehicles with specific operational needs), when the relevant constraints and limitations of the analysed system technologies are applied.

1.4 Contribution to scientific knowledge

The main contributions to scientific knowledge made through the presented research are summarised in this Section. The main focus is on the optimal on-board / off-board partitioning of the IVHM System: Here the research has been carried out on this topic for the first time in world-wide terms as discussed in the literature review. Hence, the presented contributions spans from definition of the IVHM partitioning problem and its boundaries to the novel method to address such challenge. Five main contributions to scientific knowledge presented in this work are listed below.

1.4.1 Presented contributions

The three major contributions to scientific knowledge delivered in this thesis, namely: the novel drivers, the novel optimisation criterion and the novel method for optimal IVHM System partitioning are shown on the diagram in Figure 1.2. The key-message in this diagram is that all three major contributions are linked to create the complete solution to the problem of optimal on-board / off-board partitioning of IVHM System. The complete description is given below.

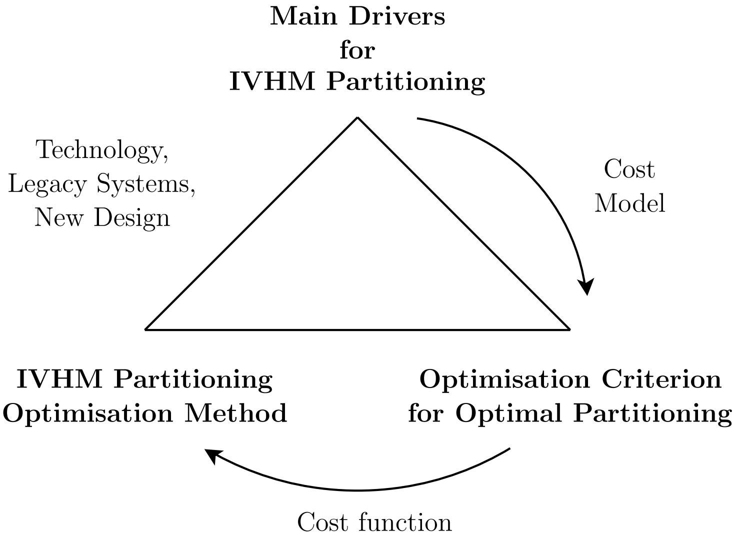

Figure 1.2: Main contribution to scientific knowledge.

1. Main drivers for on-board / off-board partitioning of IVHM System

To the best knowledge of the author of this research, no previous studies have looked into this area of IVHM partitioning. The proposed main drivers for partitioning exposes the main enablers and inhibitors to IVHM on-board / off-board implementation and provides a comprehensive understanding of this subject area.

2. The Novel optimisation criterion for optimal on-board / off-board partitioning of IVHM System

The novel criterion for optimal IVHM partitioning is proposed and developed. This criterion has been developed based on the costs and gains trade-off analysis. The novel criterion uses the main drivers for IVHM partitioning to define gains due to moving IVHM functionalities between on-board and off-board systems. The criterion is created to be sensitive to the vehicle main operational needs and the IVHM design requirements: the case-dependent weight factors derived from vehicle concept of operation (CONOPS) are proposed for the first time. This criterion is designed to select the optimal IVHM System partitioning.

3. The Novel optimisation method for optimal on-board / off-board partitioning of IVHM System

The novel method for optimal partitioning of IVHM is developed. The developed five-step method provides the complete routine to optimise partitioning of IVHM System by means of the novel criterion for optimal IVHM System partitioning. This method guides through the mapping of the vehicle CONOPS into weight factors related to each of the main drivers.

4. The novel metrics for estimation of optimal partitioning effectiveness

To evaluate results of the optimisation method the four-step novel comparative analysis of the cost effectiveness is developed. The developed performance metrics, which are based on figures of merit such as relative gain, average gain, minimum and maximum gain, provides with quantitative assessment of the optimisation results.

5. The established novel links between the main drivers and the key features of vehicle operation

The analysis of the key features of vehicle operation and the developed main drivers for IVHM System partitioning has been conducted as part of this work. As a result, the novel links between the main drivers for partitioning and the key features of vehicle operation have been established.

1.4.2 Published work

1. Sydor, P. Gelman, L., *On-board / Off-board Optimal Partitioning Problem for Integrated Vehicle Management (IVHM) System*, The Annual Conference of the PHM Society, 10–16 October 2010, Portland, USA
2. Gelman, L., Sydor, P., Jennions, I., Benoit, S., Langley, M., Nicchiotti, G., *Towards Optimal Partitioning of Integrated Vehicle Health Management (IVHM) System: A Review*, CM & MFPT Conference, 11–14 June 2012, London, UK.

Based on the work presented in this thesis a number of internal technical reports have been published internally and presented to the Industrial Partners involved in this research, including Boeing Company, Rolls-Royce, BAE Systems, Alstom, Meggitt and Thales. List of the technical reports is shown below.

1. Sydor, P., Gelman, L., *Optimal On-/Off-Board Partitioning of IVHM System: Literature Review*, IVHM Centre Internal Technical Report, IVHM/PR/10/017, May 2011, Cranfield University, UK.
2. Sydor, P., Gelman, L., *Generic IVHM Baseline Architecture – Report*, IVHM Centre Internal Technical Report, IVHM/PR/11/012, October 2011, Cranfield University, UK.
3. Gelman, L., Sydor, P., *D4: The Defined Main Drivers for Optimal Partitioning*, IVHM Centre Internal Technical Report, IVHM/PR/12/008, September 2012, Cranfield University, UK.
4. Gelman, L., Sydor, P., *D5: The Developed Novel Optimisation Criterion for Partitioning*, IVHM Centre Internal Technical Report, IVHM /PR/12/011, September 2012, Cranfield University, UK.
5. Gelman, L., Sydor, P., *D6: The Novel Method for Optimal Partitioning*, IVHM Centre Internal Technical Report, IVHM/PR/13/01, February 2013, Cranfield University, UK.

1.5 Thesis outline

Chapter 2: The purpose of this chapter is to review the state-of-the-art in IVHM System implementation. The main focus is on the partitioning of IVHM System, including existing and future system architectures, challenges and limitations of current technologies and examples of the proposed in literature solutions.

Chapter 3: This Chapter consists of two main parts: the first part provides the analysis of key features of vehicle operations. This includes analysis of maintenance operations, system faults, IVHM System architecture, vehicle concept of operations (CONOPS), as well as analysis of customers and outputs of IVHM System. The second part delivers the defined novel main drivers for IVHM System partitioning. The novel links between the defined main drivers for partitioning and the key features of vehicle operations are further defined and given in Chapter 3.

Chapter 4: This chapter considers the problem of optimal partitioning of IVHM System and introduces the novel optimisation criterion based on the cost and gains trade-off analysis. The developed optimisation criterion makes use of CONOPS driven weighting coefficients to incorporate the analysis of vehicle operational needs into the process of optimal partitioning of IVHM System. Mapping of CONOPS into weighting coefficients is also given in this Chapter.

Chapter 5: The defined novel method for optimal on-board / off-board partitioning of IVHM System is given in this Chapter. In order to evaluate the effectiveness of IVHM System optimal partitioning the novel metrics has been developed and described in this chapter. Consequently, a simulation studies using synthetic data-set to evaluate the novel optimisation method is given in Chapter 5.

Chapter 6: Summary and conclusions are given in this Chapter.

Chapter 2

State-of-the-art

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2.1 Introduction

This Chapter presents the review and discussion on the state-of-the-art in partitioning of Integrated Vehicle Health Management (IVHM) System. The overview of previously published work on related topics, that provide the necessary background for the purpose of this research, is also given here. Firstly the field of IVHM is described including the definition of IVHM System followed by the discussion on the on-board / off-board partitioning.

The scope of literature review.

Initially the search keywords were limited to "*Partitioning of IVHM System*", "*on-board / off-board partitioning of IVHM*" and "*optimal architecture of IVHM System*". Upon the immediate results the set of search phases had been extended to include also Prognostic Health Monitoring (PHM) and Integrated System Health Management (ISHM) related literature. Due to multiple applications of IVHM systems (e.g. aerospace, automotive, marine, etc.) and the fact that it is an emerging field which received significant attention from academia and industry, this literature review covers a wide range of sources, including but not limited to books, journal articles, conference proceedings, technical presentations, technology blueprints, technical standards and web-pages.

2.2 Literature review

The advancement in aviation, airspace and other high value technologies requires complex and sophisticated approach to asset health management. The concept of IVHM System encapsulates diagnostic, prognostic and maintenance activities and provides complete solution to both: engineering and business related aspects of such a complex problems [9]. IVHM System is not only focused on a vehicle itself - it addresses the whole supporting infrastructure necessary to its operations [12].

Definition of IVHM System

In this literature studies a number of IVHM System definitions have been found and analysed. The reviewed definitions highly depend on the area of IVHM System application, i.e. automotive, aviation, aerospace, etc. In addition, in e.g. [13] and [14] the word *management* is replaced with *monitoring*. In [13] it is argued that IVHM emerged from Integrated Vehicle Health Monitoring and had been extended to *Management*. In most of the reviewed sources it is clear, however, that *monitoring* relates to one of the IVHM System functions, but does not describe the overall capabilities of IVHM. Taking into account the majority of the literature sources reviewed in this work, the IVHM is therefore understood as *Integrated Vehicle Health Management*.

In Table 2.1 various definitions of IVHM system found in the literature are presented. A number of attempts to provide a generic definition of IVHM System to be used across different engineering disciplines can be found in literature, e.g. [9] and [10] (also included in Table 2.1).

The literature search showed that there is no clear or unique definition of the *Partitioned* IVHM System. In this work the *on-board / off-board partitioning of IVHM System* is defined as the spatial partitioning of IVHM System functions, i.e. Diagnostics and Prognostics, between the on-board and the off-board vehicle systems.

For the sake of clarity, in this work the overall IVHM System is written with capital "*S*" (*System*) and its on-board and off-board components (systems) are written with lower case "*s*" . Also, in some instances, the *IVHM System* is replaced with equivalent notation *IVHM*.

Taking into account IVHM System functions captured in Open System Architecture for Condition Based Maintenance (OSA-CBM), described in details in this literature review (see e.g. Figure 2.10, p. 35), *most* of IVHM systems are (to some degree) partitioned due to at least on-board data acquisition function. To justify use of the word *most* let us consider two examples of oil debris IVHM System. Chip detectors are used on-board to monitor oil debris level and to trigger alarm when it exceeds a given threshold [20]. In such case the data acquisition, processing and reasoning takes place on-board. The counterexample is the off-board oil debris analysis by spectrography, spectrophotometry, or scanning using electron microscopy. In such case the acquisition (samples), processing and reasoning are entirely performed off-board [20]. Hence, *some* IVHM Systems do not have an on-board part, and therefore cannot be partitioned in the above described way. In essence, the

Table 2.1: Definitions of IVHM System: a review.

Author	Year	Definition
NASA[15]	1992	"The capability to efficiently perform checkout, testing, and monitoring of space transportation vehicles, subsystems, and components before, during, and after operation. This includes the ability perform timely status determination, diagnostics, and prognostics. IVHM must support tolerant response including system/subsystem reconfiguration to prevent catastrophic and IVHM must support the planning and scheduling of post-operational maintenance."
Aaseng[1]	2001	"All the activities that are performed to understand the state of the vehicle and its components, to restore the vehicle to nominal system status when malfunctions occur, and to minimize safety risks and mission impacts that result from system failures."
Baroth[8]	2001	"An effort to coordinate, integrate, and apply advanced software, sensors, and design technologies to increase the level of intelligence, autonomy, and health state determination and response of future vehicles."
Roemer[16]	2001	"Integrates component, subsystem, and system level health anomaly/diagnostic/prognostic technologies, with an addresses failure mode mitigation and life-cycle costs."
Paris[17]	2005	"The process of assessing, preserving, and restoring system functionality across flight and ground systems."
Karsai[18]	2006	"Its goal is to provide better ways for operating and maintaining aerospace vehicles using techniques, such as condition monitoring, anomaly detection, fault isolation, and managing the vehicle operations in the case of faults."
Jakovljevic[19]	2007	"Ensures the reliable capture of the health status of the overall aerospace system and helps to prevent its degradation or failure by providing reliable information about problems and faults."
Benedettini[9]	2009	"The capture of vehicle condition, both current and predicted, and the use of this information to enhance operational decisions, support actions, and subsequent business performance."
Jennions[10]	2011	"The unified capability of a system of systems to assess the current or future state of the member system health and integrate that picture of system health within a framework of available resource and operational demand."

IVHM System data are gathered from sensors which seats on-board a vehicle (standard or/and dedicated IVHM sensors) but also it can be gathered during the maintenance work (e.g. wear data - physical measurement of components, off-board oil debris diagnosis) following data analysis and diagnostics / prognostics generation. This work focuses on optimal on-board/off-board partitioning of IVHM System and it is assumed here that all the analysed IVHM Systems can be partitioned.

On-board / off-board partitioning of IVHM System

A whole spectrum of an IVHM System implementation and architecture is covered in the reviewed literature sources: from systems implemented entirely off-board (e.g. [1]), through the partitioned systems (e.g. [21]), up to complete on-board configurations (e.g. [22]).

Current on-board/off-board partitioning of IVHM system

The major roadmap for IVHM System is given by Aaseng in [1]. Clear distinction between on-board and off-board systems and its functions is proposed in [1] as follows:

- On-board part which includes diagnostic systems ("that alerts the crew to a problem, providing information that they can do something about").
- Off-board part which includes diagnostic systems and prognostic systems ("complex analysis systems to confirm on-board diagnoses or to provide deeper information about the root cause") and prognostic systems.

In Figure 2.1 a model of IVHM System fault life-cycle proposed in [1] is shown. This model consists of four groups of vehicle fault cycle, namely Diagnosis / Prognosis, Mitigation, Repair and Verification. The first group (top-right corner) introduces the concept of on-board / off-board IVHM partitioning. In this simplified model diagnostics functions are implemented on-board and off-board. Further analysis and prognostics tasks are envisaged to be implemented off-board. No further details are given on differences between on-board and off-board diagnostics.

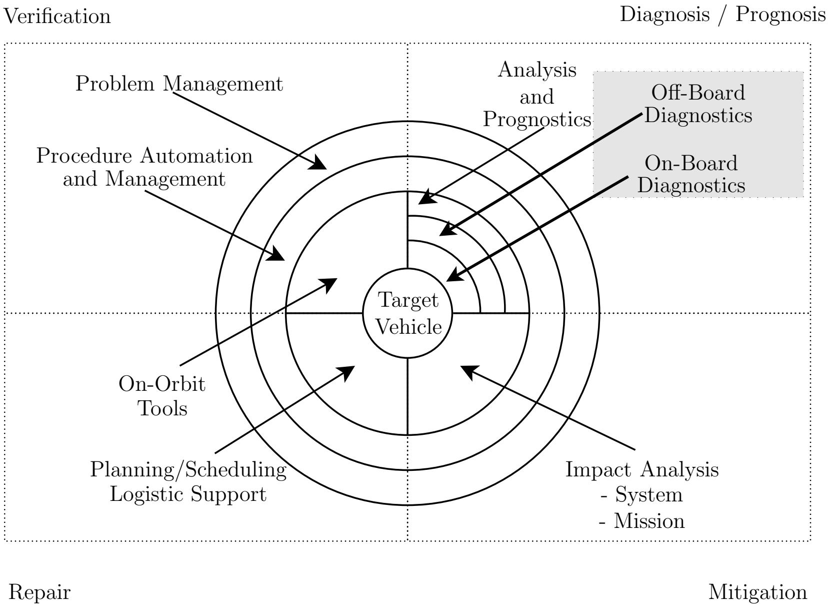

Figure 2.1: Model of IVHM System fault life-cycle [1].

An outline of IVHM System architecture proposed in [1] is shown in Figure 2.2. It is composed of on-board and off-board parts that are capable to communicate health data via downlink / uplink and process the data in-flight and post-flight, where:

- In-flight data processing: both on-board and off-board systems processes data for development of fault indicators;
- Post-flight data processing: analysis of data acquired and stored during the flight is performed off-board without constrains of a real-time on-board systems.

It is suggested in [1] that on-board diagnostic systems should provide continuous monitoring and reporting with minimal time delay: no further justification or measures of minimal time delay are given therein. It is suggested that a multi-layered diagnostics will enable to perform diagnosis / pre-processing of data within sensor area instead of sending raw data to the central computing unit. Local data pre-processing capability leads to decrease of the amount of raw data being transmitted on-board and, if needed, to the ground support stations. The discussion is based on the example of airspace vehicle however it is valid across different applications. No further details on the methods for diagnostics and prognostics are given. Note that, apart from diagnostics, prognostics and on-board / off-board communication systems, Figure 2.2 presents additional functionalities which are not in the scope of IVHM partitioning and therefore are not described in details here.

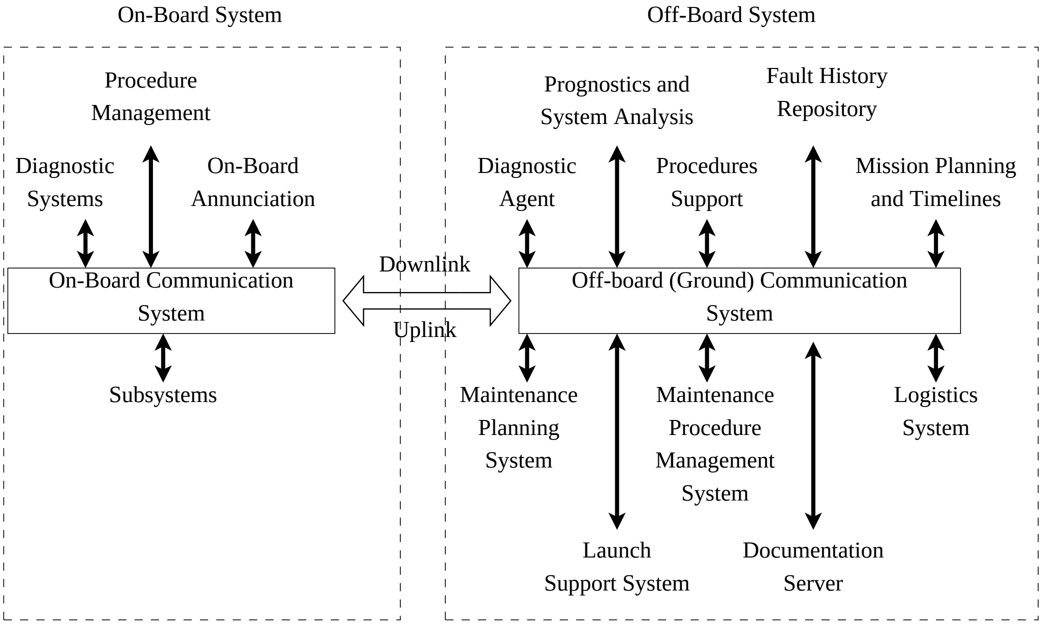

Figure 2.2: On-board / 0ff-board IVHM System architecture by [1].

The example of an aircraft IVHM System which combines on-board and off-board elements is described in [23]. The application example is given based on the DARPA/USAF[1] Unmanned Combat Air Vehicle (UCAV) programme. The generic outline of on-board / off-board IVHM System proposed by [23] is depicted in Figure 2.3.

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[1] Defence Advanced Research Projects Agency (DARPA) is an agency of the United States Department of Defence responsible for the development of new technologies for use by the military.

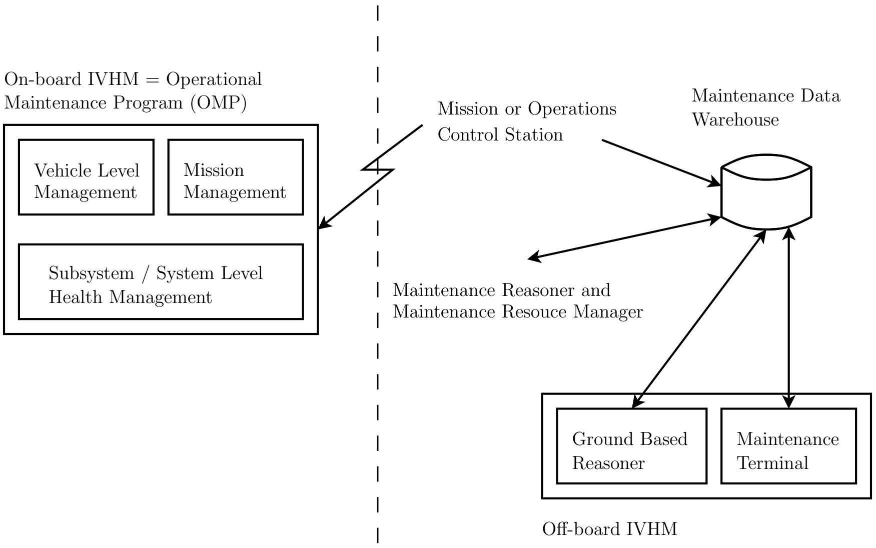

Figure 2.3: Generic On-board / Off-board IVHM Elements, [23].

The UCAV fuel system was used as an example of IVHM on-board / off-board application. An on-board system consists of flight ready power-PC (computational platform) with MIL-STD-1553 communication bus connected via emulated data-link with ground based Mission Control Station (MCS). The system was partitioned as follows:

- On-board UCAV fuel system IVHM consists of Operational Maintenance Programme (OMP) with:
    - Signal processing layer to filter and format data for interpretation,
    - Health assessment (diagnostics) layer - to process data and control the OMP.
- Off-board ground based reasoner (GBR) consisted of prognostics system.

In the described IVHM System the on-board diagnostics monitored the fuel pressurisation and gauging systems, fuel pumps, valves, sensors, and communication system (wiring). The off-board prognostics system was design to evaluate remaining useful life (RUL) of electronically actuated valves. The GBR also uses the historical health data of component and subsystem. This, as claimed by the authors, leads to improvement of health assessment and enables better prognostics. No further information about decision making process of partitioning between on-board and off-board is given in [23].

The proposed system has been classified as non flight-critical and allocated to the MMS. However, data from the MMS have to be transmitted to the Vehicle Management System (VMS) which resulted in increase of communication overload. To address the potential communication burden the authors suggested a hierarchical architecture in which the lower level nodes (e.g. component health assessment functions) would report to higher level nodes (e.g. sub-system) a health status rather than raw data, and the top-level node (system level) would act as the final arbitrator of results and control the communication up and down linking data. This, however, is a theoretical discussion and no further details on possible implementation and on-board / off-board hierarchical system are given.

In [7] IVHM System for aircraft applications is defined as a partitioned system where the on-board part captures and processes vehicle health data and the off-board (ground based) part provides further processing of the downlinked on-board data and generates vehicle and fleet health-status. The authors introduced a concept of *health-ready* aircraft system as a core element of on-board / off-board partitioned IVHM. In the proposed health-ready aircraft architecture the IVHM System is constructed as two parallel functional entities: the flight / mission critical system and the support-critical system. The term "support-critical" IVHM is defined therein as a set of functionalities that are critical to provide an effective support of a vehicle. The addition of support-critical IVHM may require additional sensors, data processing units and transfer of support-critical data to the off-board support system. Authors stated that the on-board system which translates data into information (raw sensor data into health-state information) can significantly reduce the amount of data being transmitted from vehicle to ground based system. Authors did not specified decision process behind the partitioning of health-ready IVHM System. It is, however mentioned that the design should involve trade-off between capabilities, complexity and maintainability of health-ready system. It also is indicated that further trade-off studies to define best implementation of the IVHM System into the vehicle architecture should be performed. No details about suggested trade-off studies are given therein, instead a reference is made to Keller et.al. [24] where a Boeing Company internal procedure to IVHM feasibility study is described.

The F-35 Joint Strike Fighter (JSF) health management system example of integrated system which enhances aircraft safety, reduces operation costs and maximises fleet availability. The keystone of the AL is partitioning between on-board and off-board advanced PHM system [25, 26, 27, 28]. The JSF AL is described as the example of state-of-the-art IVHM Systems in [28]. In terms of AL system partitioning, the on-board vehicle health data is transmitted to the ground support systems (maintenance / logistics) via Automatic Logistics Information System (ALIS) to minimise the unavailability and to optimally plan maintenance actions [29].

In the survey of data-driven prognostics by Schwabacher [30] an on-board / off-board partitioned Integrated System Health Management (ISHM) is described. The two key advantages of on-board part are described as:

- Increased safety by detecting and diagnosing faults so that the relatively quick response is possible to prevent major failures,
- Reduced costs by avoiding / minimising unscheduled maintenance checks.

The off-board system will be design to evaluate the historical data and to perform prognostics.

The health and usage monitoring systems (HUMS) for helicopters is a specific type of IVHM System. HUMS is defined by UK Ministry of Defence (MoD) in DEF STAN 00-970 [31] as:

> “The purpose of health and usage monitoring (HUM) is to improve flight safety, rotorcraft availability, maintainability, the ability to complete a mission, and to reduce life cycle costs. In order to fully utilise the benefits of Health and Usage Monitoring the outputs from the system should be fully integrated with the maintenance philosophy of the rotorcraft.”

HUMS play an import role in advanced helicopter IVHM systems; The concept of IVHM can be traced back to the original HUMS developed during the 1980s and 90s [32]. HUMS is a combination of sensors, data acquisition systems and algorithms. It consists of on-board and off-board components [33, 34]. A block diagram of active HUMS proposed in [33] is shown in Figure 2.4. The on-board system provides diagnostic data to diagnose faults and indicate requirement for maintenance actions. The off-board system provides prognostic information and integrated maintenance and logistic support. The main difference between HUMS and active HUMS is a two-way communication between the on-board and the off-board systems. This communication is used to provide support information from the maintenance archive to the on-board system in case if a monitored value has been identified outside the safe limits and the crew (or the on-board system) needs more detailed information in order to make a decision.

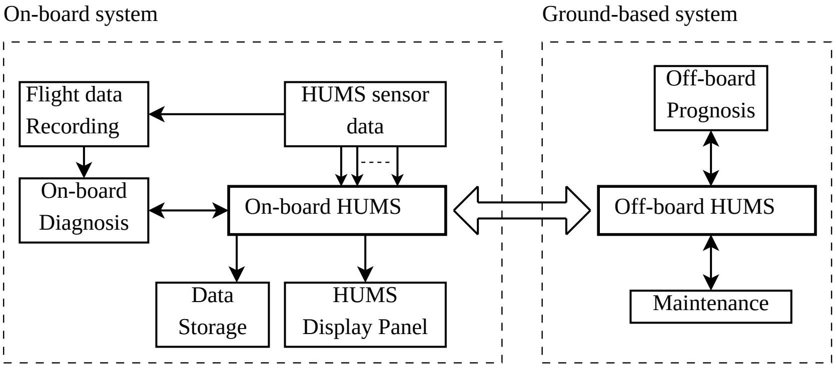

Figure 2.4: HUMS block diagram, [33].

A two-way communication system for HUMS was also proposed in Joint Advanced Health and Usage Monitoring System (JAHUMS) and presented in frames of technology demonstration programme in [35] and [36]. In [36] a HUMS In-Flight Reporting System (HIRS) is presented. The proposed data flow in HIRS is as follows: from the ground-based station the user sends a command (data request) through the satellite gateway to vehicle on-board HUMS. On-board system responds and sends out the requested data back to the ground-based station for further analysis, i.e. diagnostics and prognostics. Such system allows the vehicle maintainer to investigate intermittent problems that are difficult to recreate on the ground; while pilot is recreating the flight conditions in which anomaly was detected, the maintainer can request the HIRS to transmit health data of interest for in-depth analysis.

The Integrated Health and Usage Monitoring System (IHUMS), jointly developed two decades ago by Bristow Helicopter, Plessey Avionics, Westland Helicopter and MJA Dynamics and currently own by Meggitt PLC, is an example of evolution of classical HUMS [37]. It is a partitioned HM system in which the on-board part monitors the aircraft parameters and operating conditions, whereas the off-board part provides data analysis to assess the vehicle health state. It is said in [37] that keeping the diagnostics and prognostics off-board reduces the weigh, volume and power consumption of the on-board part, which in case of rotary wing airframes are crucial parameters. The disadvantage, however, is seen when long-duration of very frequent operations are performed by the vehicle due to limited availability of data for off-board system. Functional block diagram of IHUMS described in [37] is shown in Figure 2.5.

NASA performed a pilot study on IVHM Systems principles to support further development of Intelligent Integrated Vehicle Management (IIVM) [17]. The combination of advanced computational techniques, with sensor and communication technology for spacecraft enables detection, diagnosis, reasoning and re-configuration of affected vehicle systems / sub-systems to avoid catastrophic events. Figure 2-8 introduces the outline of the IIVM proposed by Paris et al. as a potential integration of IVHM into the overall vehicle management system [17]. One of the main parts of on-board system is ISHM/IVHM system. The components of ISHM/IVHM system shown in the Figure 2.6 are: data / information transfer system, vehicle diagnostics and vehicle prognostics.

Two main approaches to IVHM System implementation and partitioning are recognised in the literature: implementation into legacy platforms (retrofitting) and into the new design platform (at the design stage). Both approaches have been investigated and findings from literature review are given below.

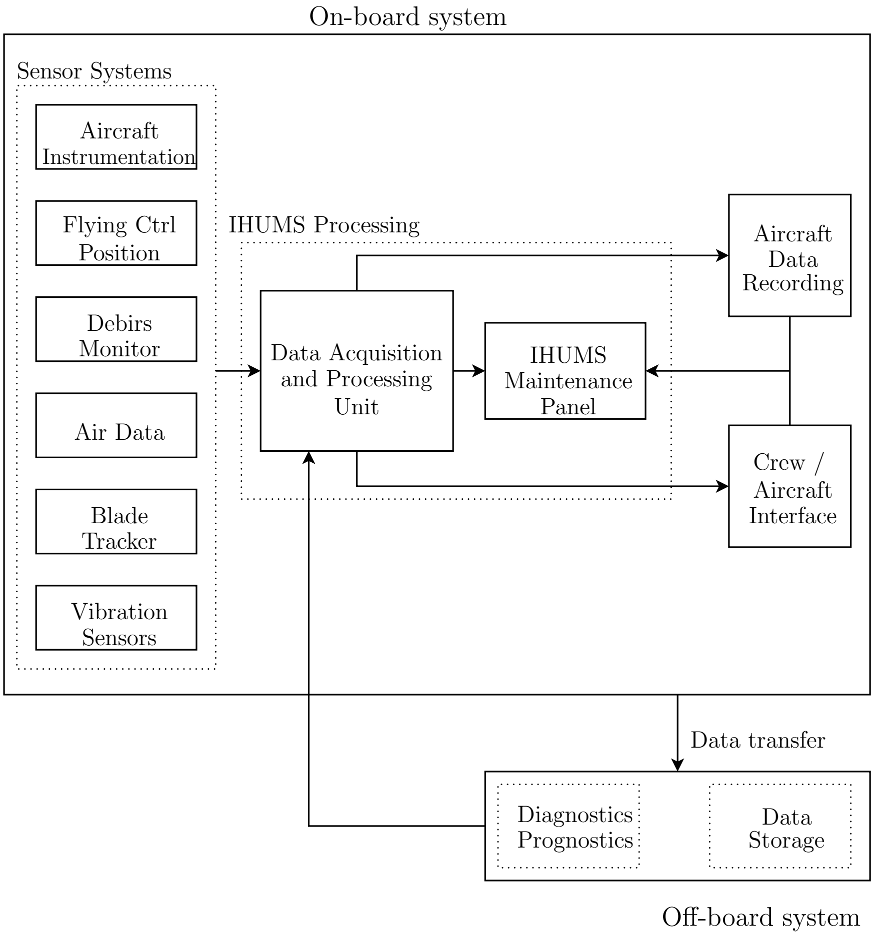

Figure 2.5: Functional block diagram of IHUMS, [37].

Partitioning of IVHM systems at the design stage

In [38] it has been suggested that the decision about a vehicle health management system should be performed prior to the vehicle conceptual design. It has been shown therein that the use of PHM / IVHM as a design variable may significantly impact the conceptual design with regard to mission reliability and mission availability. The physical implementation of IVHM and the related costs over the life cycle of a vehicle have been also influenced by implementation of PHM / IVHM as the design variable to be fed into conceptual design.

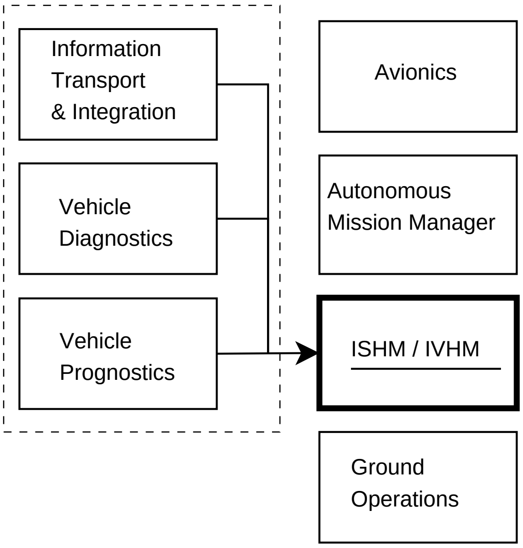

Figure 2.6: NASA Intelligent Integrated Vehicle Management (IIVM) concept: all vehicle health management systems on-board [17].

Figure 2.7 and 2.8 shows the outline of on-board/off-board partitioning of IVHM system of future vehicles. Firstly the JSF architecture is presented in Figure 2.7, where on-board part consists of the following systems: fault detection, diagnostics and fault mitigation. Off-board part provides prognostics [27].

The outline of NASA future IVHM architecture is depicted in Figure 2.8. On-board part is formed of fault detection, diagnostics, prognostics and mitigation functions. Off-board part provides diagnostics and prognostics [39]. As one can see, both on-board and off-board parts hosts the diagnostics and prognostics functionalities, however, no clear difference between those systems is given in [39].

Partitioning of IVHM systems on legacy platforms (retrofit)

In the reviewed literature a great body of work is dedicated to implementation of IVHM System into legacy platforms, e.g. [21, 40, 41, 42].

In [40] an introduction to the current challenges and motivation for IVHM

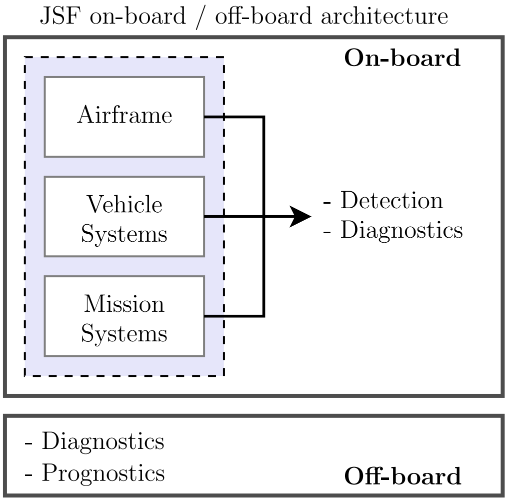

Figure 2.7: F-35 Lightning II Joint Strike Fighter (JSF) on-board / off-board architecture.

system implementation is given. Integration of IVHM with the legacy software / hardware is discussed along with a review of technology limitations which affect the IVHM retrofitting. Authors pointed out that the lack of standard implementations of data buses and communication protocols are major constrains in IVHM implementation into legacy platforms. The proposed solution is to use Open System Architecture for Condition Based Maintenance (OSA-CBM) standard which defines modular, layered architecture, including communication protocols. More details on OSA-CBM are given

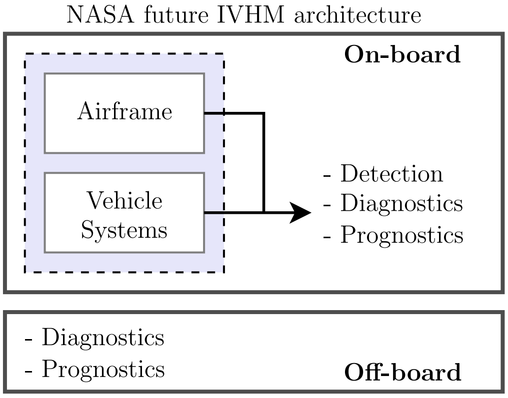

Figure 2.8: NASA future on-board / off-board IVHM System architecture.

later in this review while discussing IVHM architecture (see p. 35).

In [40] Keller et al. proposed alternative architecture configuration of avionic systems for legacy platform to enable implementation of partitioned IVHM system, the described above *support-critical* architecture. Traditionally, on-board HM system provides the built-in-test (BIT), which provides crew warnings, and in-flight data recording to supports off-board diagnostics. The new proposed architecture is a standard on-board avionics system with additional functionalities, i.e. on-board data processing and data storage that supports off-board decisions. It is not a mission, flight or safety critical system, therefore it has to have a minimal on-board footprint [40].The discussed therein solution will combine existing/current avionics, e.g. Digital Flight Data Access Unit (DFDAU) or Quick Access Recorder (QAR), and additional support-critical hardware/software equipment (e.g. dedicated vibration data analysis software embedded into DFDAU).

A limitation of the on-board communication buses is one of the major constrains when IVHM system is integrated with the legacy platforms [41]. The "Health Management Valley of Death", described by Keller et al. in [41] as a limitation in:

- Acquisition of high fidelity data,
- Cost of mission/flight critical software,
- Cost of recertification,
- Communication,
- Local processing.

The above limitations do not stop the on-going research on the implementation of partitioned IVHM System into legacy platforms.

In [42] Arnaiz argued that the prognosis is the technology which is the most potential: it may require less aircraft system modifications if it is done off-board (available data is acquired in-flight and processed post-flight). This also minimises the need for additional system certification.

In [21] an example of engine performance trend monitoring and gas path fault diagnosis system with IVHM system enhancement is proposed. Conventional system performs off-board post-flight diagnostics on engine snapshot data collected each flight. The enhanced architecture migrate part of conventional off-board diagnostics into the on-board part (Figure 2.9).

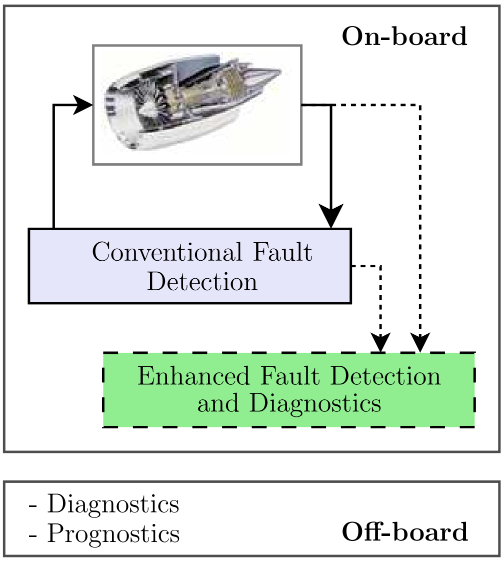

Figure 2.9: NASA proposed enhanced gas-path health management system architecture.

The enhanced system is designed to perform to provide on-board real-time health assessment of the engine. It is of great challenge to implement IVHM into existing systems; nevertheless, the benefits of such technology stimulate the effort to retrofit IVHM Systems [40]. Implementing IVHM into legacy platforms often means that the existing hardware, originally installed for different purposes (e.g. control, communication), has to perform health-monitoring / management functions. Cost of upgrading the legacy hardware may be prohibitive, but complex algorithms and the demand for high fidelity data may require, despite the costs, the upgrade of legacy hardware [43].

Limitations and barriers of IVHM on-board / off-board partitioning

Despite many benefits related to implementation and partitioning of IVHM, a number of technological limitations as well as technical and legislative barriers are recognised in the literature [9]. A list of critical aspects to IVHM System integration from an airframe manufacturer viewpoint is given in [7], which includes:

- Application value,
- Development cost,
- Hardware and software integration into vehicle on-board system and off-board architecture,
- Hardware and software integration into the customer concept of operations (e.g. maintenance, logistics, planning and control).

In [40] a list of key elements of the successful IVHM system is given, that includes availability of high-bandwidth communication, accurate sensor data, on-vehicle and off-vehicle coordinated data processing and access to maintenance and mission system. Upon further literature review the following three main limitations and challenges, namely on-board computational capabilities, vehicle-to-ground communication limitations and hardware / software certification, are defined and discussed in details here.

On-board computational capabilities

The limitation of on-board computational capability is mentioned in the literature; however no detailed parameters are presented. Set of commonly referred limitations is extracted below (e.g. [41, 44, 45, 46]):

- Hardware domain: processing unit, memory, data storage,
- Architecture domain: data-buses (on-board communication),
- Software domain: algorithm development and implementation.

In the survey on IVHM Systems by Benedettini et al. [9] it is shown that limitations of the on-board data processing capabilities are widely discussed in IVHM related literature (e.g. [1, 17, 22]). However, no detailed discussion is given therein.

In [47] a set of parameters to be considered when designing an on-board engine diagnostics and health management system is given. This includes: data acquisition (e.g. sampling rates, etc.), data processing (e.g. hardware capabilities and constrains, processing bandwidth, data communication infrastructure, etc.) and software / algorithm development (e.g. algorithm complexity).

The need for high throughput real-time IVHM on-board processing, as expressed in the literature (e.g. [8, 23, 41, 45, 48, 49]), plays an essential role in the definition of on-board hardware and software capabilities. In [8] an embedded systems for IVHM, based on the example of NASA Next Generation Reusable Launch Vehicle (RLV) and the Joint Strike Fighter (JSF) is discussed. It is claimed that the structural health monitoring system in RLV will rely on real-time data analysis: it is envisaged that a great number of sensors will be needed to cover variety of structural components (such as propellant tanks, wings, fuselages, etc.) and sensor data will be processed on-board.

Abbott et al. [48] argue that in order to understand causes of failure and to detect precursors to system failure, a continuous monitoring and a real-time diagnostics are needed: this, however, is not clearly justified by the author. As an example in [48] an event detection system (e.g. structural impact, crack) is given; multi-modal real-time detection is suggested to provide valuable information about the nature and cause of event. No further details of why the real-time system performance is needed are given by authors. In [45] and [49] the real-time response of IISHM/IVHM System is proposed as a fundamental requirement and it is suggested that such capability should be treated as a fundamental requirement at the design stage of vehicle health management systems. In [22] sensing and responding to deviations from normality in real-time combined with ability to analyse the historical data and

Table 2.2: Commercial on-board communication data-buses, [43].

Data-bus name	Data patch (bit)	Max. speed	Standard name
ARINC 429	25 (32)	100 kb/s (12.5 kb/s)	ARNIC 429
ARINC 659	32	2 Mb/s	ARNIC 469
1553 Data Bus	16	1 Mb/s	Mil Std 1553B
1773 Data Bus	32	1 Mb/s	Mil Std 1773
VME	32	40 Mb/s	IEEE P1014-1987
VME 64	64	80 Mb/s	ANSI/VITA 11994
PCI	32	132 Mb/s	PCI-SIG 2.1
ISA	16	3 Mb/s	IEEE P-1882.1
SIB	32	5 Mb/s	LeCroy P1123

expert knowledge will enable industry to shift from reactive to proactive and predictive IVHM strategies.

In [41], where architecture of IVHM System from the airframe manufacturer viewpoint is described, it is stated that real-time on-board processing combined with in-flight data download capabilities can provide an improved, more effective and timeliness response of IVHM system. This is, according to authors, a subject to limitations of on-board data processing capabilities, on-board communication systems and vehicle to ground communication.

On-board data-bus limitations are given in [43] as one of main obstacles in IVHM System implementation into existing platforms. List of commercial on-board communication data-buses is shown in Table 2.2. Authors argue that, despite the commercially available high bandwidth data-buses exist, it is costs prohibitive to retrofit modern data-buses into legacy vehicles.

To address the limited capacity of on-board communication buses and, at the same time reduce the wiring, a wireless communication system is suggested in [32]. This, according to authors, requires additional Remote Interface Unit (RIU) to be installed in close proximity to sensors and a dedicated receiver at the vehicle-level health management system.

In [41] the additional weight, power consumption, heat, on-board communication (data buses) and reliability of the on-board computer systems are considered as main inhibitors to IVHM implementation, especially in case of legacy platforms.

Example of advanced on-board diagnostics computer system is the Rolls-Royce engine health management (EHM) system described in [46]. The Aircraft Condition Monitoring System (ACMS), which is present in most modern large civil aircraft (e.g. Boeing 777, 747-400, 757, 767, Airbus A380), acquire the data from the EHM system. Prior to transmitting the data to the ground, an on-board data analysis (i.e. pre-processing) takes place. The EHM has a flexible computing platform which allows new EHM algorithms to be implemented, however due to the limitations (i.e. computational and data storage) only snapshot data are captured during the take-off, climb aircraft cruise and descent. The author stated that future platforms will be equipped with more powerful computational and data-storage units for on-board data processing and reasoning.

In the helicopter HUMS an on-board part requires high data sampling rates for signal processing to support advanced processing techniques (mostly gearbox vibration analysis). In [34] a description of HUMS on-board computer system is presented. The system enables acquisition and processing of high bandwidth vibration data on the order of 50 150kHz (e.g. Honeywell Zing HUMS provides spectrum frequency range of 0-75kHz) and low bandwidth data (e.g. temperature and pressure data) sampled with less than 100Hz. The proposed on-board HUMS consists of dedicated digital signal processing (DSP) unit for high frequency vibration data analysis (500MHz fix point processor with 128MB of memory) and central processing unit (CPU) for less intensive algorithms (650MHz Celeron processor with 256MB of memory). However, as indicated in [33], the main issue of limited on-board computer systems of HUMS is that a large amount of data are often acquired but only a limited amount is processed during the flight; most of the data are processed off-board.

Vehicle-To-Ground communication capabilities

The on-board / off-board partitioning of IVHM System depends on data communication capabilities. A generic IVHM System normally consists of the air-to-ground (ATG), ground-to-ground and air-to-air communication schemes [39]. Boeings On-Line Diagnostic Reporting described by Sudolsky in [50] is one of the examples where the ATG system plays the crucial role in aircraft health management. The ATG uses an Airline Communication Addressing and Reporting System (ACARS) communication protocol/system to transmit short messages between aircraft and ground stations via radio or satellite. ACARS is not only used for the weather condition announcements, wheelchairs requests, etc. but it has got the capabilities of reporting to the fleet management important information about an aircraft status and gives a potential to fully integrate IVHM system [50].

In [22] the limitation of in-flight telemetry is discussed the available aircraft in-flight communication data-links (e.g. ACARS) are limited and can be compared to early days of accessing the mainframes using 1.2 k baud dial-up modems. The advancement of wireless technology can allow a bulk data to be transmitted from a vehicle to the ground. As an example of existing wireless technology, Formula 1 Racing operation is given [22], where vast amount of data (i.e. performance and control signals) are streamed in real-time from a car to operational and analytical hub (pit crew) for analysis, strategy refinements and diagnosis. Nowadays aircrafts use at the gate (Gatelink) comms technology which provides high bandwidth data transfer: commercial wireless standards (e.g. IEEE 802.11) are used to access aircraft data when it is at the gate/taxi with maximum bandwidth of 150MB/s (IEEE 802.11n).

In [46] Waters discusses Rolls-Royce approach to EHM. The current method to transfer data from a vehicle (in this case Airbus A380) to the ground during flight is using ACARS VHF digital radio or satellite links. These are robust but limited media typically just 3kBytes snapshot is transferred. Future IVHM communications systems, according to Waters, will include the at-the-gate wireless communication systems. This will enable more data to be analysed but not as immediate as by using the in-flight (e.g. ACARS, satellite) communication.

On-board hardware / software certification

A software/hardware certification is required to ensure safety and quality. The main phase of certification is verification and validation (V&V) (e.g. [51]). It is a process of checking that a software being developed or changed meets specification (verification phase) and ensures that it has been built according to the requirements (validation phase).

The airborne IVHM software can be classified as flight-critical or non-flight-critical system [23]. Both require different level of V&V. The certification of the airborne flight-critical systems is a complex and expensive process which is widely discussed as a major issue in IVHM system design, integration and implementation [51]. The actual data regarding costs and time of the certification process is not given in literature.

According to Nelson and Pecheur [52] IVHM increases the complexity of software V&V due to the great number of complex IVHM software components that are often using non-conventional programming approaches (e.g. neural networks, fuzzy logic, self-learning adaptive algorithms). The authors did not provide exact figures how the implementation of IVHM increases the complexity of software V&V.

The Primus Epic central maintenance computer (CMC) from Honeywell was design as a field-loaded software (FLS) system [22]. It consists of two FLS units: CMC functional code and separate loadable database unit. The first unit is a part of the vehicle certified code. Authors stated that the second unit can be loaded / changed without aircraft re-certification; however, they did not justify this statement.

An example of the on-board IVHM system for unmanned combat air vehicle (UCAV) classified as non-flight-critical is given in [23]. Health management functions are integrated into the Mission Management System (MMS) which minimised the cost of software V&V associated with flight testing, however no details about how this set-up minimises V&V are given. The disadvantage of such solution is a communication overload between the MMS and the vehicle management system (VMS) which contains UCAV control information.

The cost of recertification of the airborne systems when IVHM is implemented into legacy platform is described as a noticeable inhibitor by Keller et al. in [41]. To overcome this, a low footprint and non-intrusive technologies to enable partitioned IVHM implementation without the need for certification as a flight-critical system are introduced, including: wireless communication, energy harvesting, technologies to improve the capacity of legacy data buses and mode dependant use of existing flight critical resources (e.g. use of flight critical processing units or communication links during vehicle taxi). Similarly, in [40] it is suggested that certification issues would be minimised if the operations of data network was restricted to selected, acceptable flight modes (e.g. after weight on wheels). The above methods to minimise the certification effort were only proposed without in-depth study or further explanation given by authors.

On-board helicopter HUMS are often classified as safety critical systems. The main reason is that rotorcraft forms a unique subset of vehicles in which propulsion system also serves as the primary source of lift and manoeuvring without duplication or redundancy [53]. The certification of HUMS includes both ground-based and airborne components [54]. Different flight/safety critical levels, which define certification requirements, are normally assigned to each of the HUMS components: on-board HUMS failure typically constitute a hazardous condition (safety critical) whereas the off-board HUMS failure in most of cases would not be considered as safety critical [54].

IVHM System Architecture

The IVHM System architecture is influence by the decision on IVHM partitioning, especially when a new design systems are under consideration. In case of legacy systems the opposite may be possible, i.e. the existing system architecture may determine (to some extend) the partitioning of IVHM System. In order to understand the correlation between the partitioning and the resulting system architecture, the following review of vehicle and IVHM architecture has been performed.

The following set of objectives for IVHM System architecture capable to support the on-board / off-board partitioning had been formulated by Boeing Company in [23]:

- To provide signal processing, state detection, health assessment, prognostics assessment and decision support.
- To provide fault models for description of grey scale conditions and degradations, and support intermittent faults.
- To support fusion of reports from multiple sources and across the component/ system hierarchy (e.g. on-board analysis results, maintenance reports, etc.)
- To manage available resources, i.e. data processing, memory/data storage and communication.

Open System Architecture for Condition Based Maintenance

Open System Architecture for Condition Based Maintenance (OSA-CBM) is a standard for building IVHM applications [55]. It provides the unified and simple development tool to support work on complex IVHM Systems with multiple partners [32, 41]. OSA-CBM defines the data-types used for processing and result reporting and how the data is transmitted between processing layers and storage points. OSA-CBM is an implementation of ISO-13374 standard and it provides six functional blocks as shown in Figure 2.10 [56, 57].

Further description of the OSA-CBM functional blocks can be found in related publications, e.g. [56, 57, 55, 32, 58, 41, 7].

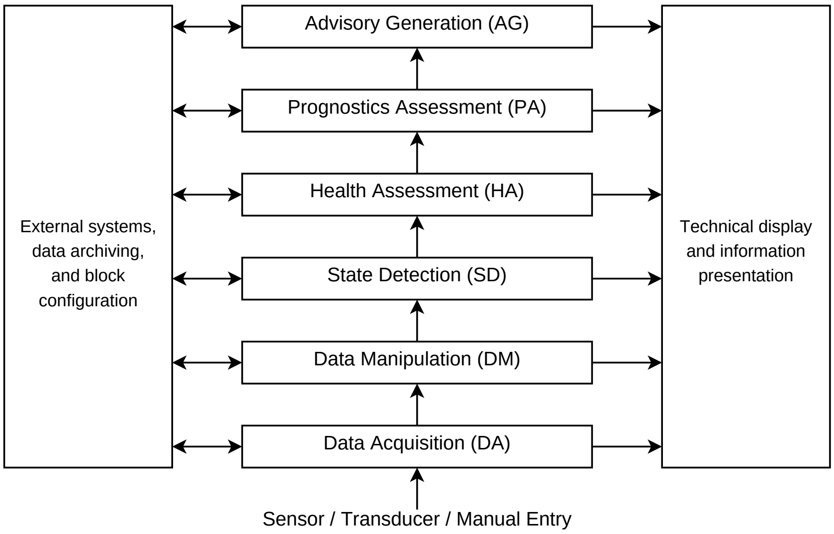

Figure 2.10: OSA-CBM outline (ISO 13374): data processing and information flow [55].

Processing Sequence in OSA-CBM

OSA-CBM provides layered approach to generic IVHM system. The processing sequence in OSA-CBM can be described as follows [59]:

At the lowest level (DA) data are acquired, then organized and manipulated (DM) into a consistent form. The data are then characterized into states (SD): features are extracted for comparison against baseline operational limits and determination of which zone data belong to (normal/abnormal). Following state detection, diagnosis information is generated (HA) to determine current health and degradation. Further on a prognosis of future health state based on current health assessment, including the remaining useful life is made (PA). At the highest level the list of actions and advises is generated (AG).

OSA-CBM supports a distributed data processing by accommodating multi inter-process communications standards [57, 59]. An interaction between OSA-CBM functional blocks that forms a complete integrated system is shown in Figure 2.11. The hub of the wheel structure is essentially a communication link which may be realised using common data buses (specific to a given system). Due to a distributed architecture the modules of OSA-CBM do not need to reside on the same hardware platform, but can be implemented anywhere in a local / worldwide network [57].

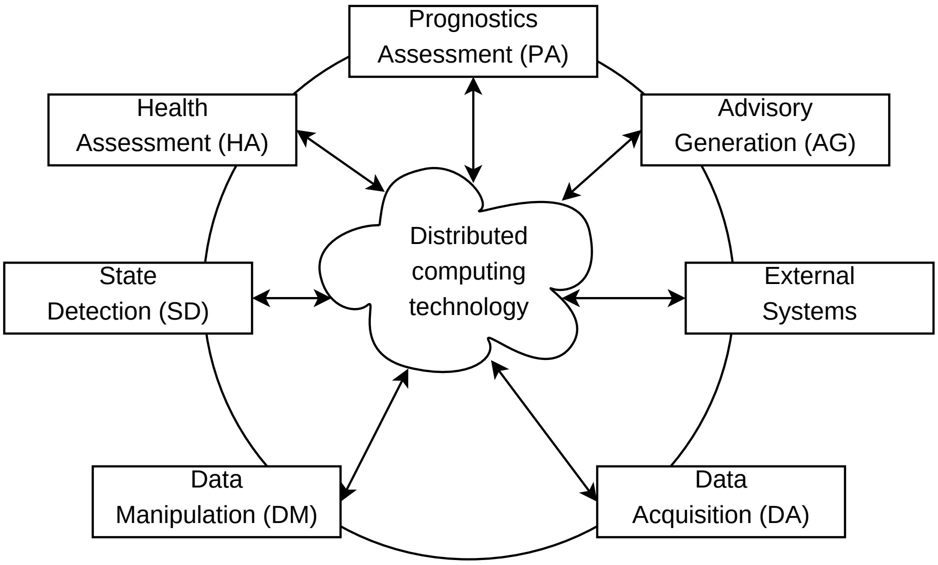

Figure 2.11: Data processing flow within a standard architecture [57].

In the processing sequence of OSA-CBM any module can host a functionality of one or more data processing blocks from OSA-CBM architecture [57]. Also a module can implement one or more block application programming interfaces (APIs): modules from other layer implement one or more layer APIs.

In the further discussion on generic architecture we will use a flattened OSA-CBM functional model denoted as diagnostic and prognostic (D/P) functional model as shown in Figure 2.12. Such approach was proposed in [58] as a part of multi-layered hierarchical IVHM architecture discussed in more details on p. 40.

In [60] a multi-agent system (MAS) implementation of IVHM based on OSA-CBM architecture has been proposed and evaluated. It is suggested that classical OSA-CBM can provide only limited self-health awareness capability, therefore the MAS approach has been proposed to enable implementation of distributed network-based IVHM System. The described therein case

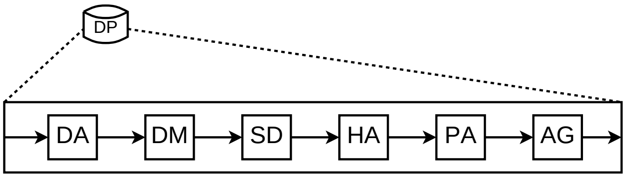

Figure 2.12: Diagnostic and prognostic (D/P) functional block described using OSA-CBM model.

study demonstrated flexibility of such approach using the example of auxiliary power generator HM where the integration between the main control module and the IVHM System using OSA-CBM approach has been successfully demonstrated.

Avionics Architecture

IVHM system is integrated into platform/aircraft avionics [7]. Therefore, the avionics architecture influences the on-board IVHM system architecture. The allocation, accessibility and management of computer resources, communication links and I/O modules in avionics play important role while designing and retrofitting an IVHM system into aircraft.

Avionics progressed from federated systems to a hierarchical, integrated and modular architecture [41]. Federated avionics consisted of dedicated functional avionics boxes or collections of avionics boxes that performed a specific function equipped with dedicated communication channels, typically inside separate line replaceable units (LRU) [41, 61].The troubleshooting and/or fault isolation in federated architecture was performed during ground-based maintenance work. In this configuration health monitoring (HM) functions were implemented as standalone dedicated capabilities of specific box with little or no system level integration [41]. Integrated modular avionics (IMA) architecture provide a shared computing/data processing resources and communication functions partitioned for use by multiple avionics functions [61, 62].

An example system shown in Figure 2.13 consists of actuators, sensor system and user interface (controls, display and graphical processing unit - GPU). The same functionality can be achieved using different architectures. In case of federated architecture the system is essentially constructed of three separate computing and input/output communication (I/O) units communicated via dedicated data channels. The IMA enables to share and optimise computer resources. The number of central processing units (CPUs) is reduced from 3 to 1, I/O and network interfaces from 5 to 4 and physical communication channels from 4 to 1. In [61] the transition from federated avionics to integrated modular avionics is described

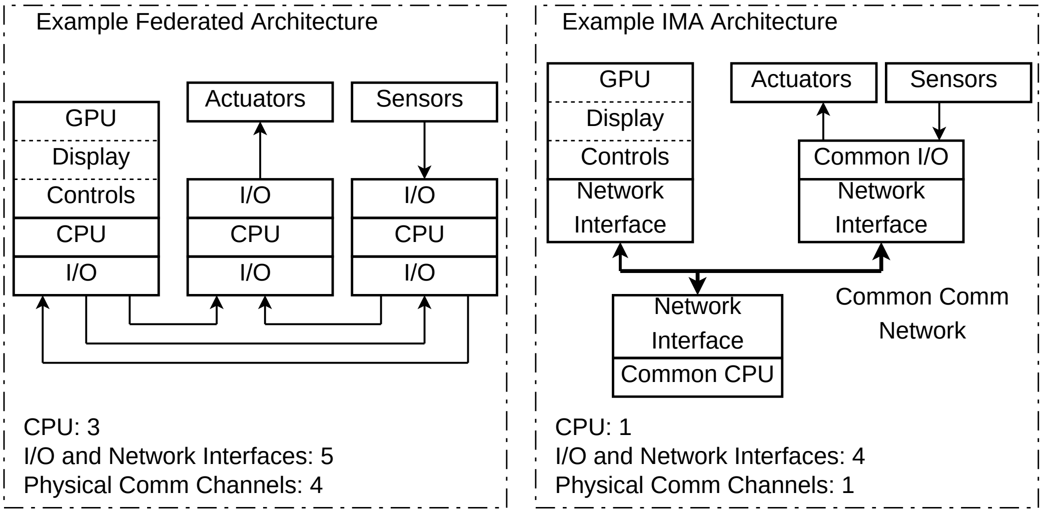

Figure 2.13: Comparison of the federated and IMA [61].

Benefits of IM Architecture

The main benefits of IMA given in [61] are:

- **Optimised allocation of spare computing resources** IMA enables system integration to increase/decrease allocation for a particular function in the future, or to add a new function without the need for new computing resources. Due to the certification the dynamics of resource allocation do not occur when system is in service. However the main advantage is when the system needs to be upgraded. IMA architecture allows the resources to be re-allocated (if needed) without the change of the hardware. The system can be then certified for use in service.

- **Optimised physical equipment weight and power consumption** Common IMA computing platform (shared computing resources) instead of separate computing units in each LRU minimises the physical dimensions, weight and power consumption. Also dedicated communication channels are replaced with common network I/O interfaces. In certain situation when a unique resource capability cannot be provided by common IMA computing platform, separate LRU can still exist.
- **Consolidated development effort** IMA architecture consolidates hardware which as a result consolidated the development. One of the advantages is that IVHM function developer dos not need to focus on computer system development and certification, instead the attention can be fully paid to the developed software.

The advantages of IMA architecture determines that a generic IVHM baseline architecture should be based on IMA architecture.

Example of IMA architecture of IVHM System

An example of existing HM system architecture where modular approach was introduced instead of federated is Boeing Central Maintenance Computer (CMC). In Boeing 777 a multiple avionics functions (e.g. power supply modules, aircraft I/O modules, communication modules, database modules) were hosted on line replaceable modules (LRMs) instead of dedicated LRUs. These modules are mounted in a rack which provides common power, cooling and data links. This resulted in fewer number of physical HM boxes, which implicates a reduced overall power consumption, cooling, wiring and weight. The CMC is design to collect and analyse the health state data from LRMs and LRUs playing essential role in the troubleshooting and repair of aircraft with modular avionic systems [22, 28].

Honeywell Primus Epic Aircraft Diagnostic Maintenance System An example of modular IMA architecture is Honeywell's Primus Epic Aircraft Diagnostic Maintenance System (ADMS) [28]. It has been designed to be scalable and extensible to aircraft and helicopters from various manufactures rather than targeting a specific system/configuration.

Lockheed Martin Joint Strike Fighter The new F-35 JSF avionics system consists of federated and integrated systems. Applications which require dedicated high bandwidth control system (e.g. flight control system) are based on federated systems. However, core processors such as vehicle and mission management are based on IMA architecture [28].

Open System Architecture for IVHM

An open architecture for IVHM discussed in [51] is an effect of a joint effort of Mitek Analytics, NASA Ames Research Center, Boeing and Honeywell Aerospace. Open architecture is a type of architecture that enables independent suppliers to architect and implement their systems on the platform by complying with industry standard interfaces at all levels within the platform [62]. Open architectures utilise open interface standards that are available in the public domain [61]. It aims to establish IVHM architectural framework, including standardisation of operations, functions, communication protocols and information management. The taxonomy of the IVHM architecture with its function types is shown in Figure 2.14.

Direct action IVHM function processes on-board aircraft sensor data and the results are used during the flight. Such functionality requires higher level certification, typically DO-178B level A or B. The DO-178B standard has been developed by Radio Technical Commission for Aeronautics (RTCA) to establish software considerations when the aircraft equipment is implemented using microcomputer techniques [63]. The DO-178B certification level is A, B, C, D, or E which correspond to the consequences of a potential

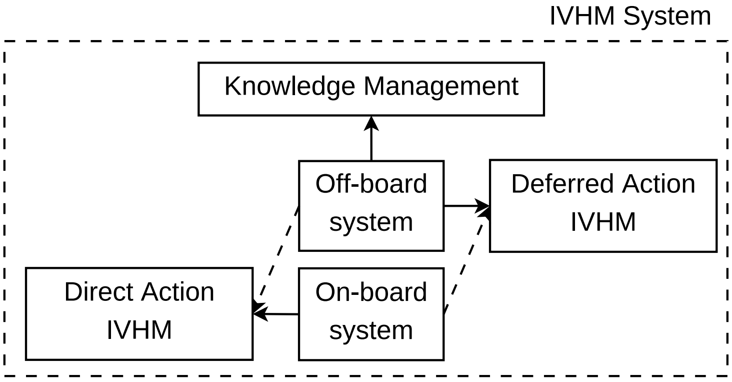

Figure 2.14: Taxonomy of IVHM functions by [51].

failure of the software: catastrophic, hazardous, major, minor, or no-effect, respectively.

Deferred action IVHM function also process on-board sensor data; however the results of the data processing can be used only off-board. In this case the function requires lower certification level (e.g. DO-178B level C, D or E). According to the authors, direct and deferred action functions can be hosted on-board and off-board (as in Figure 2.14); however on-board decisions / actions are only allowed for the direct action IVHM function. The important difference is the development and certification cost between much expensive direct action and less expensive deferred action [51, 41].

Knowledge management (KM) is a collection of off-board functions to support development and management of information models of an asset (e.g. nominal operation models, fault models) used by the IVHM algorithms [51]. KM provides tools and processes to allow integrating all models from different system suppliers into comprehensive aircraft level model [58]. KM also provides configuration data required to implement IVHM system in a specific asset and operational environment. It is virtually impossible to implement KM on-board due to need for access and exchange of fleet-wide data over a long period of time. However, it would be beneficial for on-board system to use an output from off-board KM data to make informed decisions [51]. The data from off-board KM database is used to perform diagnostics and prognostics actions.

In general IVHM can be mapped into four large classes of functional systems as shown in [51]:

1. On-board critical systems
2. On-board non-critical systems
3. Ground (off-board) systems
4. Data management systems

On-board critical systems hosts direct action functions, whereas the on-board non-critical systems hosts deferred action functions. The ground systems supports off-board deferred actions. The data management system does not provide analytical functions (i.e. diagnostics, prognostics); it provides data collection on-board and data transfer from a vehicle to the ground [51].

A four layer decomposition of on-board system is shown in Figure 2.15. It corresponds to the currently used architecture in Boeing 777 and Boeing 787 IVHM system [51]. The lowest layer represents sensor systems (common aircraft sensors and dedicated IVHM sensors). The second layer represents subsystem level HM (or LRU level as described in [58]). Often the subsystem HM is a federated system developed by subsystem providers: a coordinated effort is required between HM integrator, aircraft manufacturer and subsystem provider to ensure safe and maintainable system architecture [51, 12]. The third layer is a system level D/P. System level D/P is an analogical to LRM discussed previously in Section 2.2. The top layer represents vehicle level HM functionality: it integrates system HM functions and provides aircraft-level diagnostics, prognostics and supports maintenance. As an example, in this architecture aircraft engines together with associated fuel tanks and related hardware (e.g. fuel pump, fuel pipes, etc.) are considered as subsystems of aircraft propulsion system. A vehicle level is then understood as a set of separate systems (e.g. propulsion system, landing gear, etc.) which together forms an aircraft. Taking into account the example of propulsion system, the subsystem level D/P is an Engine health management (EHM) unit and the system level D/P is a functional block which analyses data from all the propulsion subsystems.

The implementation of advanced IVHM functions on-board requires high bandwidth data acquisition and processing (e.g. up to 20kHz - 40kHz accelerometer data per axis to monitor vibration). The current avionics buses provide typically 100Hz data bandwidth [41]. One of the ways to tackle this limitation is to use local data processing (e.g. at subsystem level), which minimises the need for vast amount of data to be transmitted via on-board buses [7].

Despite the possibility of local data processing, efficient communication between IVHM nodes (layers/elements in the hierarchical system) is needed [41].

In this architecture the on-board data storage is a data-logging function which can fetch data directly from each IVHM layer and it is managed by Vehicle level IVHM D/P. The available on-board data can be classified as unprocessed, partially processed or fully processed on-board data.

In this architecture a data / information flow can be realised in a number of different ways. The requirements for on-board data-communication will vary depending on type, size and mission of a vehicle. The main assumption made here is that a sensor data is transferred and processed by subsystem level D/P, system level D/P up-to the vehicle level D/P. This is a linear process where no sensor data or result of (pre)processing of a data from one system/subsystem is used by the other system/subsystem D/P. Only vehicle level D/P have access to all the system D/P. Such solution is currently deployed in existing systems [58].

Figure 2.15 also shows the off-board system of the discussed architecture. The off-board system provides diagnostics, prognostics, supports maintenance and enterprise level functions (i.e. maintenance control, decision support, engineering and maintenance planning) [58, 51].

The limiting factor in the design of system based on hierarchical architecture is the communication infrastructure [58, 41]. It is impossible or cost prohibitive to transfer HM data from all sensors to higher level IVHM functional blocks at all time. Therefore IVHM functionalities must be distributed across the system to allow data processing as close to the data source as pos-

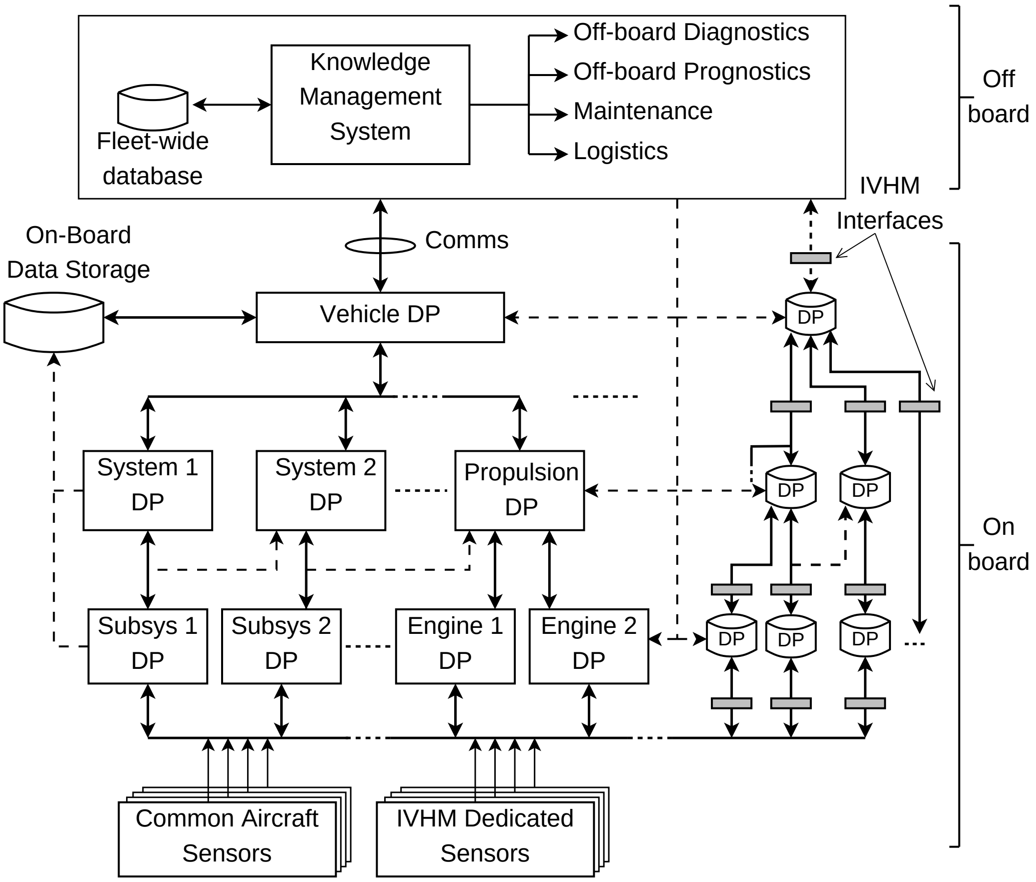

Figure 2.15: Complete IVHM System generic architecture [58].

sible. Instead of raw data, compressed data or extracted features need to be reported to the higher level IVHM components. The on-board hierarchical distributed architecture enables quicker fault diagnosis and local response to be generated [41]. The main drawback of local data processing is that the original source data may not be available for additional off-board processing and for development and validation of new HM algorithms.

Despite the sophistication and advancement of nowadays on-board computing and data processing system capabilities, the data-download capability to support further off-board diagnostics and prognostics in terms of accurate fault isolation and estimation of the remaining useful life (RUL) is essential [41]. This reinforces the need for sufficient on-board data-storage capabilities or in-flight data download capability. The hierarchical architecture is flexible in this respect and allows both schemes to work in parallel. The main limiting factors are: cost of in-flight data download and cost of data storage (it also includes weight, power consumption, cooling systems, certification, data availability and data security issues).

Distributed Hierarchical Architecture: Types of Interfaces

Generic architecture of IVHM system should provide well defined and standardised interface between elements on different layers, elements from different suppliers on the same layer and between on-board and off-board system components. Figure 2.15 also introduces the concept that each component of the hierarchical architecture is defined as functional block using OSA-CBM approach, denoted D/P (see also Figure 2.12 for OSA-CBM functional block). It is important to remember that some D/P components can be design as federated system: internal function interfaces depends strictly on system provider, however, to communicate these blocks with outside world, it is crucial to implement a standardised I/O communication interface.

Cost evaluation of IVHM System partitioning

Despite the potential benefits of IVHM the cost associated with design, implementation and, in particular, partitioning of IVHM System has to be explored. Cost estimation uses information available at the time to approximate cost or probable worth of an activity [64]. Accuracy and availability of data is therefore crucial to properly assess the related costs, risks and gains.

The challenge of accurately assessing the trade-off between the costs, associated risks, and gains is given in [9] as potential barrier to IVHM adaptation. Different techniques to justify the design, development, implementation and maintenance of IVHM / PHM system had been widely researched and described in the literature (e.g. [29, 65, 66, 67, 68, 69, 70]). In the published work the focus is mainly on IVHM System as a whole, without the consideration on IVHM System partitioning.

A comprehensive study on IVHM System implementation decision based on cost trade-offs is presented in [70]. For each of the defined nine application areas of aircraft health management, namely engine life-ing, engine CBM, engine start, environmental control system (ECS) pneumatics, ECS air conditioning, thrust reverser, tires and breaks, hard landing (structural integrity) and power generator a study of costs and gains for different system architectures is proposed to enable optimal implementation of IVHM System. The three alternative system architectures, (i.e. dedicated, shared and hybrid architecture), can be partitioned between on-board and off-board, however the partitioning is not in the main focus of the proposed optimisation approach. An extended list of cost drivers which can be adapted in on-board / off-board optimal partitioning has been proposed, and it is presented in Table 2.3.

Analysis of IVHM / EHM for civil and military aircraft is given in [71] based on cost trade-offs. A list of costs associated with the implementation and maintenance of health management system is defined and grouped into four main cost categories: development, production, operational and sustainment. Each group consist of a number of sub-categories, which can be modified according to specific system requirements (e.g. civil, military, etc.).

Table 2.3: Major cost factors in IVHM System design [70].

Cost factors
Minimize addition of communications wiring
Minimize addition of power wiring
Minimize addition of circuit breakers
Minimize weight of added hardware, excluding wiring
Minimize uncertified components/system
Minimize new hardware qualification
Minimize the number of additional part numbers
Utilize high Technology Readiness Level (TRL)/proven technologies
Maximize multi-use components
Minimize power consumption
Minimize thermal load
Minimize hardware volume
Minimize additional dedicated sensors
Minimize reliability impact
Minimize maintainability impact
Minimize impact to existing interfaces(buses, protocols, etc.)
Minimize processing requirements
Minimize flight deck impact
Minimize support equipment
Minimize training requirements
Minimize drawing changes

An overview of relative cost and weigh impact due to EHM implementation is shown in Table A.1 in Appendix. Although on-board / off-board partitioning is recognised in [71] as a crucial part of IVHM / EHM design and implementation, but the cost trade-off presented therein does not take into account partitioning of IVHM as a design trade-off attribute.

The impact on life-cycle cost due to implementation of IVHM / PHM System to helicopter avionics system has been investigated in [65]. A comparison between cost of unscheduled maintenance (traditional approach) and scheduled maintenance (due to implemented IVHM D/P) has been shown as a reliable model to enable financial based decision-making on IVHM implementation. It is claimed that life-cycle cost can be optimised using the proposed maintenance cost model.

2.3 Summary and concluding remarks

A large body of research related to IVHM System has been reviewed in this work, none of witch, however, has been found to be directly related to optimal on-board / off-board partitioning. This has been identified as a significant gap in knowledge and, in order to address it, the described literature review focused on existing IVHM Systems with attention paid to its on-board / off-board components. The detailed examination of existing publications clearly showed the need for partition of IVHM. Two main approaches to implementation of IVHM are present in the literature: at the design stage and on the legacy platform (retrofit). In both cases the IVHM System consists of on-board and off-board components.

Partitioning at the design stage is shown here using two exemplary architectures from NASA RLV and JSF Programme. In both cases on-board system consists of fault detection, diagnostics and mitigation systems, and the architecture proposed by NASA also included on-board prognostics system. Partitioning on legacy platforms is described based on example of engine performance trend monitoring and gas path fault diagnosis system with IVHM system enhancement by NASA. The enhanced architecture migrate part of conventional off-board diagnostics into the on-board part to perform real-time analysis of engine data. Review of laboratory case studies form Boeing along with the current challenges and motivations for IVHM implementation is also presented. The technological limitations and other barriers (e.g. technical, legislative) to implementation of partitioned IVHM System had been also reviewed.

This literature review showed that up to date no particular solution to on-board / off-board IVHM System partitioning problem had been proposed. In fact, the partitioning in most of the reviewed works is considered as a result of system architecture, rather than a attribute which can be optimised to provide the best IVHM solution. The optimal partitioning of IVHM System is therefore approached directly for the first time in this work.

2.4 Research Objectives

The main aim of this study is to develop a novel method for optimal partitioning of IVHM System which take into account diagnostics and prognostics effectiveness, hardware and communication capabilities and application requirements, including (near) real-time requirement, and criticality of vehicle components / subsystems. To achieve that, a number of objectives have to be met to provide the framework and to aid the development of the novel method. The objectives are:

1. To investigate and develop the vehicle life-cycle and operational needs, including maintenance operations, key features of faults, criticality of IVHM System outputs (i.e. diagnostics and prognostics) to vehicle operation.
2. To investigate and develop the main drivers for optimal on-board / off-board partitioning of IVHM System and their links to key features of vehicle operations.
3. To investigate and develop a cost model to perform trade-off analysis of partitioned IVHM System alternative configurations.
4. To investigate and develop the novel optimisation criterion for optimal partitioning of IVHM System based on the defined cost model and the main drivers.
5. To investigate and develop the novel optimisation method for optimal partitioning of IVHM System based on the developed criterion.
6. To investigate and develop new metrics to assess the cost effectiveness of IVHM System partitioning.
7. To implement the developed method in MATLAB platform.

Chapter 3

Main Drivers for Partitioning of IVHM System

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3.1 Introduction

The powerful and efficient way to capture underlying IVHM System requirements and to understand the resulting system partitioning is to define the main drivers. In the reviewed literature a vast number of drivers for IVHM System are clearly articulated, however, these are not specific drivers for partitioning of an IVHM System. The lack of defined drivers for IVHM System partitioning is addressed in this work. In this Chapter, the defined main drivers for optimal on-board / off-board partitioning of IVHM System are presented.

The development of drivers had been carried out in two phases. In the first phase the key features of a vehicle operation were defined and analysed, namely the key features of:

- Maintenance operation,
- Faults,
- Generic IVHM System architecture,
- Concept of operations (CONOPS),
- The chain: customers – outputs of IVHM System.

In the second step, for each of the key features of vehicle operation an extended list of potential drivers has been created. The potential drivers were defined based on literature review and good engineering practice (including the questionnaire sent out to aerospace industry engineers) and creative thinking. Upon further in-depth analysis some of the initially selected drivers which were not directly related or less significant to partitioning of IVHM System were excluded.

In this Chapter the resulting set of key drivers for optimal on-board / off-board partitioning of IVHM System is described in details.

3.2 The key features of vehicle operation

The main drivers should be defined and described in a way which allows stakeholders to recognise and fully understand them [72]. One of the main challenges in defining key drivers is to ensure that the adopted strategy is not only limited to what is known but also it allows exploring the novelty aspects of analysed systems / technologies. In order to provide such flexibility and to ensure the full coverage in this process, all the listed above key features of vehicle operation were investigated and the results had been scrutinised with particular attention to partitioning of the IVHM System.

3.2.1 Key features of maintenance operations of vehicles

Maintenance is an inevitable and essential part of every vehicle life-cycle. The British Standards BS 4778-3.2 [73] defines maintenance as:

> "*The combination of all technical and administrative actions, including supervision action, intended to retain an item in, or restore it to, a state in which it can perform a required action*".

Maintenance processes are defined by International Organization for Standardisation in ISO/IEC 15288 [74] as:

> "*The purpose of the Maintenance Process is to sustain the capability of the system to provide a service. This process monitors the system's capability to deliver services, records problems for analysis, takes corrective, adaptive, perfective and preventive actions and confirms restored capability.*"

A vast body of exiting research is dedicated to the role of the IVHM System and its influence on maintenance operations (e.g. [1, 75]). In [76] one of the major drivers towards implementation of health management technologies to aircraft systems is defined as low maintenance cost. In order to understand the relationship between Optimal IVHM partitioning and maintenance the following study of key features of maintenance operations has been conducted as part of this thesis.

Maintenance operations can be classified as line maintenance (LM) (also called field maintenance) and base maintenance (BM) (other names: repair shop, depot) operations. The LM tasks are dedicated to maintain on-going daily operations, i.e. minor routine maintenance, troubleshooting, root cause analysis and corrective actions. The BM consists of major routine maintenance tasks, troubleshooting, corrective actions and the root cause analysis.

Scheduling of maintenance activities combines vehicle health data (e.g. diagnostics / prognostics), maintenance operation data (cost, availability of resources, etc.) and available vehicle operation data [76, 77]. Maintenance operations are also divided between vehicle fault and no-fault condition. The breakdown structure of maintenance tasks for both conditions is presented in Figure 3.1, followed by a description of its main components.

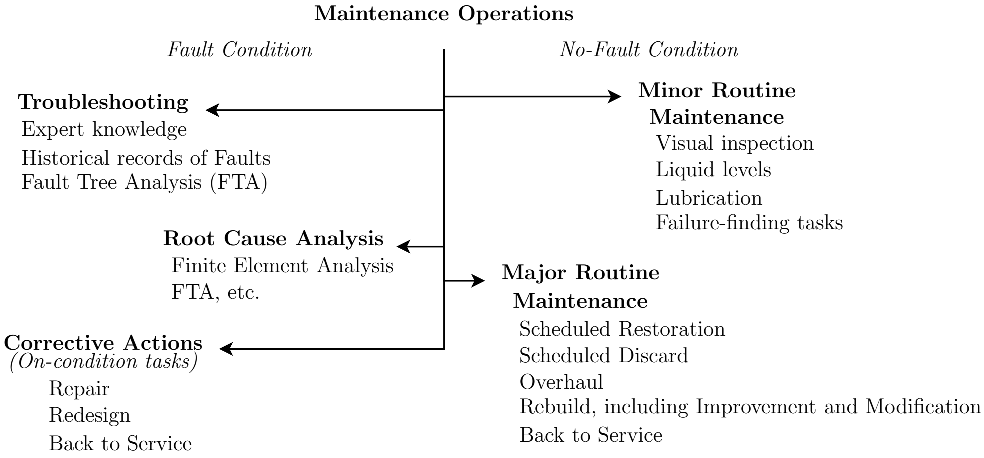

Figure 3.1: Maintenance operations breakdown structure.

Troubleshooting

It is a set of activities to trace, localise and analyse a problem (fault) in a system / process so that it can be solved and the system / process can perform its intended functions again. It can be divided into three main phases:

1. *Investigation phase*:trace and localise the problem (the use of Diagnostics output, expert knowledge, fault models),
2. *Analysis phase*:detailed analysis of detected problem and its causes, and use of previously gathered knowledge (if exists) about the problem potential causes and solutions, then propose solutions/fixes to the problem, and
3. *Implementation phase*: test and verification of the proposed fix / solution, and documentation of the troubleshooting process to create knowledge data-base.

Root Cause Analysis

The Root Cause Analysis (RCA) uses tools and methods to find and examine the main root cause(s) of a faults (or failures). It uses expert knowledge, Fault Tree Analysis (FTA), Finite Element Analysis (FEA), etc. RCA assumes that all faults / failures belong to one (or more) of the following categories: faulty design, material defects, fabrication/processing errors, assembly/installation errors, off-design service conditions, maintenance deficiencies.

Minor Routine Maintenance

It is a set of operations to retain a vehicle in a fully operational condition. It includes walk-around / visual inspection to find obvious faults / damage, e.g. leakage, structural damage, missing elements, etc., checking liquid levels, lubrication, cleaning, etc. It also consists of failure-finding tasks, i.e. inspection or testing task, designed to determine whether an item or component has failed. It is important to highlight that failure-finding tasks entail checking hidden functions periodically to determine whether they have failed whereas on-condition tasks entail checking if a system (or its function) is failing.

Major Routine Maintenance

This set of maintenance activities encapsulate more complicated or time / resource consuming tasks to retain a vehicle in fully operational condition which cannot be executed in frames of minor routine maintenance tasks. It can be further broken into following maintenance tasks categories :

1. Restoration: a task to restore a component; in preventive maintenance, at a specified, pre-determined frequency, regardless of the condition of the component at the time of its replacement, often regarded as life-limited parts (LLP).
2. Discard: discarding and replacing an item; in preventive maintenance, at or before a specified age limit, regardless of its condition at the time.
3. Overhaul: complete disassembled inspection, rework and reassembly of an item to restore it to a fully functional condition; usually performed at depot level.
4. Back to service: check-out procedures to verify proper operation and successful completion of the maintenance tasks.
5. Improvement: upgrade of an equipment without changing its required functions.

Corrective Actions

This part of maintenance activities is carried out after fault occurs and it is intended to put system into a state in which it can perform its required functions. It involves various activities, including but not limited to redesign.

Redesign, which is regarded as very conservative task, is applicable when maintenance cannot manage a particular failure mode and its effects; hence a change is necessary (to the component / system or the way it is utilised). It may include activities such as e.g.: redesigning the equipment, selecting different equipment, relocating the equipment, creating redundancies, making some other one-off change to improve the intrinsic reliability / availability of the equipment, improving something about how the equipment is used (e.g. procedures, training and/or documentation), etc.

Figure 3.2 2 introduces the relationship between LM, BM and the maintenance tasks for vehicle no-fault and fault condition.

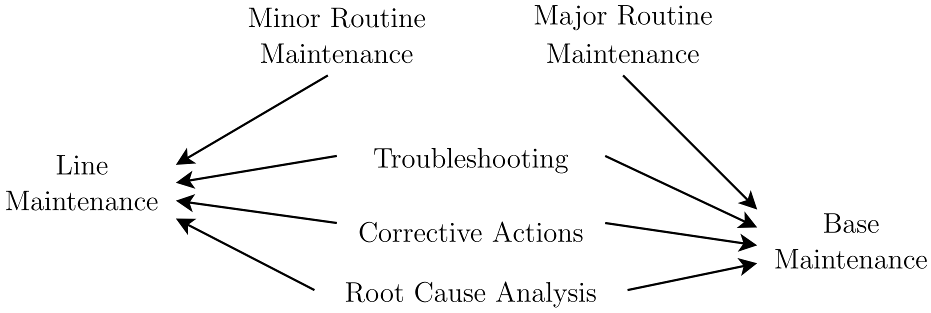

Figure 3.2: Outline of base and line maintenance tasks.

As shown in Figure 3.2 and discussed previously LM is strongly related to a vehicle no-fault condition. IVHM System features that characterise effectiveness (e.g. effectiveness of D/P) are therefore considered as potential drivers for partitioning of an IVHM System when the focus is on LM. A typical aircraft LM operation can be described as following: aircraft arrives at an airport and LM process is initiated such as: basic checks, walk-around, liquid levels checks, etc., the acquisition of vehicle health data. If the vehicle condition satisfies the Manufacturer Minimum Equipment List (MMEL) the aircraft is granted “Go” status. Otherwise a more detailed and advanced maintenance actions are triggered. On-board IVHM D/P system can potentially trigger LM operations prior to aircraft arrival; hence improve timing of LM operation. In Figure 3.3 a generic maintenance time sequence diagram is shown. Maintenance, as a part of a vehicle life-cycle can be pictured as the down time period in vehicle operational life-cycle.

In Figure 3.3, the overall maintenance time is an interval during which a maintenance action is performed. It includes active maintenance, technical and logistic delays. The active maintenance time is a portion of the main-

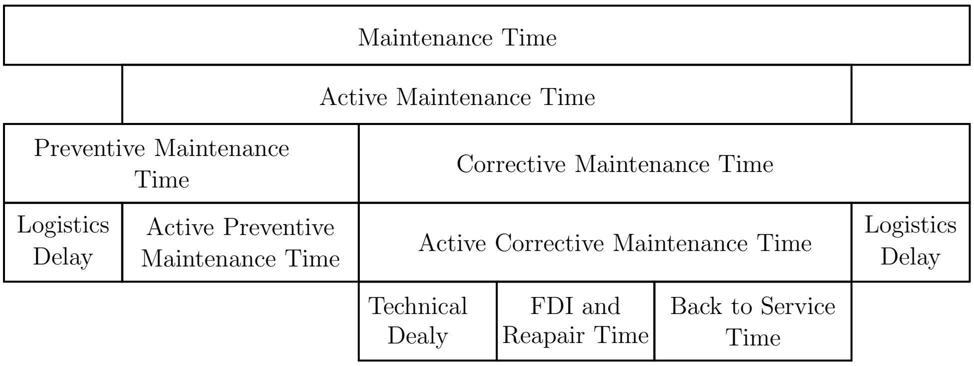

Figure 3.3: Maintenance time sequence block diagram (BS 4778 3.2, BS EN 13306:2010).

tenance time during which a maintenance action is performed, excluding the logistic delay. This delay is defined as time during which a maintenance action cannot be performed due to the acquiring maintenance resources. The other type of potential delay, shown here as technical delay, is the accumulated time necessary to perform auxiliary technical actions associated with the maintenance action itself, including recovery actions, disassembling, etc. The fault detection and isolation (FDI), followed by the repair time is a period when all the activities related to troubleshooting and repairs are performed. Back to service time is essentially the part of active maintenance time during which function check-out / testing is performed. It is also assumed that active preventive maintenance may also include minor and / or major routine maintenance tasks. For further reference see Figure B.1 (DoD breakdown of total vehicle / equipment time [78]).

Maintenance *no defect* actions, such as cannot duplicate (CND) and retest OK (RTOK), are important due to costs involved and the potential level of operational disruption. Improved diagnostics and troubleshooting are listed as possible solutions to minimise the maintenance burden caused by CND and RTOK (see e.g. [79]).

The most important result of the key features of maintenance actions analysis is the correlation between the partitioned IVHM System and maintenance operations (see Figure B.2 for overview on vehicle and maintenance operation cycle), which leads to definition of the main drivers for partitioning. The underlying assumption is that the effectiveness and efficacy of maintenance operation may be influenced by different levels of IVHM System partitioning between its on-board and off-board parts.

Key features of maintenance operation: concluding remarks

Section 3.2.1 provides an overview of the key features of maintenance operation. A number of drivers for IVHM System partitioning can be defined based on the discussed maintenance processes. The effectiveness of diagnostics and prognostics functions of a partitioned IVHM System is recognised as a major driver due to the influence on the utilisation of maintenance resources via optimal scheduling of maintenance actions, enhanced in-advance troubleshooting and fault-finding, reduced maintenance delays (e.g. due to early acquired spares), reduced CND and RTOK.

It is also recognised that effective diagnostics and prognostics can minimise the operational disruption by reducing number of unplanned maintenance shop visits, delays and cancellations. The impact of such improvements can be directly seen in minimised vehicle life-cycle cost. The second most pronounced driver emerging from the above analysis is related to the dispatch reliability and fleet readiness: to perform a given mission when required. To increase or, in some cases, to enable a window of opportunity for maintenance actions to be performed, a real time diagnostics response is required. Real time diagnostics enables detection of faults that otherwise would not be detected (e.g. fault that lasts only for short period of time) and could cause serious failures and secondary failures. It also helps to address fault scenarios such as CND and RTOK.

Early diagnostics helps to extend the time between potential fault and the functional failure (see Figure 3.12, p. 94), and therefore it allows maintenance operations to be optimally scheduled and to be performed prior to system failure. This further translates to reduced maintenance costs and minimised the disruption to vehicle operation.

3.2.2 Key features of faults

Understanding of key features of faults plays an important role in the process of defining main drivers for IVHM System partitioning. One of the key functionalities of IVHM System is to react upon unpredicted events, such as faults, and to mitigate or, in the ideal case, to avoid them. Results of this study help to project the key features of faults into the developed main drivers for IVHM System partitioning. A number of definitions for faults have been proposed in the literature, but no uniform definition has yet been proposed. Following [80] a fault can be defined as “an unpermitted deviation of at least one characteristic property (feature) of the system from the acceptable, usual, standard condition”. In [81] a fault is defined as “physical defect, imperfection, or flaw that occurs in some hardware or software component”. Further definitions can be found in published technical standards such as BS-4778-3.2, DIN 24525-3, MIL-STD-721C ([73, 82, 83]). In the existing literature faults and related failures are classified using numerous criterion. Attempts are made to propose systematic and generic classification methods (e.g. [84, 85]). In this work a structured approach has been adapted where the key features of faults are classified by:

- Root causes of fault,
- Consequences of fault,
- Fault time behaviour, and
- Fault modes.

Each group of key attributes of fault has been investigated and is described below in detail, including definitions and real-life examples.

Classification of faults by root causes

Faults can be classified by their root causes. Such classification is possible once the root cause of a fault is determined. Numbers of techniques and methods for root causes analysis (RCA) are used to identify the underlying causes of faults (see e.g. [86]). Such classification often play an important role, especially in case of high value assets or safety and critical systems, and it is used to help to further design-out, mitigate or develop corrective actions to address the identified root causes of faults.

The following six main groups of root causes have been used in this work to classify faults: faulty design, material defects, manufacturing errors, assembly or installation errors, off-design operation and maintenance errors. Each group is described here along with examples of related faults.

Faulty design mostly related to faulty decisions at the design stage, is a common root cause of multiple faults. The following examples of faults are linked to faulty design:

- Design fault: a fault due to inadequate design of a system / function
- Weakness fault: a fault down to a weakness in the system itself, which can exhibit when a system is subjected to stress within its nominal capabilities (i.e. operational envelope)
- Systematic fault: often a result of an error in the design specification of a system, and therefore may affect all examples (batch) of such a system. Providing the same circumstances in which a systematic fault exhibits, each and every example of the affected system would fail identically. In most of the cases it can be eliminated by a modification of the design, or of the manufacturing process. Corrective maintenance actions without actual modification will, in most cases, not eliminate the related cause.

Materials defects in general are causing faults due to defect of material that can be described as unacceptable imperfections of the material or discontinuities in material that degrade the performance of a system / component. Such faults can develop in a system (components) that operates inside the nominal operational envelope. Material defects occur despite the measures taken to control the processes involved in e.g. manufacturing. Examples of discontinuities which are identified in the literature as causal factors include porosity, micro-shrinkage, edge cracking, cold shuts, etc. [87]. Numerous faults can result from material defects across mechanical, structural, electrical and electronic systems. Manufacturing errors are related to non-conformity during manufacturing process to the design of a system / component or due to specific manufacturing process. Quality and reliability of an item may be affected from faults that originate due to manufacturing errors [SAEJ1739]. Variability of manufacturing processes can also lead to undesirable behaviour of an item, and cascade to fault of an item.

Assembly or installation errors are related directly to the process of physical build of a system / component. Examples of assembly and installation errors are misalignment, missing or wrong part being used, inappropriate fastening system (e.g. improper torque), improper tools used for assembly, etc. An example of fault due to assembly / installation error is a mishandling fault, defined as a fault caused by incorrect handling and / or lack of care of an item, in this case, during the assembly or installation phase.

Off-design operation is a common root cause of faults related to the use of a system / equipment outside the operational envelope. An example of fault caused by off-design operation is a misuse fault, defined as fault due to stress during operation which exceed the design (nominal) capabilities.

Maintenance errors such as use of inappropriate processes or tools at the maintenance stage, may cause variety of faults in a system. Errors at the maintenance stage are linked to e.g. mishandling faults (described above). Incorrect execution of maintenance procedures (including timing, material, parts used, etc.) may also cause further faults in a system during its operation resulting in reduced quality and performance of a system.

Classification of faults by the consequences

Faults can be further classified by the consequences, i.e. the impact that the effect of a fault have on a system [85]. In the literature the following five main consequences of faults are recognised:

Safety consequences faults with safety consequences can result in injuries or loss of life.

Environmental consequences faults with environmental consequences may temporarily or permanently impact the environment (e.g. dangerous substances released into atmosphere) and can result in breach of environmental regulations and standards.

Operational consequence fault with operational consequences have an impact not only on the related repair (including cost), but also introduce some additional impact on the operation, which directly translates to the costs and loss of revenue.

Non-operational consequences faults with non-operational consequences are faults that are evident (not hidden) and result only in the cost of the related repair.

Hidden consequences A fault may or may not affect the performance of a vehicle. When a fault can be observed or made evident by vehicle crew, operator or maintenance personal it is said to be evident. In such case a diagnostic system (instrumentation / method) exist to detect and isolate the fault. This may include automated D/P system, routine inspections (e.g. visual), etc. If, however, a fault is not evident (i.e. not observable) to the operator or maintainer during normal use, it is said to be hidden.

Faults with hidden consequences have no direct impact; however they may cause a system to develop other faults and failures. Example is a protective device that itself is not fail-safe.

IVHM System is normally expected to deal with the above types of faults / failures. The first step to select appropriate actions to mitigate consequences of failure is to identify these consequences. In Figure 3.4 steps to classify faults according to their consequences is shown.

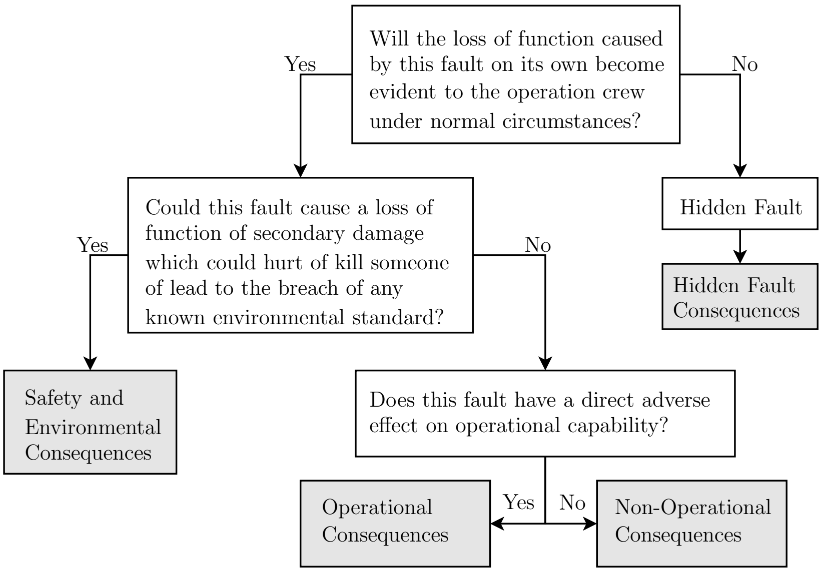

Figure 3.4: Consequences of faults.

Classification of faults by consequence often is used as a strategic framework for maintenance and diagnostics / prognostics decision making. Evaluation of consequences of faults help to focus the attention and to prioritise efforts in addressing faults within a system that results in the highest consequences which can be further translated to higher costs.

Classification of faults by time behaviour

Faults can be classified by time behaviour. Identifying the time behaviour (time duration) of fault can be crucial to determine the appropriate strategies to address the fault. Three types of fault time behaviour are recognised in the literature: transient, intermittent and permanent [81, 88, 73]. Each type of time behaviour is defined below.

Transient fault has random time behaviour, e.g. it is caused by random event [88]. It may occur once and then disappear, and if the system operation is repeated, it will behave normally (fault free). In electronic and computer systems a transient fault are mostly caused by environmental factors, such as radioactive radiation (e.g. alpha particles, atmospheric neutrons), overheating or electrostatic discharge.

Intermittent fault is defined as a one which persists in a system for a limited time, after which a system recovers from fault and is able to perform its intended functions without undergoing any corrective actions. Intermittent faults are difficult to diagnose and often are recurrent. An example can be an electronic circuit with loose solder joint subjected to vibration that causes intermittent fault (open circuit).

Permanent fault remains active until corrective maintenance actions are performed (e.g. repair, replacement). An example of permanent fault in electronic systems is short circuit, broken connection, etc.

Intermittent and transient faults are difficult to detect and isolate [89]. In literature such type of faults are often described as no fault found (NFF) phenomena. Other names used across the literature include: erroneous removal (ER), no problem found (NPF), can-not duplicate (CND), and re-test OK (RTOK). Such faults (discontinuities) are very short in duration (typically microseconds / nanoseconds) and mostly of low amplitude. In aircraft system the intermittent faults are typically manifested during high stress, e.g. high g-forces, thermal extreme cycles, high vibration, or combination of stresses. High percentage of aircraft intermittent faults is related to aging wiring and connections. It is a growing problem, especially in case of legacy aircraft, which affects electric and electronic equipment (e.g. loose or corroded wire wrap, cracked solder joint, broken wire, etc.) [90]. Therefore, in order to diagnose such faults, an on-line and, in many cases, real-time diagnostics system is required [89, 90].

The time interval between fault (which can be also understood as a symptom / potential failure) and functional failure of a system is also important, when time behaviour of fault is considered. This period is called P-F interval. The potential failure is defined as one that is identified by a condition indicator (e.g. fault detection system) and means that once detected a functional failure is imminent. The functional failure is the inability of an item (component / system) to perform its function or to meet its specified performance. An example would be a pump, designed to provide specific pressure / flow, in which the impeller wears until the pump cannot deliver the specified output. Once a lower than nominal pressure is first noticed it is the P-point (potential failure), and when the pump cannot meet a minimum output, it is the F-point (functional failure). Figure 3.5 provides a graphical representation of P-F interval.

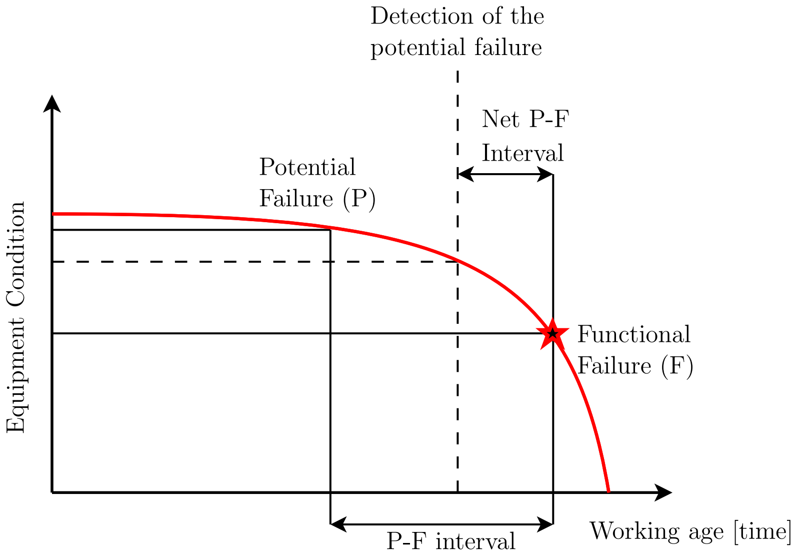

Figure 3.5: Graphical representation of P-F interval ([85]).

The Net P-F interval, as shown in Figure 3.5, is a minimum interval likely to elapse between the discovery of a potential fault and the occurrence of functional fault. The P-F interval is also used as a tool to determine condition monitoring intervals for periodical condition monitoring, and for planning maintenance strategies.

It is impossible to provide a generic classification in terms of P-F (e.g. long, short) because it is system dependant parameter. P-F interval can be expressed in time domain or by number of operation cycles between fault detection and system functional failure.

Classification of faults by fault modes

It is not possible to list all potential types of faults in a given system [81]. It is assumed that faults behave according to certain fault modes and therefore, to provide the best possible coverage of potential faults in a particular system, faults are classified according to their modes. Fault modes are defined as possible states of faulty system / component for a given function. Examples of fault modes in different type of systems can be [80]:

- Possible fault modes in mechanical systems: distortion (bucking, deformation), fatigue and fracture (cycle fatigue, thermal fatigue), wear (abrasive, adhesive, cavitation, etc.), corrosion (galvanic, chemical, biological, etc.).
- Possible fault modes in electrical systems: short cuts, broken connectors, contact problems, contamination and electromagnetic compatibility problems.

Classification of faults by fault modes is used in fault modes, effect and criticality analysis (FMECA), which is a qualitative method to analyse systems / component reliability [85]. FMECA involves fault modes analysis, effects of fault analysis, probability of fault occurrences and ranks the criticality (seriousness) of fault.

In addition to the above classification of faults by root causes, consequences, time behaviour and modes, faults can also be classified by their extent. The extent of a fault depends mostly on the importance of a component / system affected by fault and can be classified as local or global fault. A fault is classified as global when it has an impact on the whole system / vehicle. A fault classified as local fault has an impact on certain functionalities of a system, but the overall system can perform other functions. In some cases a local fault may be considered as global due to inabilities of the system to perform a specific action required to perform a mission due to the local fault.

Key features of faults: concluding remarks

The above analysis has been completed to investigate whether key features of vehicle / system / component faults can influence the decision on IVHM System partitioning, and if yes, how to reflect this in the main drivers for partitioning. It is made clear that faults and failures may take different forms, extent, and time behaviour. The consequences of faults also vary significantly (as shown in Figure 3.4) which affect the way how IVHM System is design to deal with such situation. Therefore the severity of failure consequences may also influence the decision on IVHM System partitioning, and as such becomes an important driver towards partitioning. When the time response of D/P function is vital to prevent or mitigate a system fault or failure, a real-time (or near real-time) response of diagnostics functions becomes a major driver for IVHM partitioning. Real-time response is strongly needed in case of faults with short or random time behaviour, here classified as intermittent and transient faults. In case of safety critical systems, the real-time D / P provides crucial information to both, the operator and maintainer about the current health state of a vehicle, therefore it enables inform decision making related to safety. This is especially important to prevent failures with safety, environmental or operational consequences. In case of faults with relatively short P-F interval the early diagnostics becomes an important driver earlier the symptoms / fault is diagnosed the more time is available to prevent or mitigate a failure. Early diagnostics in combination with real-time response may significantly improve the operation, safety and improve vehicle mission capabilities. This is clearly seen when diagnostics time delays due to data telemetry could be overcame by introducing on-board diagnostics functions. This can be further extended to capability of IVHM System to response to fault / failure in timeless and autonomous manner.

3.2.3 Key features of IVHM System architecture

Many different features of IVHM System architecture can be extracted and analysed. Each feature may influence the final decision on IVHM System partitioning. In Chapter 2 the in-depth review and critical analysis of the existing and future IVHM System architectures are given. IVHM System architecture strongly depends on a vehicle and its CONOPS. This makes it difficult to define a generic IVHM System architecture, although the functional architecture break-down is similar across different vehicles (e.g. sense - acquire - transfer - analyse - act as shown in Chapter 2 literature review).

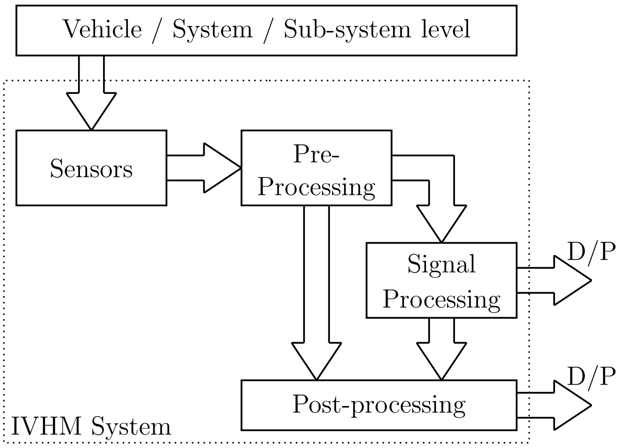

Figure 3.6: Functional breakdown of a generic IVHM System architecture.

The key functions of a generic IVHM System architecture are shown in Figure 3.6. The IVHM System senses and acquires health data from a system / sub-system (continuously or at specific intervals) using one or more sensors. The acquired sensor data are pre-processed and transformed to a suitable format (e.g. analogue to digital) for further processing stages. At the data processing stage (e.g. on-board IVHM) the condition of a system / subsystem is determined (D/P output on Figure 3.5). Also the results of data pre-processing stage can be post-processed (e.g. off-board IVHM) due to e.g. fleet-wide data analysis, trending analysis using historical data, in-depth data analysis due to higher computational capabilities, etc.

The Open System Architecture for Condition-Based Maintenance (OSA–

CBM)[1] has been proposed as a standard architecture for IVHM [55]. It aims to provide a structure in terms of functional breakdown and definition of interfaces for data gathering, data analysis and resulting maintenance actions. As it is shown in Figure 2.10 (see p. 35) the key components within OSA–CBM structure are:

- Data Acquisition (DA)
- Data Manipulation (DM)
- State Detection (SD)
- Health Assessment (HA)
- Prognosis Assessment (PA)
- Advisory Generation (AG)

In Chapter 2 detailed description of each functional block of OSA–CBM stack is provided. The key feature of IVHM System architecture, in respect to the OSA–CBM, is the definition of interfaces, including data communication formats, between different components in OSA–CBM stack. This enables the use of commercial off-the-shelf (COTS) systems to be integrated into IVHM System. Detailed study has been performed by [91] where distributed gearbox condition monitoring system has been implemented based on OSA–CBM standard. Rapid deployment and reusability of code (e.g. data processing algorithms) across the OSA–CBM block-set has been successfully assessed therein.

In general, IVHM System architecture can be classified into three main categories due to the way it is integrated into overall vehicle architecture [70]:

Dedicated architecture In dedicated IVHM System architecture the data acquisition (including sensor, wiring for communication and power), on-board data processing capabilities and data / information transfer capabilities between on-board and off-board are implemented in addition to the

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[1] OSA–CBM was developed in 2001 by an industry led team partially funded by the Navy through a Dual Use Science and Technology (DUST) program. MIMOSA (Machinery Information Management Open Standards Alliance) is a standards body that manages open information standards for operations and maintenance in manufacturing, fleet, and facility environments [55].

vehicle existing systems. Although the existing vehicle (e.g. aircraft) may be equipped with communication buses or sensor systems that could be used by IVHM System, these resources are not shared. It is assumed e.g. that existing data buses do not have capacity to host additional diagnostics / prognostics data.

Shared architecture In shared architecture the IVHM System is implemented into the overall vehicle architecture: it shares all required resources to provide D / P outputs. This type of architecture does not requires additional communication buses, sensors or computational / data processing units.

Hybrid architecture The mixture of dedicated and shared architecture is called hybrid IVHM System architecture. The main assumption is that there is some relevant data available for the IVHM System in the existing vehicle system (shared architecture). However, other IVHM functions will require additional sensors and infrastructure in order to provide D / P output (dedicated architecture).

Regardless the type of IVHM System architecture a certain limitations and constrains are present. Three main types of limitations are recognised: technological, legislative and financial. Technological limitations are mostly related to the data capture (e.g. sensor / probe sampling rate), data transfer (on-board data buses and on/off-board telemetry), data management (including on-board and off-board storage), and on-board data processing. Limitations due to legislations (e.g. FAA airworthiness certificate) are mostly related to certification and data ownership. Financial limitations, besides the direct cost of IVHMS System architecture such as cost of hardware, software, training, etc., are also related to stakeholders and the type of business e.g. service provider, vehicle owner, etc. It can be measured in terms of return on investment (ROI) in IVHM System. In most cases the final architecture of IVHM System is created as a result of trade-offs between these limitations.

All the above limitations and their impact on the partitioning of IVHM System have been shown in the literature review in Chapter 2. It has been also stressed that the described limitations apply to both: legacy platforms and to new design systems. In order to compensate limitations, especially related to technology, an appropriate architecture should be chosen to ensure the desired functionalities and effectiveness of the IVHM System can be delivered. Such decisions about the IVHM System architecture requires in-depth understanding of the vehicle CONOPS. An example is when a vehicle mission configuration requires long-term operation with no communication with the outside world (e.g. off-board MRO or mission planning). In such case the IVHM System architecture is needed to provide means to analyse data locally (on-board) to enable crew / operator to make informed decisions and to ensure mission success.

Key features of IVHM System Architecture: concluding remarks

In this work the key feature of an IVHM System architecture is to enable and support partitioning of IVHM D / P functions between on-board and off-board systems. This includes data acquisition, storage, on-board communication, data processing, and data telemetry (on-board / off-board data communication) capabilities. Other features of architecture, such as off-board data communication infrastructure and data / knowledge management, are also considered as key features in the process of defining main drivers for IVHM System partitioning.

The architecture of an IVHM System directly impacts the effectiveness of D/P through the quality and quantity of vehicle health data that is available, both on-board and off-board and through the available data-processing capabilities. Starting from the sensor, through the data communication buses, data processing, data transfer up to decision making, all limitations related to vehicle-level IVHM architecture and infrastructure-level IVHM architecture (fleet-wide view) are taken their toll on the resulting effectiveness of D/P.

Inevitably the same apply to how quick a fault / potential failure in a vehicle system can be detected and diagnose. In case where an early diagnostics is required (e.g. due to short P-F interval as described above in Section 3.2.2), IVHM architecture is a key enabler. Not only the limitations related to data capture and data transfer, but also the capabilities of IVHM architecture to enable data fusion from different areas of vehicle D/P systems. Federated architecture, which does not allow exchange of information between different D/P systems, prevents early diagnostics when early symptoms or potential faults can be observed indirectly. The integrated hierarchical architecture, as it has been shown in Chapter 2, enables data fusion and D/P decision making across different level of vehicle architecture, and therefore it may enhance early diagnostics capabilities of IVHM System.

Real-time response of D/P (i.e. minimal reaction time to fault / failure events) can be derived from the analysis of key features of IVHM architecture as potential drivers for IVHM System partitioning. When IVHM real-time response is required but limitations of data communication between on-board and off-board system (e.g. due to latency or lack of infrastructure) preclude the off-board system to generate D/P output in real time, then IVHM system architecture has to provide on-board D/P capabilities.

3.2.4 Key features of vehicle concept of operation

Concept of operations (CONOPS) describes the way a system works from the stakeholders / operator perspective, and captures requirements and expectations [92]. IEEE 1362-1998 standard defines CONOPS as “A user-oriented document that describes a systems operational characteristics from the end users viewpoint” [93]. The DOD dictionary of military terms defines CONOPS, from the military mission viewpoint, as “verbal or graphic statement that clearly and concisely expresses what the joint force commander intends to accomplish and how it will be done using available resources”. CONOPS is also known in literature as “operational concept description (OCD)” [93]. It normally consists of set of documents developed to describe all the system / vehicle operation phases (e.g. operation timelines, operational scenarios, mission profiles, communication strategy, maintenance and logistic support, capabilities, constraints, etc.) [94].

The description of operational scenarios provides the view on the system / vehicle operations, including interactions with other systems (i.e. external interfaces, vehicle on-board system and ground support system interactions), and it defines how the system / vehicle is expected to function during all the operational phases. CONOPS can provide information on different levels of granularity (extend of details to which the CONPS is broken down into), and can be developed in various ways [93]. Certain components, though, of CONOPS are usually present, including systems functions (goals, objectives, etc.), description of stakeholders (e.g. organisation, activities, interaction between stakeholders), and the description of specific to the system / vehicle operational processes. In principle of Systems Engineering (SE) the CONOPS is produced early in the design (requirements setting stage) to describe what system / vehicle is expected to do and why (rationale). It also defines the critical top-level system / vehicle performance requirements and objectives which may be expressed qualitatively or quantitatively [92].

The example of baseline operational properties within the CONOPS of a civil aircraft fleet, as shown in Table 3.1, is given in [41]. This is a top-level view on fleet operation and, despite a limited form, provides a comprehensive view on the fleet use profile.

Table 3.1: Example of fleet CONOPS: Baseline fleet properties [70].

Aircraft type	Fleet size	Average flight time [h]	Number of flight per day / year	Flight hours in 25 years life
Single aisle	200	1.9	5 / 1850	87875
Longer haul	50	4.5	2.2 / 800	90000

The example of single aisle aircraft in Table 3.1 is Boeing 737, whereas the example of longer haul double aisle aircraft is Boeing 777. Average flight time of an aircraft determines certain capabilities of the IVHM System: the example is a minimum capacity / time of on-board data recorder/ storage required to log aircraft data used by IVHM System. If certain procedure related to IVHM System takes place during the turn-around-time (TAT), then information such as number of flights per day and average flight duration can be cascaded down to determine the time-window to execute IVHM related activities, both on- and off-board. This is directly linked to the fleet readiness requirements expressed in CONOPS as part of the system use and operational constrains [95] (see also B.1 for the CONOPS document structure [96]).

Certain scenarios of vehicle operation described within the vehicle CONOPS may effect in the increase or, in some cases, request high level of autonomy: in vehicle operation and the way IVHM System operates. One of the examples is a long duration (e.g. transatlantic or transcontinental) flight mission / operation, which can also be linked directly with the extended range twin operation (ETOPS)[2], defined as the maximum time of one-engine flight away from the nearest suitable runway [97]. In case of Boeing 737 currently the FAA allows for up to 180 minutes ETOPS, whereas for longer haul Boeing 777 the ETOPS is up to 330 minutes. Older aircraft types may also require ETOPS pre-departure service check (PDSC) which is a check that is carried out immediately before aircraft dispatch [98]. In such case a retrofitted IVHM System could be used for pre-flight test to satisfy PDSC requirements.

CONOPS and top-level mission requirements are described in [99] as a result of iterative evaluation of the level of vehicle mission autonomy. In the reverse case, where CONOPS is given, the appropriate level of vehicle autonomy has to be achieved to fulfil a given mission requirements in CONOPS. This, therefore, cascade down to the level of autonomy directly related to the IVHM System.

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[2] ETOPS [97]: An airplane flight operation during which a portion of the flight is conducted beyond 60 minutes from an adequate airport for turbine-engine-powered airplanes with two engines and beyond 180 minutes for turbine-engine-powered passenger-carrying airplanes with more than two engines. This distance is determined using an approved one-engine inoperative cruise speed under standard atmospheric conditions in still air.

Key features of vehicle CONOPS: concluding remarks

CONOPS provides the outlook on the expected vehicle operation modes and operational scenarios. The vehicle / fleet operational requirements are strongly influenced by the given CONOPS. In this work it is acknowledged that it is of a great importance to incorporate CONOPS into the process of IVHM System design and development.

The set of requirements derived from the vehicle / fleet CONOPS, in terms of IVHM System, may become an important driver towards IVHM System partitioning; especially in relation to the level of vehicle autonomy and vehicle / fleet readiness, as indicated above.

3.2.5 Key features of the chain customers - outputs of IVHM System

In this work the main outputs of IVHM System are as considered to be diagnostics and prognostics (D/P). This corresponds to health assessment (HA) and prognosis assessment (PA) in OSA–CBM stack as discussed earlier in Chapter 2 and in Section 3.2.3. It is vital to understand how these outputs are used in the context of vehicle operation and fleet-wide view. Fist the main stakeholders of IVHM System are defined followed by analysis of the direct customers of D/P outputs. In [75], in order to define stakeholders objectives, three-level classifications of IVHM users have been proposed, as shown in Figure 3.7. Users related to the first category, i.e. operation, are further analysed in this work. More comprehensive outlook on the stakeholders of IVHM System has been suggested in [100]. The following groups of IVHM stakeholders are given therein:

- Pilots
- Operators
- Technicians
- Other aircrafts (fleet)
- Systems engineers

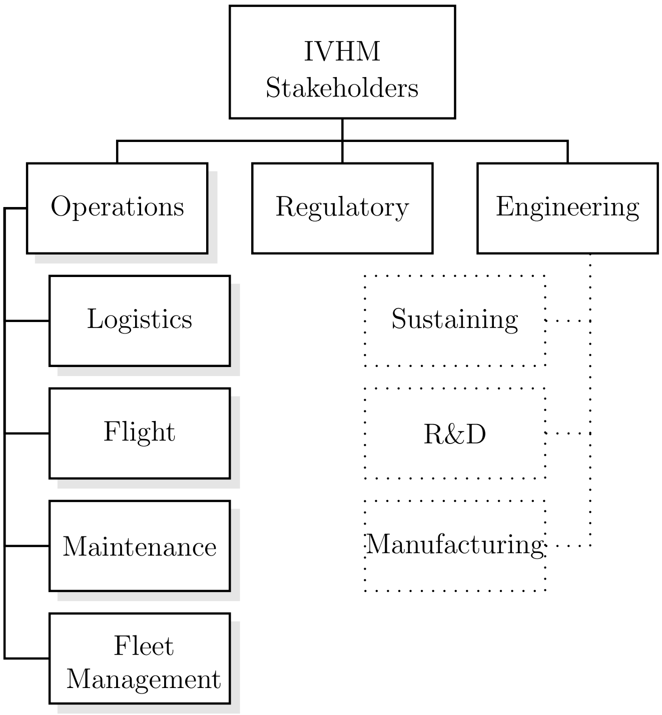

Figure 3.7: IVHM stakeholders, [75].

- Logistics
- Maintenance
- Legislators
- Vendors / OEM
- General public
- Finance / business managers

These stakeholders can be further grouped into three top-level categories, as suggested in [101], i.e.: IVHM System developer, Operator and Maintainer.

The analysis of IVHM stakeholders found in the literature are not specifically oriented on partitioning of IVHM, but are more related to general question of IVHM System implementation. Nevertheless the gathered information have been used in this project as a starting point it the process of defining main customers of IVHM System from the partitioning viewpoint, and describing the relationship and main objectives of D/P outputs customers. In this work we propose five main customers of IVHM System in terms of D/P outputs:

Logistics, Crew, Maintenance, Fleet Management and Automated Systems. Description of each group of IVHM customers, followed by mapping of D/P outputs to each customer is given bellow.

Logistics (L) This group spans over the entire logistics systems, including processes and the required resources. Logistics is related to acquisition and movement of resources required to sustain vehicle operation. The main objective is to ensure fast, reliable and low-cost execution of the logistics tasks.

Table 3.2: IVHM System customers: Logistics.

	Function	Diagnostics	Prognostics
Logistics	Reduce repair turn-around time	✓	✓
	Increase availability/decrease unscheduled maintenance	✓	✓
	Reduce periodic inspections	✓	✓
	Predict remaining useful life of components, maximize component Life usage and tracking	✓	✓
	Predict remaining useful life of expendables (e.g. oil, filter)		✓

The IVHM functions shown in Table 3.2 can be summarises as the actions towards increased vehicle / fleet readiness and reduced turn-around time.

Crew (C) Crew is not only limited to pilots and other on-board members of vehicle operation team. It also includes the remote pilots in case of UAV and all the individuals who directly benefit from IVHM System outputs in order to ensure mission success.

IVHM functions related to Crew, as it is shown in Table 3.3, are focused on

Table 3.3: IVHM System customers: Crew.

	Function	Diagnostics	Prognostics
Crew	Minimize cockpit false alarm rate	✓	✓
	Maximize time from first alert to failure.	✓	
	Enhance safety	✓	✓

providing on-time reliable and unambiguous information required to ensure mission execution.

Maintenance (M) Maintenance is defined as personnel responsible for repairing and servicing the vehicle.

Table 3.4: IVHM System customers: Maintenance.

	Function	Diagnostics	Prognostics
Maintenance	Reduce failures	✓	✓
	Reduce maintenance look-up time	✓	✓
	Identify fault location	✓	
	Reduce health management system maintenance	✓	✓
	Maximize fault coverage	✓	

The main IVHM functions in case of Maintenance, as captured in Table 3.4, are to ensure effective and efficient repair and maintenance actions. It is focused not only on the on-board but also off-board / off-line processes, such as the reduced maintenance look-up time. To reduce the maintenance burden the early diagnostics and real-time response capabilities of the IVHM System are required. The relationship between Maintenance and IVHM System has been discussed in-depth in Section 3.2.1.

Fleet Management (FM) The Fleet management are the IVHM System customers who are involved in the fleet-wide decision making, including operation, life-ing and future operation planning. FM aims to fully utilise the available capabilities by decreasing the downtime (e.g. unscheduled maintenance) and increasing the vehicle operational time and availability. Fleet readiness is a key objective of FM.

Table 3.5: IVHM System customers: Fleet Management.

	Function	Diagnostics	Prognostics
Fleet Mgmt	Life extension - in service beyond expected service life	✓	✓
	Decrease unscheduled maintenance	✓	✓
	Vehicle targeted CBM	✓	✓
	Increase availability	✓	✓

FM utilises outputs of IVHM System to make the inform decisions (see Table 3.5).

Automated Systems (AS) The last group of IVHM customers are so called Automated Systems (AS). These are the systems that can automatically act on the IVHM outputs and, in most cases, are related to real-time continuous health assessment and vehicle / mission support, as it is shown in Table 3.6.

The outputs of IVHM System, as defined in the OSA–CBM, are: HA health assessment (diagnostics), PA prognostics assessment, and AG advisory generation. In Table X the defined customers of IVHM system are mapped into

Table 3.6: IVHM System customers: Automated Systems.

	Function	Diagnostics	Prognostics
A / S	Continuous health assessment of an asset	✓	
	Support to Logistics, Crew, Maintenance and Fleet Management actions	✓	

OSA–CBM defined IVHM outputs. The AG is mostly related to higher–level decision making and, as such, is not in the main focus of this work. However, in order to cover all OSA–CBM defined IVHM System outputs, AG is shown in Table 3.7 along with HA and PA where the relation between outputs and customers of IVHM System is shown.

Table 3.7: Relation between IVHM System customers and OSA-CBM defined outputs.

IVHM Output:	HA	PA	AG
IVHM Customers:	AS, L, C, M, FM	L, C, M, FM	L, C, M, FM

Key features of the chain: IVHM System outputs customers: concluding remarks

It the analysis of the relation between IVHM System outputs and the IVHM System customers the key observation is that the same information provided by IVHM System is used to make informed decisions on different levels of the vehicle / fleet operation hierarchy from automated systems up to fleet management.

Across the whole spectrum of IVHM customers the accuracy and time of the P/D outputs provision are of the highest importance. The real-time response and the early diagnostics emerged as key attributes of IVHM System required to satisfy customers objectives. Also there is a clear need for advanced IVHM solutions which includes prognostic capabilities.

IVHM System is also required to provide on-board warnings to the vehicle crew to improve mission reliability and ensure mission success.

On-board automated systems use results of health assessment of an asset whereas the remaining customers use the outputs of health assessment, prognostics and advisory generation.

3.3 The Main drivers for IVHM System partitioning

The described key features of different aspects to IVHM Systems lead finally to formulation of the main drivers for on-board / off-board partitioning of IVHM System. The proposed main drivers for partitioning are:

1. Vehicle autonomy,
2. Fleet readiness,
3. Real-time Response,
4. Effectiveness of Diagnostics and Prognostics,
5. Early Diagnostics,
6. Severity of Failure Consequences.

The proposed drivers can be classified into two categories: business and technology oriented. The first category consists of vehicle autonomy, fleet readiness and severity of failure consequences. The real-time IVHM system response, effectiveness of diagnostics and prognostics and early diagnostics/prognostics falls into the second category of the main drivers.

The main difference between these two categories is the impact of the drivers on vehicle and its operation. This section provides the detailed description of proposed main drivers.

3.3.1 Vehicle autonomy

The generic IVHM Systems can be described using the following sequence: sense, acquire, transfer, analyse and act on a vehicle health data. Vehicle autonomy, in frames of IVHM System, is defined as vehicle's ability to autonomously perform IVHM actions to ensure safe and seamless operation and, the foremost, to enable the completion of the vehicle mission.

In this work the vehicle (IVHM) autonomy is not limited to the class of vehicles designed to operate autonomously, e.g. unmanned autonomous vehicle (UAV) or autonomous underwater vehicle (AUV). It is also applicable to the class of vehicles that are controlled by human; however decisions regarding the vehicle operation and health condition (e.g. mission planning, maintenance scheduling, etc.) are made autonomously.

Vehicle autonomy demands IVHM System partitioning because on- / off-board communication system (in this case data transfer) does not exist.

On-board health management capabilities, including data gathering within systems / sub-systems and D/P functions are designed to enable vehicle's autonomy. In [102] further discussion can be found. The provision of autonomous IVHM Systems which can isolate faults and reconfigure in the event of faults or failure influences vehicle mission abilities: it allows mission continuation and prevents (or mitigates) the effects of mission abort / cancellation.

The need for vehicle autonomy is widely discussed in the literature. In [44] an example of a future human mission to the Mars is given. Autonomous operations are assumed to be the fundamental capabilities that directly affect size and safety of both crew and vehicle. Level of autonomy can be defined by vehicle intelligence functions, including D/P functions, which allows small crew to operate and maintain complex vehicle. In autonomous vehicles an on-board system that is capable to diagnose, isolate or predict faults in the event of communication failure or lack of sufficient communication, allows the continuation or prevents the loss of a mission and/or vehicle. Taking this into account, the vehicle autonomy is a key driver for IVHM system partitioning.

The described main scenario shows that vehicle autonomy is an important driver for IVHM System partitioning. It can significantly influence the decision on partitioning, especially in the case of critical data-communication requirements. The communication latency to Mars is about 15 minutes one way, therefore, a sufficient level of autonomy (including via on-board IVHM System) is a key consideration to maintain crew safety and provide mission support.

Another example where vehicle autonomy is imposed by no communication with off-board system is a nuclear submarine (see [17]). A submarine operates without communication with outside world for a long duration of underwater operations to prevent enemy detection. The level of autonomy of nuclear submarine has to be sufficient to assure crew safety and mission success.

Data telemetry is also recognised by NASA as a potential inhibitor in the future airspace missions, especially in case of UAVs [103]. The typical constrains and driving requirements for NASA vehicle and mission autonomy when a limited contact with the Ground station is expected are shown in Table 3.8.

Table 3.8: Operation with limited Ground contact. NASA vehicle and mission autonomy: Constraints and requirements [104].

Operation description	Requirements
Extended periods with no planned contact	1 to 4 weeks
Planned contact periods may be short	1 to 2 hours
Ground may not show for planned contacts	5% to 10%
Large one-way light times	minutes to hours
Low downlink data rates	10 to 40 bps

The long-time autonomous operation as well as a limited telemetry can be observed within the core operational scenario in Table 3.8. The Increased autonomy, on-board data storage and enhanced data compression may significantly reduce the communication bandwidth requirements. The inclusion of advance on-board sensors, D / P capabilities and adaptive controls allows elevating the vehicle level of autonomy (LOA). The main benefits of the increased vehicle autonomy are leading to, according to [103], lower operating costs and increase rate of successful missions.

3.3.2 Fleet readiness

Fleet readiness is widely discussed in the literature as one of the key objectives for IVHM System implementation (see e.g. [22, 26, 79, 105]). An aircraft and fleet dispatch reliability, also termed as operational reliability, is a vital part of the overall fleet readiness. It is measured as the percentage of scheduled flights which depart within 15 minutes, without technical delay or cancellation. According to [106] the cost due to delays and cancellations reaches about 2% of the total airline revenue, thus it is an important driver for IVHM System. In this work, fleet readiness has been studied from the partitioning of IVHM System viewpoint. The result of this view is that the partitioned IVHM Systems enables improvement of fleet and vehicle readiness. This is demonstrated using the example of a vehicle operation scenario in which fault forwarding plays a key role in fleet readiness. Let assume that a vehicle on-board D/P system detected and diagnosed a fault. The output of D/P on-board system is capable to define exactly the Line Replaceable Units (LRU) in which a fault occurred. The fault forwarding system transfers the diagnostics information to the off-board system. This information is then use to allocate maintenance resources (e.g. spares, maintenance team, facilities) and schedule a repair / replacement prior to the aircraft landing. Similar scenario has been discussed in [22] as a justification for an aircraft IVHM System implementation. It is therefore assumed here that the pre-maintenance tasks (e.g. fault isolation, part preparation, etc.) triggered by on-board D/P system as a part of partitioned IVHM System plays a major role in fleet and vehicle readiness improvement.

In the case study presented in [79], a fleet of aircraft with on-board IVHM system diagnosis and fault forwarding capabilities (in-flight data communication) is studied. Different operational scenarios were simulated, including one in which the on-board system has been used to broadcast fault reports to the ground system during the flight. It is shown that such configuration significantly improved the fleet readiness by minimising overall maintenance time (see Figure 3.3). Further examples where fleet readiness and aircraft turn-around-time (TAT) are improved via on-board IVHM D/P functions were discussed in literature review in Chapter 2.

Table 3.9 introduces set of possible scenarios of IVHM implementation in respect to the improvements of fleet readiness. Two data communication schemes are shown: in-flight and at-the-gate (ATG). Two schemes for data-processing / diagnostics / prognostics are also considered: on-board and off-board.

In Figure 3.8 the graphical representation of different IVHM System configuration and its influence on fleet readiness improvement is introduced.

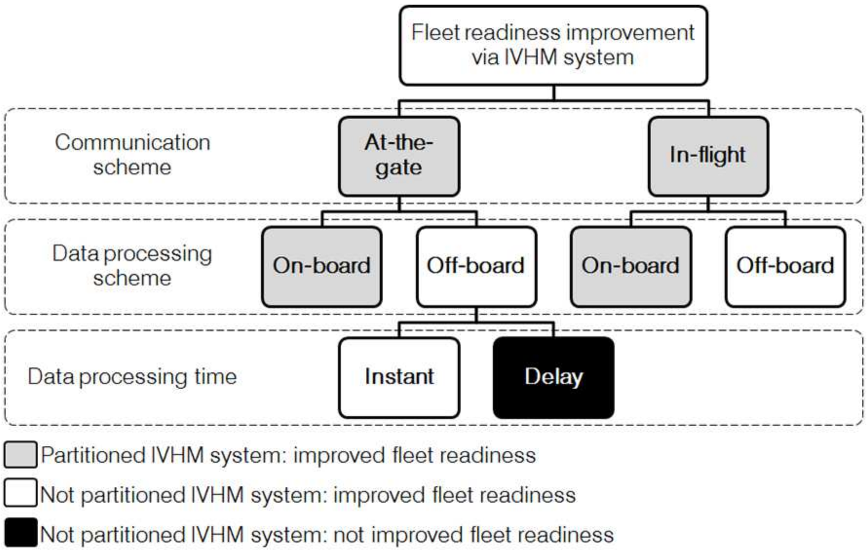

Figure 3.8: Improvement of fleet readiness via partitioning of IVHM System.

The above considerations can be concluded as following: the IVHM System

Table 3.9: Improvement of fleet readiness (DP - Diagnostics/Prognostics).

D/P	Comm.	Description	Partitioning of IVHM system	Improvement of fleet readiness
On-board	ATG	If data processing/ diagnostics/ prognostics take place on-board and diagnostic/ prognostic decisions are downloaded at-the-gate, an improvement of fleet readiness is achieved	Yes	Yes
Off-board	ATG	If raw/pre-processed data are downloaded at-the-gate in order to be processed off-board, then a fleet readiness improvement is only achieved if there is no delay in off-board diagnostic/prognostic results. In real life it is impossible to avoid delays; so, in the considered case a fleet readiness improvement normally is not achieved	No	No
On-board	In-flight	If diagnostics/prognostics take place on-board and the resulting decisions are communicated during flight, an improvement of fleet readiness is achieved	Yes	Yes
Off-board	In-flight	If the raw/pre-processed data are downloaded using in-flight communication to be processed on-ground, an improvement of fleet readiness is achieved	No	Yes

with on-board diagnostics and fault forwarding capabilities (i.e. partitioned IVHM System) allows in-flight maintenance triggering, and as a result, it minimises turn-around-time (TAT) and increases vehicle availability, thus improves the fleet readiness.

In Figure 3.9 it is shown how an early warning (fault forwarding) generated by on-board system helps the ground crew (off-board part) to prepare for the unscheduled maintenance / repair hence minimising the TAT (see also [42] for further references). A three scenarios are depicted in Figure 3.9

- Todays aircraft: the diagnosis and maintenance work are done after the aircraft landed.
- Next generation: the implementation of IVHM systems leads to in-flight diagnostics and allows ground-based support to prepare maintenance and (if needed) repair activities. This can improve the TAT and fleet readiness.
- Future platforms: Future platform are envisaged to perform diagnostics and prognostics in-flight, which in result will eliminate unscheduled maintenance and enhance the planning of maintenance / repair activities.

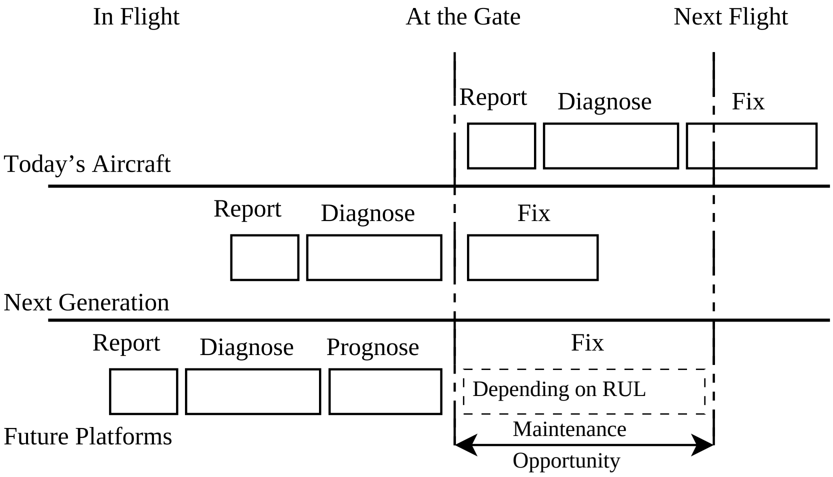

Figure 3.9: The effect of maintenance opportunities on turn-around-time: a generic approach [42].

It is, however, not specified by authors in [42], what exactly the "next" and "future" generation platforms are. The term "next generation" platform is often referred to a vehicle capable to on-board diagnostics and prognostics (e.g. [52, 107]).

3.3.3 Real-time IVHM response

The real-time response of IVHM System often referred as near real-time response, is widely discussed in the literature. According to the state of the art, the real-time capabilities of an IVHM System are highly demanded especially in safety / flight critical systems with high-speed mechanical components (e.g. turbines or pumps) where diagnostics systems, in order to provide the best performance, has to work at very high data sampling rates and in case of fault or failure incident it has to react instantaneously. It has been shown, based on analysis of real systems and simulation / theoretical examples, that in order to understand causes and to detect precursors to system failures, a continuous monitoring and real-time diagnostics are essential (see e.g. [1, 34, 48]). Further discussion on the real-time response of IVHM System is given in the literature review Chapter 2.

In this work the performed analysis of key features of faults (see Section 3.2.2 for details) resulted in numerous conclusions, among which some are related to real-time diagnostics system response to certain groups of faults and failures. It is believed that (near) real-time[3] response should be provided by IVHM system in respect to the P-F interval. The P-F interval is defined as the time period between a potential failure (P) and a functional failure (F), as described following by the graphical representation of P-F interval (Figure 3.5, p. 66) in Section 3.2.2.

A concept of two types of IVHM System responses, classified as very short-time and a long-time response is given in [48]. These types of response are described as:

---

[3] The term *near real-time* or (NRT) refers to the time delay due to e.g. automated data processing or data transmission, between the occurrence of an event and the use of the processed data. In most cases the name "real-time" is used.

- Very short-time response is associated with threats (faults / failures) that potentially lead to catastrophic events. The response must be as quick as possible (i.e. real-time) and occur automatically.
- Long-time response is when relatively long time is available before any serious consequences will occur, therefore a real-time performance is not required.

In essence, the first group addresses faults with relatively short P-F interval, and the second group deals with faults with relatively long P-F interval. Combination of two types of responses is also possible.

Real-time response is regarded in this work as an important driver in decision making process on the IVHM System partitioning. The real-time (or near real-time) IVHM System response should be provided when components with a relatively short P-F interval (e.g. potential failure propagates to functional failure during single operation) are considered. Continuous monitoring, real-time diagnostics/prognostics capabilities are redundant if the P-F interval is relatively long (e.g. longer than duration of single operation/ maintenance check).

3.3.4 Effectiveness of diagnostics and prognostics

Effectiveness of diagnostics and prognostics (D/P) depends on variety of factors / parameters, including quality and quantity of available data, complexity and sophistication of algorithms, time constrains, etc. The effectiveness of D/P is also influenced by features of faults the system is design to deal with.

To measure the effectiveness of diagnostics and prognostics functions a performance assessment is required (see e.g. [108, 109, 110]). The evaluation of effectiveness (e.g. accuracy, robustness) of a particular D/P function is more precise when each D/P function is assessed separately [109]. It is important to note, though, that each of D/P functionality (algorithm) directly contribute to the effectiveness of the overall IVHM System.

In this work the modified Performance Metrics, initially proposed in [111], as it is shown in Figure 3.10 is proposed. The performance of diagnostic system measured using three main quantities: the probability of diagnosis (proportion of faults that are identified correctly), rate of false positive (proportion of non-fault conditions diagnosed as faulty), and repeatability (robustness) of the diagnosis. The extended view on diagnostics system effectiveness metrics is discussed in detail in [111, 108, 109]. The prognostic system performance assessment uses the following three metrics: probability of correct prediction (proportion of correctly predicted time of failure), predicted condition (measured in terms of how close the predicted failure time is to the actual failure), and RUL estimation precision. Further details can be found in [111, 110].

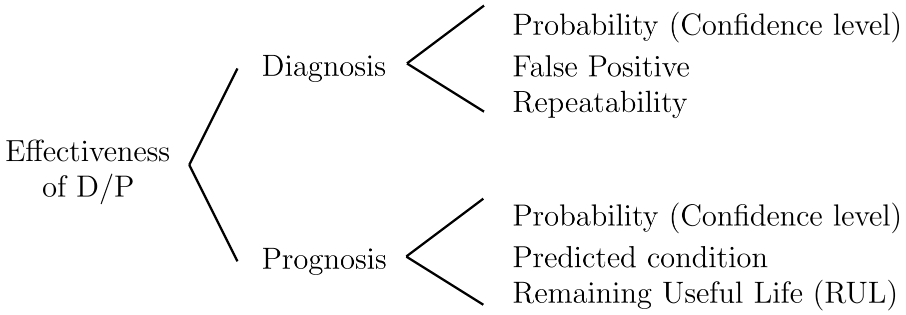

Figure 3.10: Effectiveness of D/P: performance measure.

In most cases, the on-board data analysis system acts on long duration data rich in information, thus increasing effectiveness of on-board D/P. On-board diagnostic system is, therefore, perceived in this work as being capable to provide continuous health monitoring with minimal time delay and relatively high effectiveness of D/P. This requires sufficient on-board computing resources. Off-board system may provide the same level of D/P effectiveness if the vehicle sensor data is downlinked to the ground station during the vehicle operation (in-flight) seamlessly with no time-delays. In many real-world applications, due to limited telemetry, only a snapshot data is sent to the ground support centre (e.g. EHM system described in [46]) that in result constrain the off-board D/P performance.

If the same quantity and quality of data are available on-board and off-board, as shown in Figure 3.11 a) and b), partitioning of IVHM system will not improve the effectiveness of diagnostics and prognostics, moreover, additional effort will be required to implement the on-board systems. In the situation where a vast amount of data is available on-board, but only the data snapshots are available on the ground (e.g. due to telemetry constrains), as shown in Figure 3.11 c), the partitioning of IVHM System (i.e. diagnostic/prognostic action to be taken on-board) will improve the effectiveness of both diagnostics and prognostics.

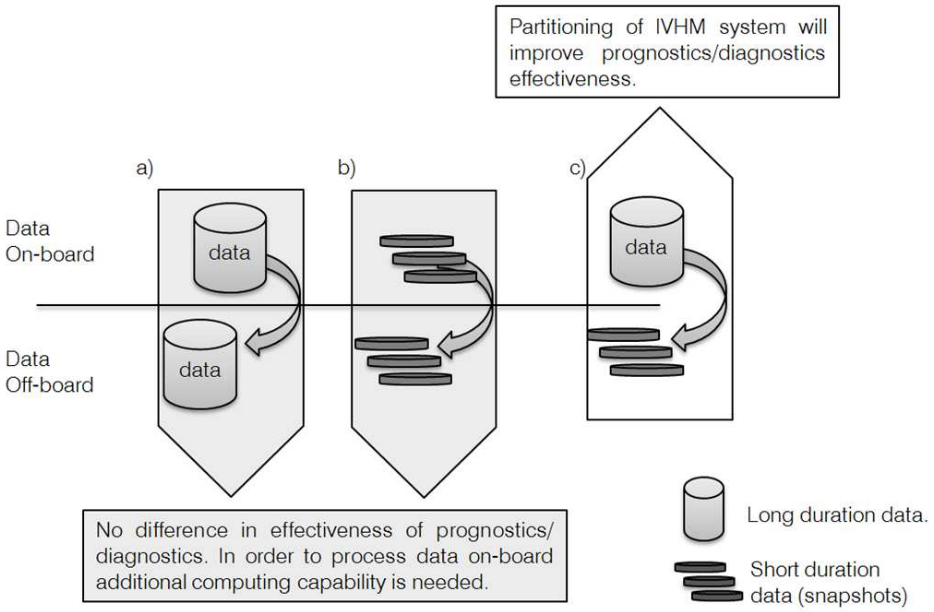

Figure 3.11: Influence of on-board / off-board IVHM System partitioning on the effectiveness of diagnostics and prognostics.

The effectiveness of D/P depends on types of faults and certain features of fault, as shown below, influence the performance of D/P functions.

Types of fault: Systematic faults are more likely to be incorporated in the maintenance procedures; however random faults, less predictable, can significantly interrupt a system/ subsystem operation. Faults which exhibit certain behaviour (e.g. random - unpredicted) should be taken into account for IVHM partitioning. Also systems which may develop hidden fault, or the probability of fault masking by the system is high, should be considered.

Time behaviour: Intermittent / transient fault that are often difficult to recreate in the maintenance environment, resulting in high percentage of no fault found (NFF) should be considered. The on-line, (near) real-time fault diagnosis method is desired when dealing with such faults.

Extent: Global or local extent of a fault can significantly influence the decision on the implementation (partitioning) of diagnostic system. This feature should be also taken into account combined with the criticality of fault (definition of global and local fault is given in Section 3.2.2).

Criticality/importance of fault: Major faults and critical faults are the most important from both, economical and safety view point. Criticality and importance (major/ minor) are the most important features of fault due to the potential consequences of such faults.

Detectability of fault: This feature strongly depends on available technology (fault diagnostics, prognostics) and knowledge of fault mechanisms. This feature should be always considered as the most varying feature, yet important for the IVHM partitioning.

The required level of D/P effectiveness can significantly influence on/off-board partitioning. This includes, but is not limited to on-board computer capabilities, air-to-ground (ATG) communication capabilities, off-board data processing capabilities and data-transfer infrastructure.

3.3.5 Early diagnostics and prognostics

On-board early D/P becomes a driver for IVHM System partitioning when the time between detection of fault and functional failure needs to extend. It translates to extending the net P-F interval (see Figure 3.5 for reference). The main assumption for extending the net P-F interval is to allow mitigation action, to reduce secondary damage and to avoid hazardous situation, including loss of an asset. The graphical representation of early D/P is shown in Figure 3.12. Early diagnostics is related to net P-F interval, but mostly related to overall P-F interval.

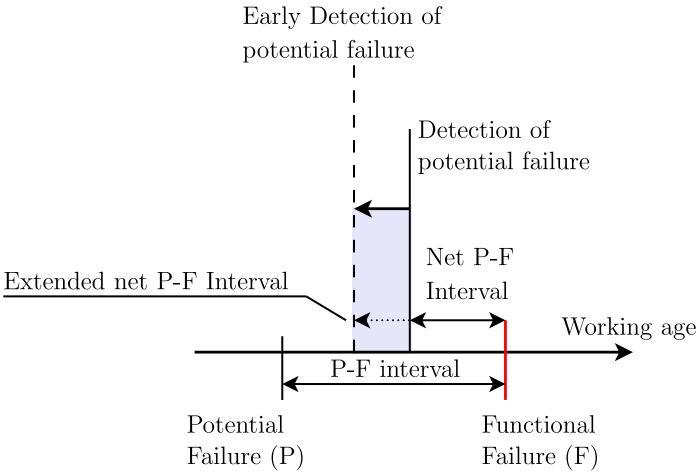

Figure 3.12: Early D/P: Extended net P-F interval.

The early D/P depends mainly on the capability of employed diagnostic technologies and available duration of raw data. The assumption here is that the raw sensor data is not compressed and, therefore, rich in information. In most cases diagnostic technologies of high capabilities are complex and, therefore, require relatively high computational capabilities. In case of limited on-board computing capabilities the implementation of complex diagnostic algorithms (technologies) may be prohibitive. Intuitively, if the on-board computational capabilities are limited, a potential solution to provide early D/P would be to process the data off-board. Since long duration of raw data is normally available on-board this would require a sufficient data communication system, which in real systems turns to be often limited.

Timely access to a long duration raw data has been already discussed in Section 3.3.4 (see Figure 3.10).

Taking the above into consideration, early D/P can be provided on-board or off-board depending on available raw data duration and/or on-board computing resources.

3.3.6 Severity of failure consequences

The severity of failure consequences (similarly as in the Failure Modes and Effects Analysis - FMEA) can be ranked from “no effect” to “critical”, as it is shown in Table B.3. In this work, however, the severity of failure consequences is related to the mission and operation, rather than to vehicle safety : IVHM System, as defined previously, is not directly related to safety-critical systems. The IVHM System, as it is discussed in this work, does not directly influence the vehicle safety-critical systems (e.g. control). Its main aim is to ensure an efficient and optimal vehicle and fleet operation (life-cycle). The rationale behind this driver can be expressed as follows: if the failure is not safety critical, however its consequences are severe (e.g. high costs, losses, etc.) and in order to avoid / mitigate such failure consequences a partitioned IVHM System has to be implement, then the severity of failure consequence becomes an important parameter in the optimisation of IVHM partitioning.

The severity of failure consequences driver is therefore related to mission (e.g. loss of mission) and operational / non-operational consequences (e.g. increased / additional maintenance costs).

Failure modes that cause operational consequences are described in [112] as “modes that might reduce the operating capability of the aircraft to meet the intended functionality and performance requirements”. The effect is an interruption to the planned flight operations and the completion of the planned mission. Operational interruption is defined here as an event which affects the aircraft mission execution and completion. In case of civil airline the operational consequences are usually expressed as inability to dispatch flights on time. Such events may lead to disruption of aircraft scheduled operation (e.g. delays, cancellation, etc.) and may result in additional costs [113].

Consequences of faults and failures can impact on-ground and in-the-air aircraft operation. Examples of ground impact include delays related to flight dispatch, back-to-gate (on-ground turn-back), aborted take-off, and cancellation of flight. Examples of in-air impact may be in-flight turn-back, diversion, go-around, and re-routing.

Both, on-ground and in-air consequences cause financial losses, mostly due to the additional / unexpected costs related to aircraft crew (e.g. re-location, substitution), airport crew and facilities (e.g. fees and penalties), passengers (e.g. re-routing, hotels and meals, refund), and vehicle itself (extra fuel, depreciation, unplanned maintenance, etc.).

The non-operational consequences of fault are mostly related to the direct cost of repair, including cost of labour, spare parts, maintenance and repair facility, and all other cost incurred as the direct result of repairing the vehicle [87, 114]. These consequences are less important from the partitioning of IVHM System viewpoint, especially when compared with the operational consequences, yet the cost of non-operational consequences of faults is used when alternative system configuration are compared.

The type and severity of fault and failure consequences discussed in [113] are shown in Figure 3.13. The higher the severity of consequences the shorter the system response is required. This can be directly adopted when IVHM System partitioning is analysed: higher the severities of fault consequence the lower the time-response of IVHM System should be ensured. The severity of failure consequences, therefore, plays an important role in overall life-cycle cost of an aircraft and its impact should be taken into account in the analysis of IVHM System partitioning.

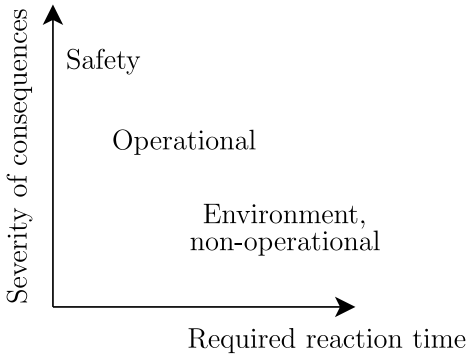

Figure 3.13: The severity of fault and failure effects, [113].

3.4 Summary and Concluding Remarks

In this Chapter the novel drivers for IVHM System partitioning have been defined for the first time in world-wide terms, namely vehicle autonomy, fleet readiness, real-time diagnostics and prognostics systems response, effectiveness of diagnostics and prognostics, early diagnostics and prognostics, and severity of failure consequences.

The described main drivers are based on analysis of vehicle operational and non-operational features, including but not limited to key features of maintenance, potential faults and failures, and IVHM System architecture. Links between key features of an IVHM System and the defined main drivers for partitioning have been defined and described in detail.

The defined main drivers are aimed to fill the gap in knowledge which has been recognised upon the literature review on IVHM System and related to IVHM subjects.

Chapter 4

Optimisation Criterion for Partitioning of IVHM System

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In this section the novel optimisation

4.1 Introduction

In this work, the optimisation of IVHM System partitioning is essentially a method of allocating the IVHM diagnostics and prognostics (D/P) functions to either on-board or off-board system. The ultimate goal is to achieve the best possible system configuration in terms of effectiveness, which satisfies a given requirements. The great challenge is to define measures of effectiveness and efficacy of the resulting system configuration. Despite the fact that the discussed problem has been limited to D/P outputs of IVHM System, an on-board / off-board partitioning is a multi-dimensional problem in which optimisation parameters and constrains varies greatly from design attributes (e.g. size, weight, etc.), through technology insertion, certification and D/P performance levels, up to operational and business related factors (e.g. availability, mission planning, logistics, etc.). We propose that a common parameter allowing different system configurations to be compared is the cost associated with each system configuration. The developed novel optimisation criterion for optimal IVHM System partitioning provides a cost trade-off analysis of the alternative system configurations. Cost analysis trade-off had been adopted as a starting point in the process of defining costs of the partitioning of IVHM System.

In general the cost analysis estimates money value of the costs and gains of projects in order to establish whether they are profitable and beneficial to the stakeholders [115, 116, 117].

In this Chapter the cost trade-off technique is used as a building block for the optimisation criterion. Analysis of costs and the related gains is, according to [67, 29], a key to prove and demonstrate the value of IVHM technology to aircraft OEM stakeholder and operators.

This work delivers a novel aspect to IVHM System cost trade-off analysis by addressing the optimal on-board / off-board partitioning of IVHM System.

In this Chapter a set of cost factors related to IVHM System partitioning had been defined. Later the defined factors are used in the proposed novel optimisation criterion.

4.2 Main Cost Factors in Partitioning of IVHM System

Partitioning of IVHM System D/P outputs, i.e. allocating D/P to either off-board or on-board/off-board (partitioned) system, introduces some additional costs and, at the same time, enables to save and/or avoid some costs, as well as delivers measurable gains when compared to the baseline system architecture. Costs and gains can be expressed in terms of monetary values. The challenge is to define and quantify relevant cost factors. In [29] a level of difficulty and lack of dedicated tools to address cost trade-off for PHM / IVHM is highlighted. In many available literature sources it is also stressed that the complexity of such task highly depends on the platform / vehicle system and its desired CONOPS. In this Section the relevant cost factors to IVHM System partitioning are defined. These cost factors had been grouped into two main categories: Cost and Gains.

4.2.1 Costs

This category consists of all the costs (investments) required to deliver a given D/P IVHM system. In this work the main focus is on partitioning of IVHM system, therefore, our novel proposition is to consider two main types of costs related to IVHM partitioning: the basic costs and the additional costs. Both are case-dependant, i.e. depends on type of vehicle / platform, CONOPS, etc. In order to address a broad spectrum of cases, a generic description of each cost category is given here.

Basic Costs

Basic costs, C_B, are essentially the development, testing, and integration costs of the baseline system configuration. In this work the baseline system configuration is defined as the IVHM System in which D/P functions are implemented off-board, and only minimal on-board functionalities, such as sensors, data acquisition, data storage and data communication are implemented on-board in order to provide off-board D/P with the required data. The following list of basic cost elements, based on e.g.[118, 10] is a generic set of potential costs applied to IVHM System.

1. Development cost:
    - Hardware / software: design, development, testing and certification,
    - Cost of integration with existing systems, installation costs.

This includes hardware / software to collect data, to transfer data between on-board / off-board and to off-board process the captured health data.

Cost of development and implementation can be further categorised as non-recurring and recurring cost [118, 119]. Non-recurring costs are the costs of one-time-only activities. Development of hardware and software are good examples of non-recurring costs. Recurring costs are mostly associated with activities that occurs number of times during the life of IVHM System, e.g. integration and installation.

2. Cost of IVHM infrastructure (creating, maintaining):
    - Data archiving,
    - Maintaining the PHM structures (logistics footprint),
    - Training personnel,
    - Creating and maintaining documentation.

Infrastructure costs are associated with creating and maintaining necessary infrastructure and its on-going operation and support throughout the entire life of IVHM System.

1. Cost of IVHM operations:
    - Cost of data collection, cost of data analysis cost of data transfer from the ground to a vehicle.

Cost of IVHM System operations is mostly related to the cost of providing diagnostics and prognostics outputs from the gathered and processed data.

1. Financial costs:
    - Present value (see Eq. 4.1).

The financial cost, in other words the cost of money, means that one dollar today may not be worth one dollar in the future. Money available in the present could be invested and generate revenue, but if spent today cannot [120, 118]. Therefore, if IVHM system is planned to operate over number of years then cost of maintenance and operation of IVHM system may be substantial. A way to obtain the cost of money due to is to estimate its present value as:

$$Present\ value = \frac{V_n}{(1+r)^{n_t}}. \tag{4.1}$$

where V_n is the value of investment when it is made, n_t is time unit (e.g. year), and r denotes the interest rate per time unit (e.g. annual discount rate).

Baseline system is already partitioned: i.e. except the usual off-board components / infrastructure it also contains the minimum set of on-board components (e.g. sensors, data acquisition, data storage, communication systems, etc.) required for baseline system to fully function. This set is highly depends on the platform and its configuration. The cost of minimum set of on-board components is included in the basic cost of IVHM System.

The total cost of baseline system configuration is calculated as the sum of all related basic costs.

Additional Costs

Additional costs of IVHM System partitioning, C_A, are formed by all the costs related to further partitioning (moving some D/P functions from off-board to on-board system) of baseline system. Essentially, these are all the costs of partitioned system that goes beyond the C_B, i.e. cost of the baseline system architecture. Some examples of additional costs are listed here: costs of additional communication system, additional power wiring, additional weight introduced by added on-board hardware, cost of creating and maintaining the infrastructure for partitioned IVHM System, etc. Another example is related to movement of an existing D/P system from off-board to on-board system. On-board systems are usually implemented as embedded systems, whereas off-board are mostly PC-based applications, therefore an additional cost of transferring algorithms from PC to embedded systems is present. An on-board systems requires higher level of certification than off-board system (see e.g. [41, 71]), therefore in this example the cost of certification should be also included in CA. In some literature (e.g. [71]) the additional costs associated with product manufacturing are also highlighted, including recurring cost per product for additional hardware, additional processing, and additional recurring functional testing.

The financial costs also apply to the group of additional costs. Similarly as in the basic costs, the annual discount rate should be calculated and accounted.

Finally, the total value of additional costs is calculated as the sum of all related costs, as described above.

4.2.2 Gains

Gains are understood in this work as the value derived from partitioning of IVHM System. It can be accounted as a saving on the costs or avoidance of certain costs due to partitioning of IVHM System (see e.g. [121, 122]). The cost savings exists when a partitioned system can provide better performance (i.e. in terms of drivers / cost associated with drivers) compared to the baseline system configuration. An example is the reduced cost of a regular inspection due to on-board on-line D/P [123]. Other common example of gained cost given in the literature is gain due to changes in off-board part and less data communication due to partitioning (i.e. on-board data processing) [34, 21]. Each of the cost components is described in details below.

Saved Costs

Cost saving can be seen in lower costs directly related to IVHM System operation, e.g.: data communication, infrastructure. The baseline IVHM System configuration (all functionalities off-board) requires considerable amount of data to be downlinked (from on-board to off-board system) to perform D/P. In case of partitioned IVHM System, where optimally selected D/P functions are implemented on-board, only information (or decision/ advice) has to be transmitted to off-board system instead of raw (or pre-processes) data. Due to the further partitioning of IVHM System higher costs of communication can be therefore saved with the same level of D/P. Part of the costs related to the off-board system will also be saved due to further partitioning (e.g. hardware, software, etc.) when certain functionalities of IVHM will be moved on-board and, therefore, not present off-board.

The annual discount rate used to represent a financial cost (cost of money) gained due to partitioning should be also estimated for the group of saved costs (see Eq. 4.1).

In this work the Saved Costs are denoted C_S, and the value of C_S is calculated as the sum of all related saved costs due to partitioning.

Gains related to main drivers for partitioning

The main drivers, previously proposed in Chapter 3, are now used here to define total gain, denoted B, which is related to partitioning of IVHM System. For each of the main drivers a sub-group of gains, which is strictly related to a given driver, is defined:

1. Gains due to vehicle autonomy
2. Gains due to fleet readiness
3. Gains due to real-time response
4. Gains due to effectiveness of D/P
5. Gains due to early diagnostics
6. Gains due to minimised failure consequences

It is worth to notice here that effectiveness of D/P (4) depends on available data and data processing capabilities; in some cases the on-board system and in other cases the off-board system may provide better performance. On-board early D/P (5) becomes an important driver when e.g. there is a need to extend P-F interval.

Gains, similarly to the discussed above costs, are quantified and expressed in monetary values. Let b_j be a cost value of gain related to j^{th} main driver and $j = 1, \ldots, 6$, then the total value of B is calculated as:

$$B = \sum_{j=1}^{6} b_j. \tag{4.2}$$

The above described gains related to the main drivers for IVHM System partitioning are further divided into three main groups of gains that are defined as follows:

- Improved Maintenance Planning and Scheduling
- Improved Maintenance Operation
- Improved Mission Effectiveness and Reliability

It is essential to relate the main drivers to the maintenance / operation / mission gain groups. The relation between each gain group and the main drivers for IVHM partitioning is captured in Table 4.1.

The rationale and detailed explanation of the relationship between the main drivers and the gain groups (as shown in Table 4.1) is given below. The description provides a generic approach and, once the platform / vehicle and

Table 4.1: Main drivers for optimal IVHM partitioning vs. the defined gains related to partitioning.

	Main drivers					
	Vehicle autonomy	Fleet readiness	Real-time response	Effectiveness of D/P	Early D/P	Severity of failure cons.
Improved Maintenance Planning and Scheduling		x	x	x	x	
Improved Maintenance Operation		x	x	x	x	
Improved Mission Effectiveness and Reliability	x	x	x	x	x	x

its set of functional and mission requirements are specified, more detailed study can be performed.

Vehicle autonomy Vehicle autonomy, in terms of IVHM System partitioning, is defined as the ability to autonomously perform IVHM actions, i.e. diagnostics / prognostics, to ensure mission success. Autonomous IVHM System can trigger maintenance directly; on-board recommended actions (related to vehicle health) can also be provided to the vehicle crew to maintain the mission. Autonomous IVHM System can automatically monitor a vehicle health and assess it against the required vehicle performance to ensure mission success. The vehicle autonomy is related to Improved Mission Effectiveness.

Fleet readiness Fleet readiness is defined here as the ability of a fleet to performed mission when required. The effectiveness of a mission can strongly depend on the fleet readiness. The fleet readiness is related to the group Improved Mission Effectiveness. Examples of costs / gains due to improved mission readiness are: cost of mission termination, penalties for delay, etc. Fleet readiness is also correlated with optimal maintenance, both planning and utilisation. Thus it is related to the group of gains: Improved Maintenance Scheduling and Improved Maintenance Operation.

Real-time response of D/P In general, real-time system is defined as one that must provide a response to the input data within strict time constrains (deadlines). In this work the real-time response of D/P functions is defined as the ability of IVHM System to produce D/P output (i.e. decisions) immediately (with no time delay) after data capturing.

For certain types of faults with short P-F interval a real-time response is essential to ensure early action (e.g. early mitigation and reconfiguration, etc.) in order to avoid mission termination and secondary faults / failures. Real-time response also has a major impact on avoidance of failures caused by faults with fast damage propagation. It is also to ensure that diagnostics / prognostics data are present for a crew in the right time to take an informed decision and appropriate actions to prevent failure consequences.

Real-time response is related to Improved Maintenance Scheduling, Improved Maintenance Operation and Improved Mission Effectiveness and Reliability.

Effectiveness of D/P Effectiveness of D/P measures the performance of partitioned IVHM System in producing the D/P outputs based on the available data. The diagnostics functions can be assessed in terms of probability of correct identification of system condition (e.g. expressed as confidence level) or probability of false anomaly detection by a diagnostic system (e.g. frequency of false positive). In case fault occurred and it has been detected, the ability to identify the root cause and corrective actions for the detected fault can also be assessed. The prognostics functions can be assessed in terms of probability to correctly forecast the future condition (e.g. expressed as confidence level), such as correct estimation of remaining useful life (RUL).

Example of D/P performance metrics is shown in Figure 3.10 (Section 3.3.4, p. 91) based on [108] and [109].

The major impact of the effectiveness of D/P can be observed in the improvement of maintenance operation and maintenance scheduling. Effective D/P minimises unnecessary maintenance actions (no false positive) and ensures appropriate maintenance action when needed (avoid false negative).

Effective D/P helps to re-plan or re-assess the mission in the event of fault (or failure) of e.g. mission-critical systems.

The effective D/P shortens vehicle maintenance unavailability time. It enables condition-based maintenance and allows opportunistic (e.g. overnight, when vehicle is not in use) maintenance actions to be carried out. Effectiveness of D/P is related to all the listed gain groups.

Early D/P In this work the early D/P is defined as the ability of IVHM System to provide diagnostic and prognostic information early enough to avoid consequences of fault and the resulting failure and provide sufficient time for the system operator / maintainer to react (e.g. to perform preventive and corrective actions). Early D/P, therefore, reduces the possibility of failure.

Early diagnostic and prognostic actions extend the P-F interval (see Fig. 3.12, p. 94) and therefore, lead to improvement of maintenance scheduling and avoidance of component/system failures due to e.g. fast damage propagation.

Gains attributable to the early diagnostics and prognostics are related to the avoidance of functional failure (due to extended P-F interval) and an improvement of time horizon for maintenance scheduling.

Early diagnostics and prognostics are related to Improved Maintenance Planning and Scheduling, Improved Maintenance Operation and Improved Mission Effectiveness.

Severity of failure consequences Failure consequence is the impact that the effects of a failure have on safety, operations, and the environment. Safety consequences are related to injury or death due to a system failure. The environmental consequences are related to the breach of environmental laws (e.g. noise, pollution, etc.) and damage to the environment due to system failure. The operational consequences are directly related to the disruption or termination of the system nominal operation (e.g. mission termination, delays, cancellation, etc.) In addition all the consequences also carry the cost of corrective action due the failure. Once the consequences are determined, a metrics to describe or quantify the severity of failure consequences can be introduced. It can be ranked (similarly as in Failure Modes and Effects Analysis - FMEA) from *no effects* to *critical* effects. In this work the severity of failure consequences is focused on mission and operation, rather than the vehicle safety critical events. It is related to the following gains: Improved Mission Effectiveness and Reliability.

The cost / gain estimation due to a particular failure and its consequences takes into account e.g. cost of mission loss, cost of mission termination, etc.

Data communication delay, e.g. transmission of sensor data from vehicle to off-board systems, causes delay between events such as fault and diagnostics / prognostics actions. This leads to delays in mitigation actions to minimise the effect of possible failure. In case of on-board system, providing that the available D/P functionalities can provide the same quality of information as off-board system, data communication delay does not occur, and this results in minimum time delay between data acquisition and D/P output availability. Thus the on-board (partitioned) IVHM System can minimise the severity of failure consequences due to elimination of data communication delays.

4.2.3 Cost and gain trade-off

The previously described cost factors are gathered together in Table 4.2), where values of basic and additional costs (C_B and C_A) are presented with negative sign ($-$), and values of saved costs and the related gains (C_S and

B, respectively) are shown with positive sign (+). This notation is used in the further steps of optimal partitioning cost trade-off analysis.

Table 4.2: The main cost factors in partitioning of IVHM System.

Variable	Name	Value
C_B	Basic costs	(-)
C_A	Additional costs	(-)
C_S	Saved costs	(+)
B	Gains	(+)

The cost trade-off in IVHM System partitioning should be produced for all of the possible system configurations. Let S be the set of all possible system configurations and $s_i \in S$ to be the i^{th} system configuration. Let also $f(S)$ be the set of all cost functions for all system configurations, and $f(s_i)$ to be the cost function of an i^{th} system configuration, then $\forall i = 1, \ldots, N$, where N is a number of all possible system configurations, the cost function generated for each system configuration $f(s_i) \in f(S)$ is:

$$f(s_i) = \underbrace{-[C_B(s_i) + C_A(s_i)]}_{\text{Costs}} + \underbrace{[C_S(s_i) + B(s_i)]}_{\text{Gains}}. \tag{4.3}$$

where $C_B(s_i)$, $C_A(s_i)$, $C_S(s_i)$ are basic, additional and saved costs of s_i system configuration, respectively. $B(s_i)$ is the total gain related to s_i system configuration. $B(s_i)$ is calculate as sum of gains related to each driver b_j related to s_i system configuration (see Eg. 4.2).

It is emphasized in the published literature that the cost and gains trade-off analysis is highly dependent on the requirements of the vehicle stakeholders and the end customer (see e.g. [71]). The proposed method, in which firstly, the main drivers are captured, and then a list of relevant gains is generated helps to relate the analysis to the requirements specified by the stakeholders and end users. Having this in mind, the cost function (Eq. 4.3) has been used in the further developed criterion for optimal partitioning of IVHM System.

4.3 Novel Optimisation Criterion

One of the core aims of this work is to define an optimisation criterion to select the optimal system configuration of a partitioned IVHM System. The results of literature review described in Chapter 2 showed that there is no optimisation criterion existing in the published work. In this Section the novel optimisation criterion for optimal on-board / off-board partitioning of IVHM System is proposed and developed.

This criterion is based on the previously defined cost function $f(s_i)$, where $s_i \in \{s_1, s_2, \ldots, s_N\}$, as shown in Eq. 4.3. The value of the defined cost function is a sum of costs and gains (benefits) components related to partitioning of IVHM System for a given system configuration. The resulting value of $f(s_i)$ can be positive, negative or equal to zero:

$$f(s_i) := \begin{cases} > 0 & \text{if } [C_B(s_i) + C_A(s_i)] < [C_S(s_i) + B(s_i)] \\ 0 & \text{if } [C_B(s_i) + C_A(s_i)] = [C_S(s_i) + B(s_i)] \\ < 0 & \text{if } [C_B(s_i) + C_A(s_i)] > [C_S(s_i) + B(s_i)] \end{cases} \tag{4.4}$$

In Eq. 4.4 the first case, where the overall gain resulting from partitioning of IVHM System is higher than the related cost, can be instantly recognised as the best among the three presented cases.

4.3.1 Driver weighing coefficient

The above costs analysis is not sufficient to make a decision about the optimal IVHM system partitioning. The examples of such situation is when, in order to fulfil a mission requirements, a vehicle require a high level of autonomy (e.g. due to Concept of Operations, CONOPS), and then the financial aspect, i.e. cost trade-off, is less important (e.g. case 2 and 3 in Eq. 4.4). An example is a nuclear submarine: it must operate without communication with outside world for a long duration of underwater operations to prevent enemy detection. The level of autonomy of nuclear submarine has to be sufficient to assure crew safety and mission success.

In this work a novel proposition to IVHM System partitioning cost trade-off is made. The proposition is to weight the defined drivers, and therefore costs associated with these drivers, are CONOPS dependant. We propose to use weights (weighting coefficients) $\boldsymbol{\lambda}$ of drivers (costs associated with drivers) to incorporate vehicle CONOPS into the process of defining gains. $\boldsymbol{\lambda}$ is defined as:

$$\boldsymbol{\lambda} = [\lambda_1, \lambda_2, \ldots, \lambda_j], \tag{4.5}$$

for each $j = 1, \ldots, 6$ main driver. An example of vehicle CONOPS is *long duration mission with no communication* operational requirement (e.g. a submarine described in Chapter 3, p.84). In such case, in order to provide the vehicle crew with IVHM System D/P information, a certain level of the on-board IVHM System autonomy is required. The proposed weighting coefficient modifies the value of the gain related to IVHM System autonomy hence prioritising system configuration which can provide or increase on-board IVHM autonomy.

The idea proposed in this work is to define weighting coefficients $\boldsymbol{\lambda}$ for each group of gains (see Eq. 4.2) linked to the six main drivers for IVHM System partitioning.

The total benefit $B_\lambda(s_i)$ related to i^{th} system configuration is calculated as follows:

$$B_\lambda(s_i) = \sum_{j=1}^{6} b_j(s_i)\lambda_j. \tag{4.6}$$

The cost function based on Eq. 4.3 is now expressed as follows:

$$f(s_i, \lambda) = -[C_B(s_i) + C_A(s_i)] + [C_S(s_i) + B_\lambda(s_i)]. \tag{4.7}$$

Detailed description of the defined and quantified main drivers weights $\boldsymbol{\lambda}$ is given in Chapter 5.

4.3.2 Optimisation criterion

In this section the novel optimisation criterion to find the optimal IVHM System configuration, in terms of on-board / off-board partitioning, is proposed.

Let S be a set of size $j = |S|$ of all possible system configurations, and s_i to be the i–th system configuration, so that $S = \{s_1, s_2, \dots, s_i, s_{|S|}\}$. Let also assume that the optimal IVHM System configuration exist and is denoted $\hat{s}$, and $\hat{s} \in S$. Using the cost function, derived in Eq. 4.7 for each system configuration, a set of all system configurations cost functions, denoted $f(S, \lambda)$, is defined as follow:

$$f(S, \lambda) = \{f(s_1, \lambda), f(s_2, \lambda), \dots, f(s_{|S|}, \lambda)\}. \tag{4.8}$$

The optimisation task is to find the IVHM System configuration with the maximum value of the cost function $f(s, \lambda) \in f(S, \lambda)$. The IVHM System configuration with maximum value of the cost function signifies the optimum system configuration in terms of on-board / off-board partitioning, i.e. a system configuration for which the maximum trade-off between expenditures and gains is achieved. Note that, as shown in Eq. 4.4, the value of the cost function for a given system configuration can be positive, negative or zero, thus the optimal system configuration is indicated by the absolute maximum value of $f(S, \lambda)$. The optimal system configuration, $\hat{s}$, can be found using the optimisation criterion defined as:

$$\boxed{\begin{aligned} \hat{s} \equiv s_i : f(s_i, \lambda) &= \max\{f(s_1, \lambda), \dots, f(s_{|S|}, \lambda)\} \qquad (4.9)\\ &= \max_{\forall i} \left(-[C_B(s_i) + C_A(s_i)] + [C_S(s_i) + B_\lambda(s_i)]\right) \\ &= \max\{f(S, \lambda)\}. \end{aligned}}$$

The optimum solution is the optimal IVHM System configuration in terms of cost and gains trade-off, denoted $\hat{s}$, and to find the optimum solution the novel optimisation criterion shown in Eq. 4.9 is proposed. This optimisation criterion for optimal partition of IVHM System is novel due to:

- the use of vehicle CONOPS and weighting coefficients determined by the analysis of CONOPS (nobody considered these weighting coefficients linked to CONOPS before in worldwide terms),
- the novel drivers for partitioning are employed (nobody considered these drivers before in worldwide terms),
- the consideration of novel drivers related costs (nobody considered these costs before in worldwide terms),
- the consideration of basic costs and costs related to partitioning (nobody considered these costs before in worldwide terms.

The weighting coefficients $\boldsymbol{\lambda}$, related to main drivers for optimal partitioning, are included in the optimisation criterion, as it is shown in Eq. 4.6 and Eg. 4.7. For the sake of clarity all symbols used in the proposed optimisation criterion, including costs, gains, weighting coefficients and IVHM System configuration are gathered and described in Table 4.3.

Table 4.3: Summary of the optimisation criterion: symbols and definitions.

Symbol	Definition
s_i	i^{th} system configuration
$S = \{s_1, \ldots, s_i\}$	set of system configurations
$C_B(s_i)$, $C_A(s_i)$	total costs of i^{th} system configuration
$B_\lambda(s_i)$, $C_S(s_i)$	total gain due to i^{th} system configuration
$\boldsymbol{\lambda}$	vector of weighting coefficients
$f(s_i, \lambda)$	cost function of i^{th} system configuration
$f(S, \lambda)$	set of all system configuration cost functions
$\hat{s} \in S$	optimal system configuration
$\hat{s} = \max\{f(S, \lambda)\}$	cost function of optimal system configuration
$f(\hat{s}, \lambda)$	cost function of optimal system configuration

The proposed above optimisation uses the exhaustive search, also known as brute-force search, approach i.e. for every possible system configuration the related cost trade-off is generated (value of cost function) and the results are analysed using optimisation criterion. In principle a brute-force search will always find the solution if exists, the computational cost is proportional to the size of optimisation problem space[1].

The process of optimisation framework is depicted in Figure 4.1, including steps to define and to use the optimisation cost function and the novel optimisation criterion.

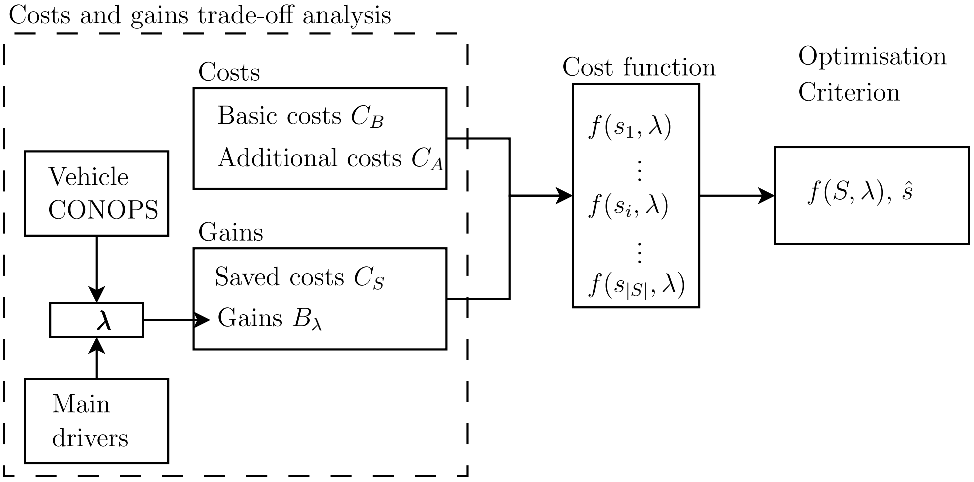

Figure 4.1: Development process of the optimisation cost function $f(s)$ and the novel optimisation criterion.

The initial step, as shown in Figure 4.1 inside the dotted line, is the cost and gains trade-off analysis, as described in Section 4.2, followed by the cost function value calculation for each possible system configuration (the middle block in Figure 4.1) and the search for optimum configuration using the proposed novel optimisation criterion.

A description of how to apply the proposed optimisation criterion to a practical engineering problem is given in Chapter 5 (Section 5.3) where a case study is described

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[1] A range of methods exists to improve and speed-up a brute-force search, such as reduction of search space, re-ordering and clustering the potential solution search space (e.g. by use of heuristic or metaheuristic methods specific to a given problem). This, however, is outside the scope of this thesis.

4.4 Summary and Concluding remarks

Cost trade-off analysis can be used in optimal partitioning of IVHM System problem as a benchmark approach to compare possible system configurations. In this Chapter the objective (cost) function has been defined based on the defined cost and gain factors related to partitioning of IVHM System. The proposed trade-off analysis uses main drivers for partitioning, discussed previously in Chapter 3, to define the related gains.

The novel cost and gain trade-off has been proposed to reflect on vehicle operational requirements: vehicle CONOPS-driven weighting coefficients to prioritise and modify the value of related gains are proposed in this Chapter.

Finally, based on the defined cost related to IVHM partitioning and the costs and gains trade-off analysis proposed in this Chapter, the novel optimisation criterion for optimal on-board / off-board optimisation of IVHM System has been proposed and developed. The proposed optimisation selects system configuration with the highest value of optimisation cost function.

Chapter 5

Novel Method for IVHM System Partitioning

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5.1 Introduction

In this Chapter the proposed novel method for optimal partitioning of IVHM system is developed. This method is based on the novel optimisation criterion developed in Chapter 5. It is worth to mention that the optimisation criterion allows generic approach to the optimal on-board / off-board partitioning of

IVHM system. It allows analysis of a range of different vehicles / platforms via fine-tuning of the components of optimisation criterion to provide the best solution. This criterion requires quantifying or defining in a qualitative way all costs and gains described in Chapter 5.

Once the quantitative / qualitative cost data are available, the cost-driven optimisation criterion can be applied to find the optimal partitioning. It has been shown in Chapter 2 that the methods described in literature do not include partitioning of IVHM system as a design or trade-off variable. In this work it has been recognised that optimal partitioning influences the overall system architecture. The work described in this chapter is addressing this gap in existing approaches to the design and implementation of IVHM system.

This Chapter provides development of the novel method and defines the required steps towards the decision on optimal partitioning of IVHM system using novel optimisation criterion.

The important advantage of the proposed and developed method is that it could work with quantitative and qualitative cost and gain data.

5.2 Novel Optimisation Method

The novel optimisation method was proposed and initially developed by thesis supervisor and was given to PhD student for further novel development and novel investigation.

The method presented here combines the outcome of work presented in Chapter 3 (i.e. drivers for optimal IVHM partitioning) and Chapter 5 (i.e. the developed novel optimisation criterion for optimal partitioning). It provides a generic framework towards the optimal on-board / off-board partitioning of IVHM system. The overall problem addressed in this work, as it has been discussed in previous chapters, is of high degree of complexity, thus it is essential to introduce a set of initial conditions to set the stage for further analysis. In

Section 5.2.1 initial conditions along with the problem boundaries are given.

5.2.1 Initial conditions for optimisation

Initial conditions strongly depend on the analysed system. In case of legacy platforms high number of constrains due to technical limitations of existing systems are mostly expected. New design systems are, in general, more flexible and capable to facilitate and fully support IVHM system. Therefore, when contemplating the partitioning of an IVHM system for legacy or new design systems, different approaches that are focusing on a different sets of priorities, key enablers and inhibitors needs to be considered. A list of technical challenges and differences between legacy and new design systems are explored and discussed in Chapter 2.

The specific vehicle systems and subsystems which are to be monitored as well as the features of corresponding IVHM D/P system technologies should be determined first, prior to the analysis of optimal partitioning. In this work it is assumed that all of the quantitative / qualitative costs associated with design, tests, implementation and partitioning of IVHM system are known and this information is accessible to the analyst / system designer.

Throughout this work it has been emphasised that the main outputs of IVHM systems are diagnostics and prognostic decisions. Therefore, the main focus of this work on partitioning of IVHM system a spatial division of D/P functions between vehicle on-board and off-board (e.g. ground-based) systems. In Chapter 2 the partitioning of IVHM system has been defined.

In the classical approach of designing and implementing an IVHM System the initial step is to define stakeholders needs, system requirements and to generate alternatives [6, 124, 125]. Different IVHM System configurations (partitioning) delivers different level of D/P performance. It is, therefore, crucial to determine alternative IVHM system configurations which satisfy a given set of requirements and stakeholders needs, and then to choose the best configuration. The optimal partitioning method proposed in this work provides means to select the best system configuration, in respect to the developed here novel optimisation criterion.

The initial assumption in the optimal partitioning analysis is that a vehicle / platform CONOPS are specified and available. It is common in most of the real-life cases that during the conceptual design CONOPS are available. It is an important remark since in the presented method the vehicle CONOPS influence significantly the final decision on IVHM system partitioning. CONOPS are mapped into the analysis via weighting coefficients that increases or decreases the importance of certain drivers for partitioning. The exact definition and examples of vehicle CONOPS being used for partitioning analysis is shown in Section 5.2.1 (5.2.2).

5.2.2 Main Steps of the method for optimal partitioning

For the sake of brevity the proposed method is described as a five-step process. Each step is described in a clear, detailed generic level, thus it can be tailored to a specific vehicle, platform of fleet of vehicles.

Step 1: Define weighting coefficients

Values of weighting coefficients, denoted as the six-dimensional vector $\boldsymbol{\lambda}$ (see Eq. 4.6) are defined based on vehicle / platform concept of operations (CONOPS) and related main drivers for IVHM system partitioning. CONOPS, as previously discussed in Chapter 3 (Section 3.2.4), are primarily used to communicate quantitative and qualitative characteristics of a vehicle / platform. In the proposed method this information is used to modify the optimisation criterion. CONOPS are case dependant, i.e. even the same vehicle / platform may be required to fulfil different operational needs. Therefore, it is not possible to define generic values of weighting coefficients. The key assumption here is that weighting coefficients could be defined in quantitative or qualitative way.

To estimate values of vector $\boldsymbol{\lambda}$, firstly the relationship between CONOPS and the main drivers for optimal partitioning has to be determined. The key drivers for IVHM System partitioning, described in Sec. 3.3 p. 82, are formed through in-depth analysis of key features of vehicle operations thus the developed drivers can be linked with the operational, functional and non-functional vehicle requirements. This is a vital step in defining the weighting coefficients since a vehicle operational, functional and non-functional requirements are used as a bridging between CONOPS and drivers for partitioning. This is realised as follows: for each of the given CONOPS one or more drivers (relevant to the CONOPS) are assigned and the weighing coefficients of the assigned drivers are also estimated. The mapping of CONOPS into the weighing coefficients of main drivers starts from CONOPS and cascades down, through vehicle / system / sub-system requirements related to IVHM implementation, to the main drivers for IVHM System partitioning. The outline of proposed mapping of CONOPS into main drivers for IVHM System partitioning is shown in Figure 5.1.

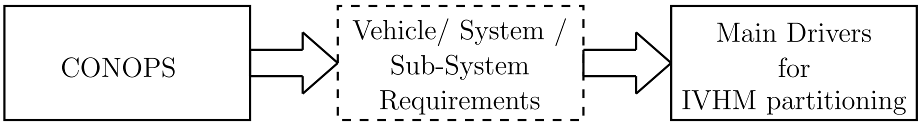

Figure 5.1: Outline of the proposed mapping of CONOPS to the defined main drivers.

The expert engineering knowledge of the vehicle, its operation requirements and CONOPS, is required to generate a comprehensive mapping and to ensure the full coverage of related drivers.

In order to demonstrate the process of defining weighting coefficients, the example of CONOPS for a civil airliner is given here. In this example qualitative values of defined coefficients are estimated. The following example aims to demonstrate a generic approach to the proposed method.

Example: The process of defining weighting coefficients. Let assume a minimum turn-around time (TAT) as one of the vehicle CONOPS.

TAT, defined as the time an aircraft is on the ground for servicing between flights[1], is often used in the literature as an example of CONOPS (e.g. [42, 23]). The process of defining weighting coefficients starts with analysing all possible vehicle features that are required to ensure that the selected CONOPS can be satisfied.

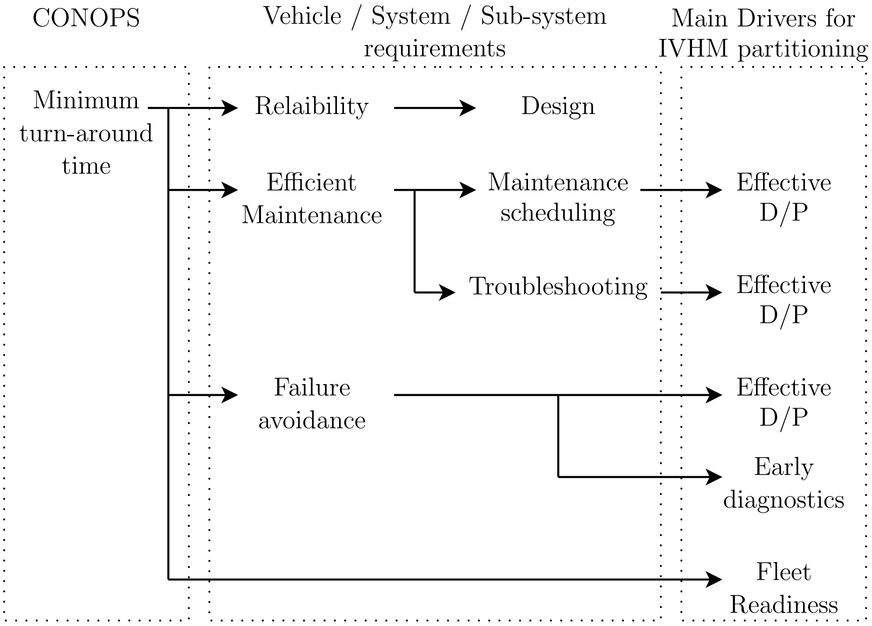

Figure 5.2: Example of defining weighting coefficients for minimum TAT using the proposed method of mapping vehicle CONOPS to the main drivers for IVHM partitioning.

The Figure 5.2 shows the mapping of minimum TAT (CONOPS) into main drivers, namely: effective D/P, early diagnostics and fleet readiness. Also a set of application drivers has been generated (the middle part of the diagram). An interesting feature of the proposed method can be observed when analysing the first application driver, i.e. Reliability. It is assumed here that the overall system reliability depends mainly on the design, which does not belong to the group of main drivers. Therefore it cannot be cascaded down

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[1] The most significant elements of turn-around time (TAT) include: pre-flight check, passengers en-planing and unloading, cargo unloading and loading, refuelling, servicing (e.g. cleaning, catering), clearing the write-ups and performing scheduled maintenance, de-icing. In case of military TAT the a differences can be observed, such as armament loading, target / mission programming, etc.

to the main drivers for IVHM partitioning and it is not taken into account in the process of defining weighting coefficients. Remaining application drivers have been extended to main drivers. Also a direct link between CONOPS and main drivers can be seen on this diagram. Fleet readiness is directly populated from the minimum TAT.

Once the mapping is finished, the next step is to analyse the results and use it to define values of weighting coefficients. A number of occurrences of a particular driver determine subsequently the importance of such driver, which then is translated to the value of the corresponding weighting coefficient. In the presented example the occurrence of each driver is summarised in Table 5.1. The most frequently linked driver is the *Effectiveness of D/P*.

Table 5.1: Weighting coefficients for minimum TAT: Results. The number of connections to each of the main drivers based on the analysis shown in Figure 5.2.

Main drivers for IVHM System partitioning

Vehicle autonomy	Fleet readiness	Real-time response	Effectiveness of D/P	Early D/P	Severity of failure cons.
0	1	0	3	1	0

Based on the information captured in Table 5.1 the system designer can use $\boldsymbol{\lambda}$ for each driver. Choosing numerical values of $\boldsymbol{\lambda}$ is application-specific process and will vary between different vehicle CONOPS. Once a strategy of assigning numerical or qualitative values to $\boldsymbol{\lambda}$ is decided, the same strategy should be used in the further analysis of each of the vehicle CONOPS.

Step 2: Generate all system configurations for optimisation

For a given number of vehicle systems, denoted $N_{sys} > 1$, to be partitioned between on-board and off-board IVHM systems, a finite set S_{max} of all system configurations can be generated:

$$S_{max} = \{s_1, s_2, \dots, s_i, \dots, s_{|S_{max}|}\}, \tag{5.1}$$

where s_i is the i-th system configuration and $|S_{max}|$ is the number of all system configurations:

$$|S_{max}| < |\mathbb{N}| \, . \tag{5.2}$$

The number $|S_{max}|$ can be calculated using methods known from binomial theory. Number of k elements combinations of a set of n elements is equal to the binomial coefficient $\binom{n}{k}$. Using factorial notation the the number of all system configurations can be expressed as:

$$\binom{n}{k} = \frac{n!}{k!\,(n-k)!}. \tag{5.3}$$

Let substitute n by N_{sys} to be the number of all systems analysed for optimal partitioning, $k : 0 \leq k \leq N_{sys}$ to be a number of systems implemented on-board for a particular system configuration. Also let assume that for $k = 0$ the IVHM system is fully implemented off-board (the baseline configuration), and for $k = N_{sys}$ assume that the IVHM System is fully implemented on-board. The number of all system configurations $|S_{max}|$ for all k system combinations is calculated as:

$$|S_{max}| = \sum_{0 \leq k \leq n} \binom{n}{k} = 2^n. \tag{5.4}$$

Essentially, for N_{sys} systems, the number of all system configurations is equal to the sum of corresponding N_{sys} row of binomial coefficients in Pascal's triangle [2].

The number $|S_{max}|$, as defined above, is the total number of all system configurations. The underlying assumption here is that all system configurations are possible. This, however, may not always be the case. Certain system

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[2] Pascal's triangle is a triangular array of the binomial coefficients, named after mathematician Blaise Pascal. For further reference see [126].

configurations may not be feasible, if not impossible. The reasons may be e.g. technical limitations, legislations, etc. Therefore a maximum number of possible system configurations is used in this work, denoted $|S| \leq |S_{max}|$, as opposed to the number of all system configurations. The $|S|$ is calculated as $|S| = 2^{N_{sys}} - |S^{-}|$, where the $|S^{-}|$ is a number of system configurations considered as not valid.

> **Remark 1** *For the sake of brevity it is assumed here that* $S^{-} \in \emptyset$*, and therefore* $|S^{-}| = 0$*. In this case* $|S| = 2^{N_{sys}}$*.*

Step 3: For each configuration quantify costs and gains or estimate costs and gains in a qualitative manner

At this stage, all costs and gains for all possible system configurations $\forall s \in S$ have to be defined in qualitative of quantitative manner. In Chapter 4, the main cost components are defined as: the basic, the additional and the saved costs; while the gains were defined as the gained costs achieved due to the system partitioning. The detailed description of the cost components is given in Section 4.2, p. 100.

Defining and estimating values of costs components is the most demanding part of the overall optimisation method. The main reason is that in order to ensure the best estimation of costs for each system configuration, a vast amount of data, often difficult to acquire at the design stage, is required. The weighting coefficients obtained based on the vehicle CONOPS, as shown in **Step 1** of the methodology, are also used here.

First, we need to estimate the costs and gains of all system configurations by generating $(N_{sys}+1)$ number of values for the following system configurations:

- Estimate the value of optimisation criterion of the baseline system (all systems off-board),
- Estimate the value of optimisation criterion of N_{sys} system configurations generated such that each of N_{sys} system is separately implemented

on-board.

Once the above is completed, the remaining $(2^{N_{sys}}) - (1 + N_{sys})$ values of optimisation criterion (for all possible system configurations, see Eq. 5.4) are estimated based on the costs of each system being implemented on-board or off-board.

This method provides values used in further steps in optimisation of the IVHM System partitioning. For further development of the method we need to take into account possible shared costs . In this work a shared cost comes to play when two or more systems are sharing resources (software or hardware) and therefore the cost of these resources (e.g. development, implementation, integration, etc.) are shared. This, however, not necessarily imply that overall cost of a particular configuration is reduced. In some cases the implementation of two or more systems (with shared resources) on-board can increase significantly the overall cost when compared to the sum of costs of each system being implemented on-board separately.

For example, let's assume a two systems being implemented on-board in the same LRU (shared cost is the hardware of the data-processing unit) and both systems requires data form two different sensors in remote locations with a high sampling rate, so that the capability of the existing data buses can provide the data communication for only one of the systems. In this situation an additional wiring may need to be installed to ensure the required capabilities. However, if only one of the two mentioned system is implemented on-board, existing data bus would be sufficient and no extra cost regarding data communication would be added. In this case, if the cost of data buses is higher that the savings on the shared costs of hardware platform, the overall cost of this particular system configuration would be increased when compared to the sum of the costs of two systems separately .

The above can be addressed by estimating costs and benefits for each system configuration individually, i.e. for each system configuration costs and gains should be estimated to include e.g. shared costs. In case of individual assessment of the related costs for a given system configuration, a more precise results can be obtained. It is assumed that this process requires a number of iterations in order to provide best possible cost estimation.

In Section 4.2.3 the cost function has been developed (see Eq. 4.7). This cost function uses all costs components specified in cost and gain trade-off in Section 4.2. The ultimate goal is to define which of the specified cost components are relevant to the given system configuration, and then, to quantify the selected cost components. An expert knowledge, access to historical maintenance and operation data as well as a projection of the future operational costs (including, but not limited to the total cost of ownership, through-life costs, etc.) are essential in this process. The exact procedure of quantifying these costs is not the main subject of this work and it has not been discussed here. However, a list of the relevant literature is suggested in Chapter 2. In order to project a future operational costs, or to perform a cost and risk analysis, often in the absence of reliable maintenance data, a range of stochastic and probabilistic methods exists that can be employed. Maintenance cost optimisation methods using probabilistic analysis to maximise benefit-to-cost ratio, i.e. the ratio of monetary benefits resulting from HM system implementation, have been already established in the literature and can be used to aid the process of cost estimation and analysis at this stage of the proposed methodology (see e.g. [127]). Probabilistic models are widely used for the risk-based condition assessment and life prediction, also including the uncertainties in maintenance cost. Generic algorithms (GA), Bayesian models or Markov models are often used to evaluate probabilistic maintenance models; a great variety of techniques are described in the existing literature (see e.g. [128, 129, 130]). Such methods may also be used when dealing with a new design systems, for which the maintenance data does not exist or the maturity level has not been achieved yet. This, however, is beyond the research scope presented in this work.

Step 4: Find the optimal partitioning using cost function

In this step the value of costs and gains for each system configuration are estimated in quantitative or qualitative manners. Now, using these data, further actions need to be performed in order to find the optimal system configuration in sense of the partitioning between on and off-board. The cost data are now used to calculate value of the optimisation criterion for each system configuration $\forall s_i \in S$. The optimisation criterion (Eq. 4.8) uses the cost function (Eq. 4.7) which essentially combines all costs and gains related to a particular system configuration.

> **Remark 2** *In this work it is assumed that all costs and benefits can be determined in a quantitative or qualitative way. In the domain of cost engineering, systems engineering and systems design the use of qualitative data and descriptive data is regularly observed. In case of qualitative data of costs and gains often an additional step in cost analysis has to be implemented in order to translate qualitative values into quantities (i.e. numerical values). However, mixed-type data methods exist to cope with combination of quantitative and qualitative data.*

As a result of the above, the $2^{N_{sys}}$ elements vector, denoted $f(S)$, is generated (see also Eq. 4.7). This vector consists of all values of optimisation cost function for each system configuration.

$$f(S) = \begin{bmatrix} f(s_1) \\ f(s_2) \\ \vdots \\ f(s_i) \end{bmatrix}_{i=2^{|S|}} \tag{5.5}$$

To find the optimal system configuration, in other words, the optimal partitioning of IVHM System, the optimisation criterion is applied to the cost vector $f(S)$. The criterion determines the system configuration which provides the highest value of the optimisation criterion. It has been discussed in Section 4.3 that an optimisation criterion can either search for *maximum gain*, or *minimum costs*. In this work the maximum value of optimisation cost function, $f(S)$, is used as optimisation criterion. The optimal system configuration, denoted $\hat{s} \in S$, is defined as:

$$\hat{s} \equiv s_i\{i : i \in [1, 2^{N_{sys}}], s_i \in S\} : f(s_i) = \max f(S). \tag{5.6}$$

It is shown in Eq. 5.4 that the number of system configurations is $|S| = 2^{N_{sys}}$, providing that all configurations are possible (i.e. $|S^-| = 0$), therefore:

$$f(\hat{s}) = \max\{f(s_1), f(s_2), \ldots, f(s_{2^{N_{sys}}})\}. \tag{5.7}$$

It is assumed here that at least one system configuration is the optimal system configuration in terms of on-board / off-board partitioning. It is however possible that more than one system configuration will achieve the highest gain-to-cost ratio, i.e. will be selected as an optimum system configuration according to the proposed optimisation criterion. The following is given to describe such scenario. A set of optimal system configurations is denoted $\hat{S}$ and contains one or more optimal system configuration $\hat{s}_i\{i : i \in \left[1, \left|\hat{S}\right|\right]\}$. The $\hat{S}$ is a subset of S, so that:

$$\hat{S} \subsetneq S \quad \wedge \quad \hat{S} \subseteq S. \tag{5.8}$$

Let define S^* as a complement of a set of system configurations $\hat{S}$ so that:

$$S^* = S \setminus \hat{S}. \tag{5.9}$$

In special case when all system configurations, including baseline system configuration, has the same value of the optimisation cost function $\forall s : f(s) = f(\hat{s})$ and therefore $\hat{S} \subseteq S$, then

$$S^* = \emptyset. \tag{5.10}$$

As a result of the described optimisation steps, more than one system configuration, including baseline configuration, may be selected as the potential optimal system configuration, i.e. have the same value of the optimisation criterion. In such case a further steps have to be taken, e.g. expert judgement, to enable the final decision on the optimal system configuration. In addition, the effectiveness analysis of the obtained results delivers additional knowledge to in order to make an informed decision on final system configuration.

Step 5: Estimate cost effectiveness of IVHM partitioning

In order to estimate cost effectiveness due to optimal IVHM partitioning, an analysis of the effectiveness of optimisation results is required. For this method, the four performance metrics are proposed to estimate effectiveness of optimal IVHM partitioning. These metrics are based on figures of merit, i.e. relative gain, average gain, minimum and maximum gain, estimated using values of optimisation criterion obtained in the previous steps.

The Overall Gain $G(\hat{s})$

The overall gain due to optimal IVHM partitioning, $G(\hat{s})$ is the difference between value of the optimisation cost function of the optimal configuration $f(\hat{s})$ and the baseline configuration $f(s_1)$. For $f(\hat{s}) \geq f(s)$

$$G(\hat{s}) = f(\hat{s}) - f(s_1). \tag{5.11}$$

If the value of optimisation cost function of the optimal and the baseline system configuration are greater than zero, i.e. $f(\hat{s}), f(s_1) \geq 0$, then the gain can be also presented as the relation between $f(\hat{s})$ and $f(s_1)$ as percentage:

$$G(\hat{s})_{[\%]} = \left| \frac{f(\hat{s}) - f(s_1)}{f(s_1)} \right| \cdot 100\%. \tag{5.12}$$

Figure 5.3 shows the graphical interpretation of this difference.

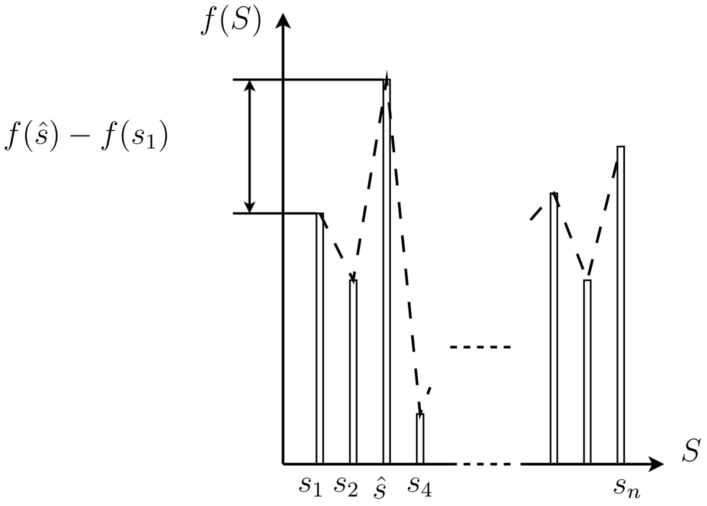

Figure 5.3: Overall gain $G(\hat{s})$ due to system partitioning.

Average Gain $\bar{G}(\hat{s})$

The average gain due to optimal IVHM partitioning vs. nonoptimal partitioning as the mean cost difference between values of the optimisation criterion for all non-optimal partitioning (including baseline configuration), S^* defined previously in Eq. 5.9 and value of the optimisation criterion for the optimal partitioning. The average value of optimisation function for non-optimal system configurations $\bar{f}(S^*)$ is defined as:

$$\bar{f}(S^*) = \frac{\sum f(S^*)}{|S^*|}. \tag{5.13}$$

where $|S^*|$ is a number of non-optimal system configurations, previously defined in Eq. 5.9. The average gain, $\bar{G}(\hat{s})$ is calculated as:

$$\bar{G}(\hat{s}) = f(\hat{s}) - \bar{f}(S^*). \tag{5.14}$$

The graphical representation of the average gain is shown in Figure 5.4.

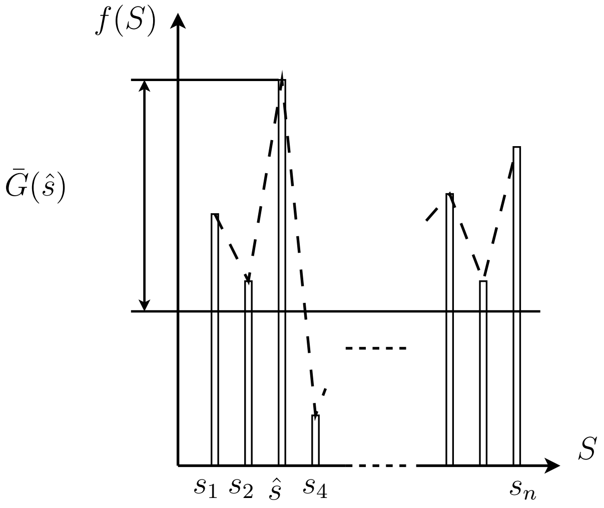

Figure 5.4: Average gain $\bar{G}(\hat{s})$ due to system partitioning.

Minimum Gain $G_{min}(\hat{s})$

The minimum gain due to optimal IVHM partitioning is calculated as a difference between the value of optimisation cost function of the optimal partitioning system configuration $f(\hat{s})$ and the nearest value of the optimisation cost function for non-optimal partitioning defined as $(\max f(S^*))$. The minimum gain therefore is calculated as follows:

$$G_{min}(\hat{s}) = f(\hat{s}) - \max f(S^*). \tag{5.15}$$

With the underlying assumption is that if $S^* \neq \emptyset$ then $\forall s \in S^* : f(\hat{s}) > \max f(S^*)$. If $f(\hat{s}), \max f(S^*) \geq 0$ then the relative value of the minimum gain expressed in percentage is calculated as:

$$G_{min}(\hat{s})_{[\%]} = \left| \frac{f(\hat{s}) - \max f(S^*)}{\max f(S^*)} \right| \cdot 100\%. \tag{5.16}$$

The $G_{min}(\hat{s})_{[\%]}$ carries the information of how sensitive is the optimal solution when compared to the second best. The final decision on the system configuration is in hands of the decision maker (DM), i.e. system designers and analysts. If the value of $G_{min}(\hat{s})_{[\%]}$ is small (e.g. less than a threshold set by a DM) then both solutions may be taken into account as preferable / possible system configurations. Figure 5.5 shows the graphical representation of the minimum gain.

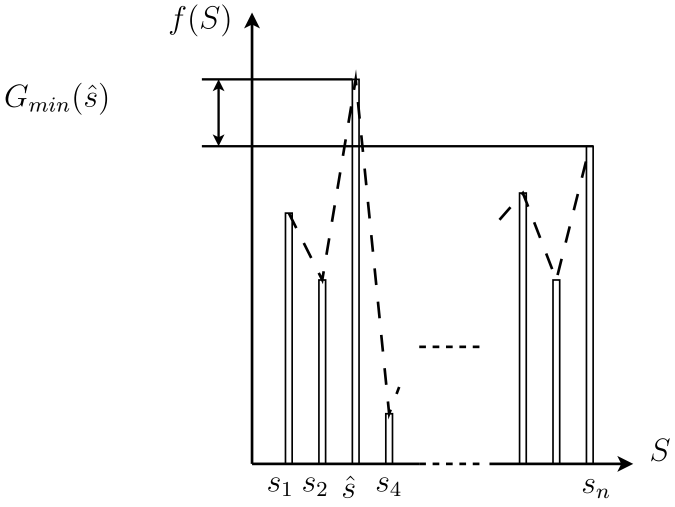

Figure 5.5: Minimum gain G_{min} due to system partitioning.

Maximum Gain $G_{max}(\hat{s})$

The maximum gain due to optimal IVHM partitioning is calculated as a cost difference between maximum and minimum values of the optimisation cost function. The minimum value can be selected from either S or S^* sets of system configurations since $(\min f(S)) = (\min f(S^*))$. The maximum gain is then calculated as:

$$G_{max}(\hat{s}) = f(\hat{s}) - \min f(S^*). \tag{5.17}$$

The $G_{max}(\hat{s})$ highlights the span of the value of optimisation cost function between the worst and the best (i.e. optimal) system configuration. The graphical representation of maximum gain is shown in Figure 5.6.

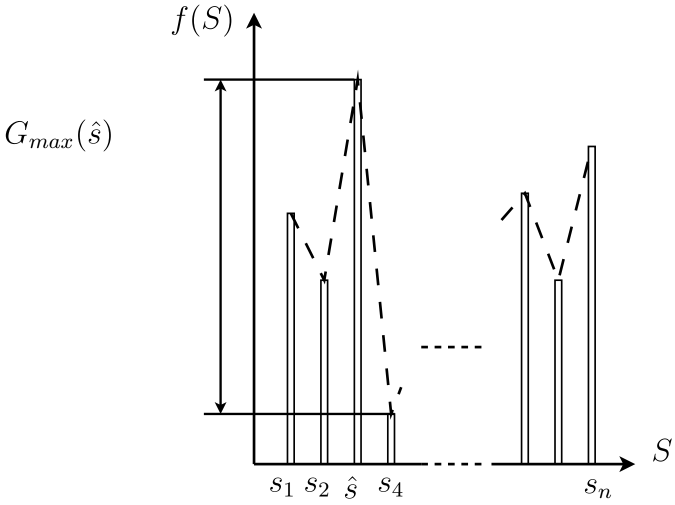

Figure 5.6: Maximum gain $G_{max}(\hat{s})$ due to system partitioning.

In summary, all of the defined cost effectiveness matrices for optimal IVHM System partitioning are gathered in Table 5.2.

The block diagram for the proposed method for optimal on-board/off-board partitioning is outlined in Figure 5.7.

Table 5.2: Metrics to evaluate effectiveness of the optimisation procedure

Name	Symbol	Expression
Gain	$G(\hat{s})$	$f(\hat{s}) - f(s_1)$
if $f(\hat{s}), f(s_1) > 0$	$G(\hat{s})_{[\%]}$	$\left\lvert \frac{f(\hat{s})-f(s_1)}{f(s_1)} \right\rvert \cdot 100\%$
Average Gain	$\bar{G}(\hat{s})$	$f(\hat{s}) - \bar{f}(S^*)$
	where:	$\bar{f}(S^*) = \frac{\sum f(S^*)}{\lvert S^* \rvert}$
Minimum Gain	$G_{min}(\hat{s})$	$f(\hat{s}) - \max f(S^*)$
if $f(\hat{s}), \max f(S^*) > 0$	$G_{min}(\hat{s})_{[\%]}$	$\left\lvert \frac{f(\hat{s})-\max f(S^*)}{\max f(S^*)} \right\rvert \cdot 100\%$
	where	$\forall s \in S^* : f(\hat{s}) > \max f(S^*)$
Maximum Gain	$G_{max}(\hat{s})$	$f(\hat{s}) - \min f(S^*)$
	where	$\min f(S) = \min f(S^*)$

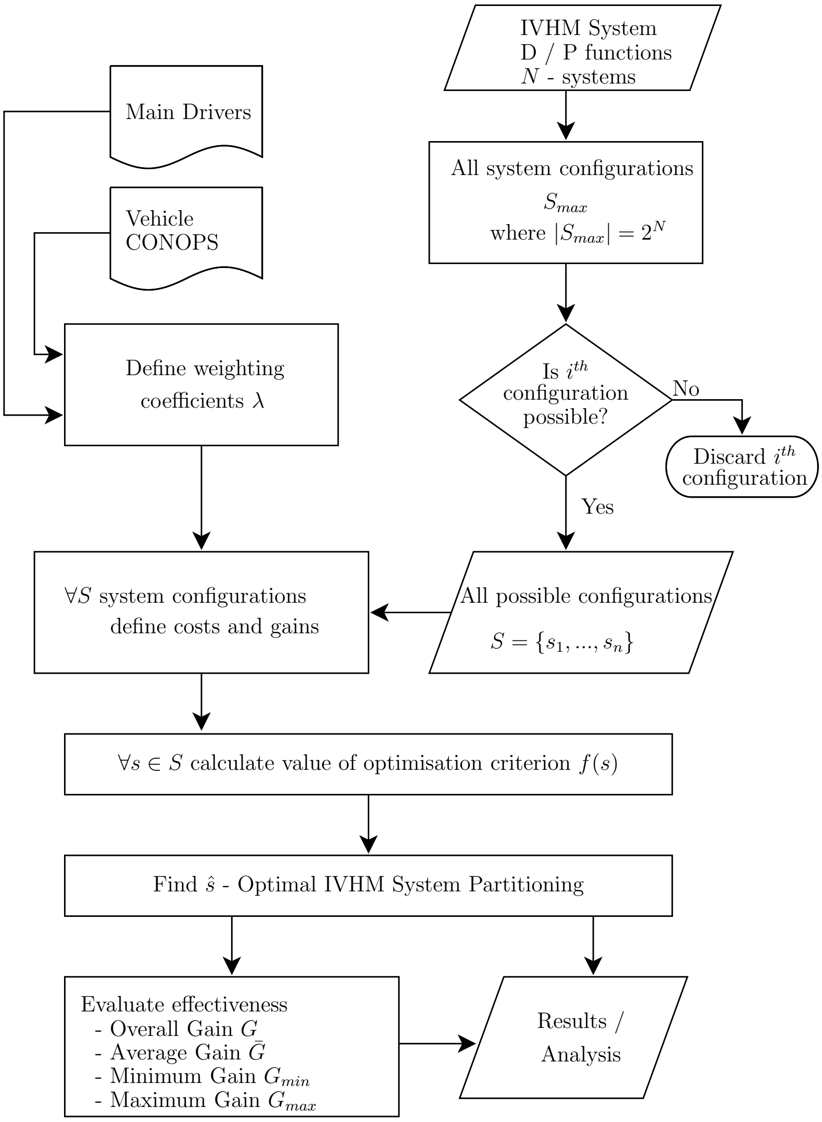

Figure 5.7: Outline of the proposed novel optimisation method.

5.3 Case study: Implementation and Verification of the Proposed Method

Based on the developed method for optimal on-board / off-board partitioning of IVHM System, a MATLAB®[3] program has been developed to verify and exemplify the use of this method. MATLAB is regarded by industry and academia as a rapid code development platform, flexible (read/write data to/from multiple file formats), and is providing numerous tools to represent results.

5.3.1 MATLAB implementation of the optimisation method

The developed MATLAB code consists of three main functional blocks (see Figure 5.8):

- `Data`: input data read/write, data generate,
- `Processing`: data processing,
- `Results`: presentation of results (figures and log-file).

Figure 5.8 presents block diagram of the implemented novel partitioning methods in MATLAB.

The functional blocks of the MATLAB implementation, as shown in Figure 5.8, are described in detail below.

Input Data

In Figure 5.8 a `User input data` is the cost and benefit input data stored in Microsoft Office Excel file (.xlsx) or MATLAB native data-file (.mat) and it consist of:

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[3] MATLAB® from MathWorks is a high-level computer programming language and interactive environment for numerical computation, visualization, and programming.

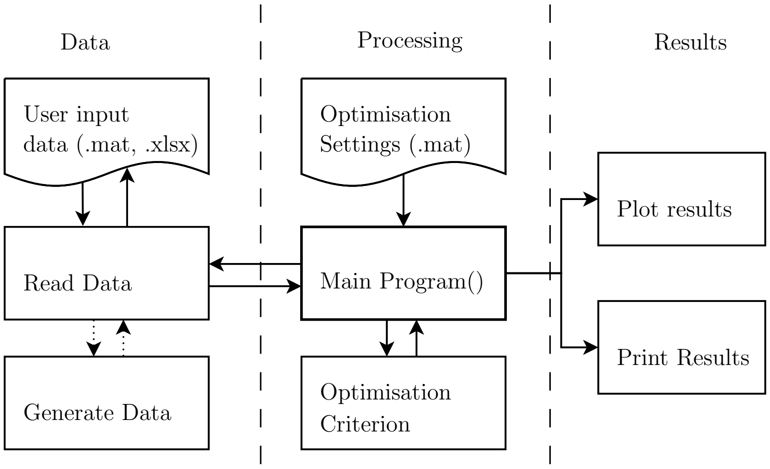

Figure 5.8: MATLAB implementation of the optimisation method: block diagram.

- basic information about the data used for analysis (i.e. file-name, number of systems, etc.)
- $(N_{sys} \times 2^{N_{sys}})$ matrix of `0` and `1`. Each row indicates a system configuration, where `0` is off-board and `1` is on-board.
- $(N_{sys} \times 2^{N_{sys}})$ matrix providing all possible system configuration of `'On'` for on-board and `'Off'` for off-board.
- $(N_{sys} \times 2^{N_{sys}})$ matrix of costs data. The data is a sum of basic, additional and saved cost for the each of N_{sys} systems for all system configurations.
- $(N_{sys} \times 2^{N_{sys}})$ data matrix of benefits / gains data for the each of the analysed systems for all system configurations.

Data Processing

The program displays initialisation data (i.e. number of systems, input data file) and program settings specified by user in (in the *Optimisation settings* file). Once the data are uploaded to the program, the value of the optimisation criterion for each system configuration is calculated. The optimisation algorithm is solely based on the proposed optimisation criterion.

Once the optimal system configuration is determined, the effectiveness of the optimisation is estimated. All of the cost effectiveness metrics, as shown in Table 5.2, are used here.

Output Data

The results of optimal partitioning are displayed on the computer screen. Two main groups of results are shown:

- Optimal on-board / off-board partitioning system configuration $\hat{s}$,
- Comparison of the trade-off results between the costs and benefits of optimal system configuration $f(\hat{s})$ and the baseline system configuration $f(s_1)$.

All results of the optimisation cost effectiveness estimation are also displayed on the computer screen.

The program provides a graphical representation of the obtained results of the optimal partitioning analysis. Three main plots are generated. For the illustration purposes of the data-plots produced by the MATLAB program, a uniformly distributed random data-set for $N_{sys} = 3$ systems had been used as cost and benefit input data.

Data plot 1: Values of optimisation criterion for all system configurations. The results for baseline and optimal system configuration are highlighted. An example of *Data plot 1* is shown in Figure 5.9. In this figure a value of the optimisation criterion for baseline system configuration is indicated as a dotted red line. The green line indicates the highest value among the partitioned system configurations. If this value is higher than the value of baseline configuration, the green line indicates the optimal solution.

Data plot 2: Values of costs $\sum C(s)$, gains B_λ and optimisation criterion $f(S)$ for user-defined number of best system configurations including the optimal solution and the baseline configuration. The baseline system is marked with red dotted line. An example of such plot is shown in Figure 5.10 where

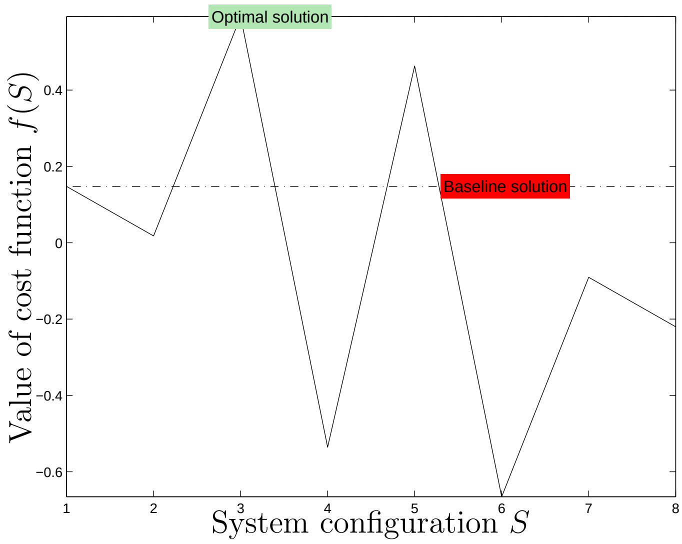

Figure 5.9: An example of the result of optimisation procedure: values of optimisation criterion $f(S)$.

the optimal system configuration, second best system configuration and the baseline configuration data are displayed (the user-defined number of systems is set to 2).

Data plot 3: Values of costs, benefits and optimisation criterion $f(S)$ for all system configurations, including for the baseline configuration that is highlighted on the plot. An example of Data plot 3 is shown in Figure 5.11. The baseline system configuration is marked with a dotted red line. Values below zero i.e. $f(s) < 0$ indicates that the cost of a particular system configuration is higher than the benefits it provides.

In **Data plot 2** and **Data plot 3** the baseline configuration is indicated with the red dotted line. The main reason is to improve readability of the figure, since the system configuration are now organised in the descending order of the calculated optimisation cost function value.

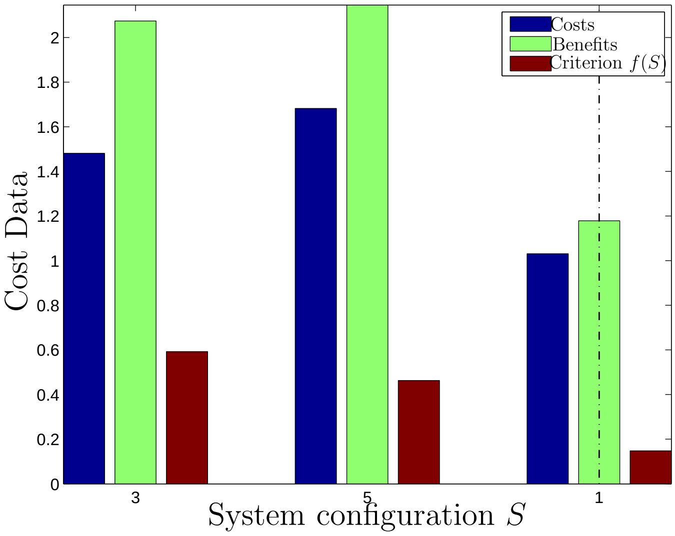

Figure 5.10: Values of costs, gains and optimisation criterion for two best system configurations and the baseline configuration. The baseline system is highlighted.

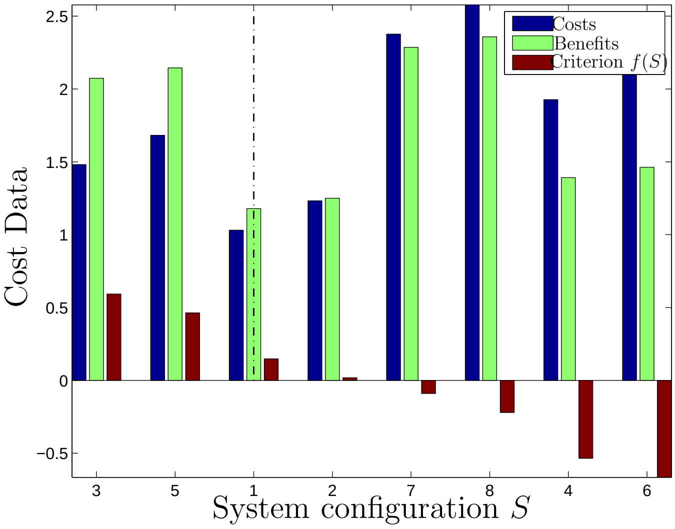

Figure 5.11: Values of costs, gains and optimisation criterion for all system configurations, including baseline that is highlighted on the plot.

5.3.2 Case study using synthetic data-set

The case study has been design to test the proposed optimisation method using the developed Matlab program. The work presented in this thesis is a part of on-going research project which aims to deliver optimisation method for real-life industrial problem of the partitioning of IVHM System. It would be beneficial to the project at this stage to validate the proposed method using real industrial data. However, due to a number of serious constrains, such as commercial sensitivity, and the fact that this research has been carried out to address the problem of partitioning of IVHM System at a low level of technology readiness (system maturity), it has not been possible to obtain relevant data. This has been addressed by generating a synthetic data-set.

Case study: Initial conditions

The number of systems has been set to $N_{sys} = 9$, where $|S| = 2^{N_{sys}}$ (as shown in Eq. 5.4) therefore $|S| = 512$ system configurations were analysed. This is an arbitrary number of systems. Cost and gains data ($\sum C(S)$ and B_λ)for the baseline system configuration (off-board) had been generated as an uniformly distributed random numbers $U(0,1)$. Matlab (pseudo)random data generation function has been used to produce the data-sets, i.e. an $(2^{N_{sys}} \times N_{sys})$ matrix of costs, an $(2^{N_{sys}} \times N_{sys})$ matrix of gains and an $(2^{N_{sys}} \times N_{sys})$ matrix of system configuration. In this study a scenario with no shared costs between systems is implemented (shared costs had been discussed in *Step 3* of the optimisation method). The remaining cost data i.e. costs and gains for partitioned systems had been generated using following method:

- Cost of a system implemented on-board is calculated as cost of corresponding off-board system multiplied by factor of 2.5,
- Gains from a system implemented on-board is calculated as cost of corresponding off-board system multiplied by factor of 2.

The above factors had been chosen to exemplify the difference between on and off-board implementation of the same D/P systems as part of overall IVHM system. The value of 2.5 and 2 have been assign to ensure the resulting cost and gains will noticeably change when compare to the baseline system configuration to highlight the transition from on-board to off-board system. The key assumption is that both, the cost and resulting gains related to on-board implementation will increase.

Case study: Results

The results of the case study are depicted in Figures 5.12. It is important to note that data used in this case study is a synthetic data-set with no reference to real industrial data. Taking this into account, the results are not analysed more than it is necessary to exemplify the use of the developed optimisation software.

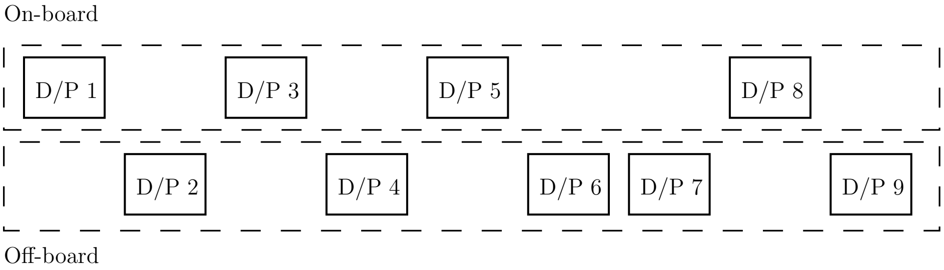

Figure 5.12: Result of the case study: optimal partitioning system configuration. 'D/P' - diagnostics / prognostics system.

For $N_{sys} = 9$ number of D/P system a matrix of 512 system configurations had been generated. The optimal partitioning system configuration is the configuration $\hat{s} \equiv s_{228}$ and $\left|\hat{S}\right| = 1$. The optimal system configuration consists of five off-board D/P systems and four on-board D/P systems. A graphical representation of the resulting system configuration is shown in Figure 5.12.

The cost data-set is generated as a random data therefore the analysis of results is only limited to optimisation effectiveness measures and graphical representation of the obtained results. In case of real engineering data a more detailed analysis should be expected.

Result of the cost-gain trade-off analysis where the optimal solution has been compared to the baseline system configuration is depicted in Figure 5.13. The complete listing produced by MATLAB program as a result of optimisation procedure is provided in the Appendix C. Graphical representations of the obtained results are shown in figures bellow. In Figure 5.14 values of the optimisation cost functions $f(S)$ for all system configurations are shown. The value of $f(\hat{s})$ and $f(s_1)$, i.e. optimal system configuration and baseline system configuration, respectively, are highlighted.

```
Costs-Benefits Analysis results
- Costs:
Baseline: 3.531192
Partitioned: 3.487643
- Gains / Benefits:
Baseline: 6.341092
Partitioned: 9.460460
- Costs-benefits analysis (value of optimisation criterion)
Baseline: 2.809900
Partitioned: 5.972817
```

Figure 5.13: Case study: MATLAB listing of the cost-gain trade-off results for optimal system configuration $f(\hat{s}$ and baseline system configuration $f(s_1)$.

In Figure 5.15 values of costs $\sum C(s)$, benefits B_λ and optimisation cost function $f(S)$ for optimal ($f(\hat{s})$), second best ($\max f(S^*)$) and the baseline configuration ($f(s_1)$). In this Figure one can see that the bar which corresponds to the value of benefits in the second best system configuration is higher than in case of $f(\hat{s})$. The associated costs of second best system configuration are also higher compared to $f(\hat{s})$ and therefore the resulting value of optimisation costs function of $f(\hat{s})$ is higher than the second best configuration. It has been discussed in Section 4.3 that a change of optimisation criterion would result in different system configuration being selected as optimal. In case of *benefits driven* approach second best outperforms the currently selected optimal system configuration. This illustrates the importance of correct selection of the optimisation criterion.

In Figure 5.16 values of costs, benefits and optimisation cost function are shown for all system configurations $f(S)$. These values are shown in des-

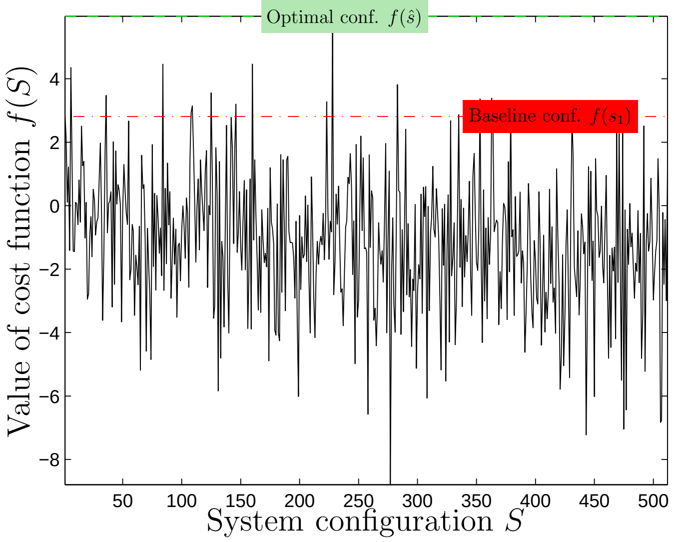

Figure 5.14: Values of optimisation cost function for all system configurations $f(S)$. The result for baseline $f(s_1)$ and optimal $f(\hat{s})$ system configuration are marked with dotted lines.

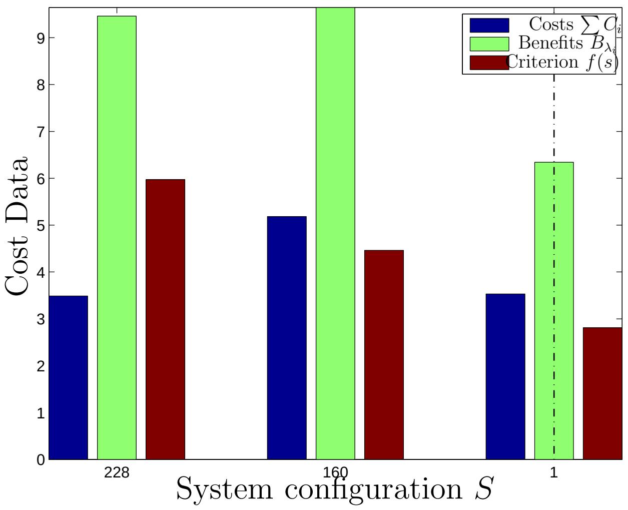

Figure 5.15: Values of costs, gains and optimisation cost function for optimal ($f(\hat{s})$), second best ($\max(S^*)$) and baseline ($f(s_1)$) system configuration.

cending order of $f(s_i)$ starting from the highest value, i.e. parameters of $f(\hat{s})$. The baseline configuration is marked with dotted line. When costs are higher than benefits the value of optimisation cost function is negative, as it can be observe in Figure 5.16.

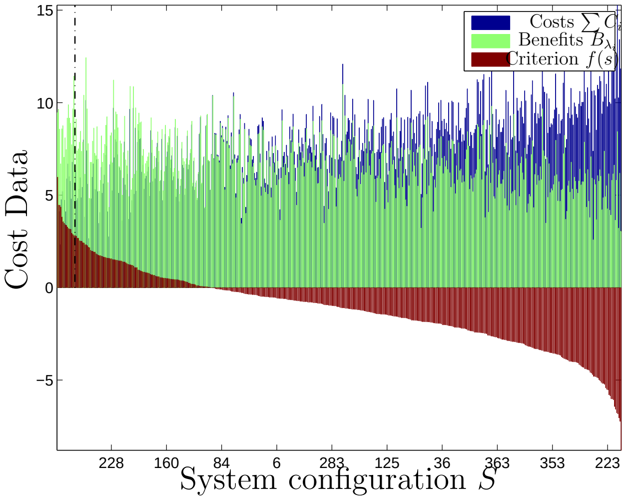

Figure 5.16: Values of costs, gains and optimisation cost function for all system configuration in descending order. The baseline system configuration is marked with dotted line.

The result of effectiveness assessment of the optimisation procedure in this case study is shown in Figure 5.17. The proposed four effectiveness metrics allow relative comparison of the optimal system configuration to the baseline and other non-optimal system configurations.

```
Effectiveness of the optimal partitioning of IVHM system
1. Gain due to partitioning vs. baseline system
1.1 Optimal - Baseline:  = 3.162916
1.2 Optimal vs. Baseline Gain [%]:  = 113 %

2. Optimal solution vs. mean value of non-optimal solutions
2.1 Optimal Gain:  = 5.972817
2.2 Average Gain:  = -1.161346
2.3 Optimal - Average Gain:  = 7.134163
2.4 Optimal vs. Average Gain [%]:  = 614 %

3. Minimum gain: optimal vs. nonoptimal IVHM partitioning
3.1 Minimum Gain:  = 1.510329
3.2 Optimal vs. Minimum Gain [%]:  = 34 %

4. Maximum gain: optimal vs. nonoptimal IVHM partitioning
4.1 Maximum Gain:  = 14.765400
4.2 Optimal vs. Maximum Gain [%]:  = 168 %
```

Figure 5.17: Case study: MATLAB listing of the partitioning effectiveness estimation results.

5.4 Summary and Concluding Remarks

In this Chapter the novel method for optimal partitioning of IVHM System is proposed and developed. This method uses the novel optimisation criterion proposed and developed in Chapter 4.

The proposed method consists of five main steps that are described above. The first step is to quantify CONOPS related weighting coefficients for the selected drivers (Step 1 in Sec. 5.2.2, p. 120). In this step a mapping of vehicle CONOPS into the weighting coefficients of the main drivers for partitioning of IVHM System is considered (see Figure 5.1). This mapping allows quantifying weighting coefficient used in the proposed optimisation method. In the second step all possible system configurations are generated. We assumed that in some cases a particular system configuration may not be possible (e.g. due to technological limitations) and therefore the number of possible system configurations may vary from the total number of system configurations calculated as $2^{N_{sys}}$. In step three all costs and gains, related to each system configuration, are generated. In step four the novel optimisation criterion, proposed in Chapter 4 is used to calculate cost trade-off for each IVHM System configuration generated in Step three and define the optimal configuration. The last step provides a set of tools to perform cost effectiveness analysis of the IVHM System partitioning. This analysis enables to assess the results of the optimisation method and it provides framework to compare all system configuration in terms of value of the optimisation criterion.

The described method requires in-depth understanding of the analysed vehicle design, architecture, and its CONOPS. This can be noticed specially when all costs and gains related to a particular system configuration has to be determined. The values of weighting coefficients are based on the vehicle CONOPS, therefore, CONOPS influences the resulting optimal system configuration, as previously discussed in Sec. 3.2.4.

The proposed novel method can be adapted to different vehicles at all design and exploitation (life-cycle) stages and across multiple industrial sectors (e.g. aviation, marine, ground, etc.). It allow customisation to a specific requirements and operational needs. The proposed novel optimisation criterion and optimisation method make use of the vehicle CONOPS thus allowing to fine-tune the analysis and to adapt it to the vehicle actual operational and non-operational needs. The proposed novel optimisation method make use of the vehicle CONOPS, thus allow to fine-tune and adapt the analysis to the vehicle actual operational and non-operational needs.

Chapter 6

Summary and Conclusions

The research presented in this thesis addressed for the first time in worldwide terms the optimal on-board / off-board partitioning of IVHM System. The analysis of published literature related to IVHM System, presented in Chapter 2, showed that this problem has not been studied before.

Based on the state-of-the-art review a set of objectives have been defined to investigate the optimal partitioning of IVHM System, from which the three main themes can be distinguished: the main drivers for IVHM partitioning, the optimisation criterion and the optimisation method for optimal on-board / off-board partitioning of IVHM System. Each theme is addressed in separate Chapter of this thesis with the resulting novel contributions to scientific knowledge.

This Chapter consists of two main parts. In the first part (Section 6.1) a summary of the presented research is given. In the second part (Section 6.2) the main conclusions are drawn.

6.1 Summary

The outcome of the research is presented in this thesis.

1. A comprehensive review of state-of-the-art on the IVHM System has been conducted and critically assessed to identify current state and gaps in the scientific and engineering knowledge (Chapter 2).
2. The novel main drivers for IVHM System partitioning, where the research has been focused on understanding, developing and analysing the main drivers with respect to the vehicle operation, technology and business related features related to the IVHM System implementation (Chapter 3).
3. The novel links between main drives for partitioning of IVHM System and the key features of vehicle operation (Chapter 3).
4. Novel optimisation criterion for optimal on-board / off-board partitioning of IVHM System where the emphasis is on the trade–off analysis of costs and gains related to partitioning, including the developed main drivers for partitioning (Chapter 4).
5. Novel method for optimal on-board / off-board partitioning of IVHM System where the emphasis has been focused on developing a framework that utilises the developed main drivers and the novel optimisation criterion (Chapter 5).
6. The novel cost effectiveness analysis of the resulting optimal IVHM System configuration, including the novel metrics to estimate effectiveness of the IVHM System partitioning. These metrics are based on a comparative analysis of cost and gain trade-off results obtained for each generated system alternative (Chapter 5).

6.2 Conclusions

In this thesis at the end of each Chapter the summary and concluding remarks are given. The final conclusions drawn for the research work and the resulting major contributions are given in this section.

Novel main drivers for partitioning of IVHM System

In this thesis the novel main drivers for IVHM System partitioning, namely: vehicle autonomy, fleet readiness, real-time diagnostics and prognostics systems response, effectiveness of diagnostics and prognostics, early diagnostics and prognostics, and severity of failure consequences have been defined. The main aim was to deliver novel approach in the analysis and decision making process of IVHM partitioning, and to fill the gap in knowledge that has been recognised through the state-of-the-art review as part of this research work.

The novel links between main drives for partitioning of IVHM System and the key features of vehicle operation, maintenance, architecture and fault/failures are developed. Thus, the main drivers were investigated using a systematic approach. The proposed main drivers capture vehicle operational and non-operational features key features of maintenance, potential faults and failures, and IVHM System architecture. In this research the analysis of key features of a vehicle design and operation has been recognised as the most effective and comprehensive method to define and justify IVHM partitioning between on-board and off-board system.

The analysis of the key features of vehicle maintenance, completed as a part of the conducted literature review, showed a strong correlation between vehicle / fleet readiness and partitioning of IVHM System. It has been shown that the unavailability due to the non-optimal maintenance process can be minimised by IVHM System functions such as fault-forwarding, in-advance troubleshooting, reduced NFF and reduced unplanned maintenance shop visits. This is a result of effective on-board diagnostics and prognostics capabilities of the IVHM System.

The IVHM System abilities to provide an early diagnostics / prognostics have been identified to optimise the planning of maintenance actions, thus improve the mission readiness.

Real-time response of IVHM System has been also linked to the optimal maintenance planning and scheduling, and therefore improvement of vehicle / fleet readiness.

The performed analysis of key features of faults, as described in Sec. 3.2.2, indicated the need for a real time response, especially when dealing with faults characterised by a relatively short P-F interval, as well as in the case of intermittent and transient faults.

Further analysis of faults and consequences of related failures highlighted the importance of early diagnostics. The early diagnostics can be used as way to extend the P-F interval, i.e. to allow appropriate maintenance actions to be taken to minimise the effect of underlying faults. Early diagnostics in combination with real-time responses, therefore, have been found to significantly improve maintenance operation, safety and vehicle mission capabilities.

Further on, consequences of failures, resulting from faults, have been selected as an essential part of the IVHM System requirements setting, and as such, influence the partitioning.

Finally, the effectiveness of diagnostics and prognostics, which is directly linked to the granularity of data, has emerged from the performed analysis as an important driver towards the IVHM System partitioning.

The analysis of the IVHM System architecture revealed how the limitations of on-board systems and the telemetry systems can be tackled by the adequate partitioning of an IVHM System. It has been shown that data granularity, which further translates to the effectiveness of diagnostics and prognostics, strongly depends upon the IVHM System architecture.

Vehicle / platform specific features can be mapped into the proposed set of main drivers for partitioning. Although in this thesis an aircraft system is used as a leading example of a vehicle, the defined main drivers are generic and can be applied to any vehicle.

Novel optimisation criterion

To compare all the alternative system implementations and to find the optimal IVHM partitioning, a unified and reliable method is needed: different system configuration (i.e. diagnostics and prognostics function implemented fully off-board, fully on-board or any combination between) results in different financial costs and related gains. Based on this observation cost and gains trade-off has been used in the development of novel optimisation criterion for optimal on-board / off-board partitioning of IVHM System. Costs and gains models related to baseline IVHM System configuration (i.e. fully off-board) and related to partitioning of IVHM System have been studied in details in Chapter 4 to enable comprehensive trade-off analysis.

The proposed novel optimisation criterion uses the main drivers for IVHM partitioning, discussed in Chapter 3, to define gains related to each main driver due to further partitioning of IVHM System.

The optimisation criterion is designed to reflect on vehicle operational requirements: for the first time in world-wide terms vehicle CONOPS-driven weighting coefficients are proposed to prioritise and modify the value of gains related to the main drivers. This allows flexibility of the criterion by adjusting the trade-off analysis to a particular vehicle / platform and to its specific needs, and, thus, allows to widely apply the novel optimisation method for various vehicle domains and various CONOPS.

For each system configuration all related costs and gains, expressed in financial terms, are estimated, and then all costs are summed and subtracted from the sum of all related gains in order to calculate the value of optimisation cost function for a particular system configuration. In the real world some system configuration may not be possible, e.g. due to legislative or technological limitations, and therefore, in such situation the value of optimisation criterion cannot be estimated.

Finally, based on costs and gains trade-off analysis, which includes the defined cost related to IVHM System partitioning, the CONOPS - driven weighting coefficients and gains related to the defined main drivers, the proposed novel optimisation criterion determines the optimally partitioned IVHM System by selecting system configuration with the highest value of optimisation cost function.

Novel method for IVHM System partitioning

The novel method for optimal partitioning of IVHM System is proposed for the first time in world-wide terms in Chapter 5. This method combines the research work on main drivers for partitioning and the novel optimisation criterion. It consists of five main steps to enable a generic application to different vehicles / platforms.

At first the CONOPS - driven weighting coefficients are estimated: the six-dimensional vector, $\boldsymbol{\lambda}$ (see Eq. 4.6), which corresponds to the defined main drivers for partitioning is defined. An example of aircraft turn-around time (TAT) is used to demonstrate the mapping of CONOPS into main drivers and, as a result, the estimation of weighting coefficients.

In the second step the total number of all possible system configurations is generated. It has been already noted that in some cases, due to e.g. legislative or technological limitations, not all the system configuration are possible. Thus it is important to exclude the non-feasible system configurations from the defined set. Once it is done, values of costs and gains, related to each system configuration, are generated in step three.

In step four the novel optimisation criterion, described in Chapter 4 is used to calculate values of optimisation cost function for each IVHM System configuration that has been generated in step three. At that stage the optimal system configuration is selected.

In step five the novel cost effectiveness analysis of the resulting optimal IVHM System configuration is performed. It is aimed to assess the results of the optimisation procedure and to provide a framework to compare all generated system configurations in terms of the value of optimisation cost function. The novel metrics to estimate effectiveness of the IVHM System partitioning are proposed based on a comparative analysis of cost and gains trade-off results obtained for each generated system alternative.

This method requires a high level knowledge of the vehicle / platform in question, including design, architecture, and its CONOPS. Different level of complexity can be seen for new design and the legacy (existing) system. Also the availability of e.g. in-service data plays important role especially when all costs and gains related to a particular system configuration has to be determined.

The proposed method is designed to be adapted to different vehicles / platforms at the different design stages and across different sectors (i.e. military aviation, civil aviation, marine systems, etc.).

The defined method for optimal partitioning has been implemented as a computer program in MATLAB. The implementation was validated using synthetic data-set. The MATLAB implementation and the obtained results were review and accepted by the project industrial partners. Finally, the technical report which consists of the method description and MATLAB implementation has been successfully submitted to the project industrial partners and accepted as one of the core project deliverables. The resulting computer program has been acknowledged by partners as potential future tool for IVHM System partitioning analysis.

Industrial application

The research work, presented in this thesis, has been completed is a part of the joint project between Cranfield University / Cranfield IVHM Centre and industrial partners from the aerospace sector: Boeing, Rolls-Royce, BAE Systems, Meggitt, and Thales Group. The research work has been monitored and actively supported by the industrial collaborators: this helped the author of this thesis to focus on the crucial aspects of IVHM System and to address the current gaps in scientific and engineering knowledge.

The presented in these thesis novel findings have been assessed in detail by the industry experts, principally from Boeing and Meggitt, and analysed during numerous technical progress review meetings. The key finding have been turned into technical reports and submitted to the project collaborators.

The developed method for optimal partitioning of IVHM System has been positively assessed and accepted by industrial partners. The computer program implementation of the developed method has been delivered to all partners and, upon detailed discussions and evaluations, it has been recognised as a novel technology available to partners, ready to be implemented to tackle real-life engineering problem of optimal partitioning of IVHM System. Multiple discussions were undertaken with Boeing that was particularly interested in project outcomes. Finally, Boeing accepted the developed method as a valuable option for performing Boeing's partitioning of IVHM System.

“We can only see a short distance ahead, but we can see plenty there that needs to be done.”

-*Alan M. Turing, (1950).*

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Appendices

Appendix A

Relative Impact on Cost and Weight due to IVHM / EHM System Implementation

Table A.1: IVHM / EHM System implementation relative costs and weigh estimated impact by [71], where: H - high, M - medium, and L - low. The

					Cost Impact		
		Element	**Sub-element**	Weight Imp.	Retrofit	New	Recurring
On-board	Engine	Sensor	Pressure (air, oil, fuel, hydraulic)	H	H	L	M
			Pressure Delta (oil/fuel filter, valves)	H	H	L	L
			Temperature (air, oil, fuel, hydraulic)	M	H	L	L
			Vibration	M	H	L	M
			Debris (oil, inlet, exhaust)	H	H	H	H
			Condition(oil, airfoils)	H	H	H	H
			Position (solenoids, actuators, etc.)	H	H	L	M
		Sensor Port or Mount	Tubing	M	H	L	L
			Casting	M	H	M	L
			Casing	M	H	M	L
			Bracket/mounting block	L	M	L	L
		Wiring		H	H	L	M
		Signal Conditioning/Power Supply		H	H	M	L
		Data Capture Hardware	EEC/FADEC	L	H	M	L
			Other Box (CEDU, PHMU, etc.)	H	H	M	M
		Airframe Interface		L	H	L	L
		Software	EEC/FADEC	L	H	L	L
			Other Box	L	H	L	L
		Testing		–	M	L	–
		Certification		–	M	L	–
	Aircraft	Signal Conditioning /Power Supply		H	H	L	L
		Engine	Interface	M	H	L	L
		SnapShot Data Capture Hardware	FDAU, DMU, DFDR, etc.	H	H	L	L
		Streaming Data Capture Hardware	QAR, DFDR, eFAST, etc.	H	H	L	M
		Data Storage	Hardware	H	H	L	L
			Software	–	H	L	L
		Data Reductio–nalysis	Hardware	H	H	L	L
			Software	–	H	H	L
		Data Transmission In Flight	ACARS	H	H	M	H
			Satellite Narrow Band	H	H	M	H
			Satellite Broad Band	H	H	H	H
		Data Transmission On Ground	Cellular	M	H	L	M
			Wi-Fi	M	H	L	L
			Manual - Removable Mia	L	M	L	L
			Manual - ownload	L	M	L	L
		Testing		–	H	H	–
		Certification		–	H	H	–
Off-board	Ground Station	Data Receipt	–	M	M	L	
		Data Unencryption		–	M	M	L
		Data Decompression		–	M	M	L
		Data Storage		–	M	M	L
		Data Analysis	Steady State	–	M	M	M
			Streaming	–	H	H	M
		Information Delivery to End user		–	H	H	L
		System Upgrades		–	M	M	M
		System Maintenance		–	L	L	L

Appendix B

Key Featurs of Vehicle Operations

B.1 CONOPS Document Structure: Example

Table B.1: Example of fleet CONOPS document structure [96, 95].

Sec.	Title	Key Elements
1	Introduction	Brief overview, Stakeholders
2	References	
3	Problem Statement	High level problem statement
4	Program or System History	Current needs, *likes* & *dislikes*
5	System Use	Detailed explanation of the system use including:
		Users, External system interfaces
6	System Boundaries	Graphic representation of the external system interfaces
		Text explanation of the details of each interface
7	System Environment	Basic system operating environment
		Operator and Maintainer environment
8	Constraints	Details to be designed around, including:
		Cost, Schedule, Technologies, Power, Weight, Life expectancy, Space to design in, Environment, Performance
9	System Models	Models or simulations that help to show how the system will be used
10	System Peripherals	Training, Supportability, Maintainability
11	Expected Output	Summary of what is to be done
		Prioritization of what is to be done
		Measure of effectiveness
12	Acronyms and Definitions	

B.2 Vehicle Maintenance Operations

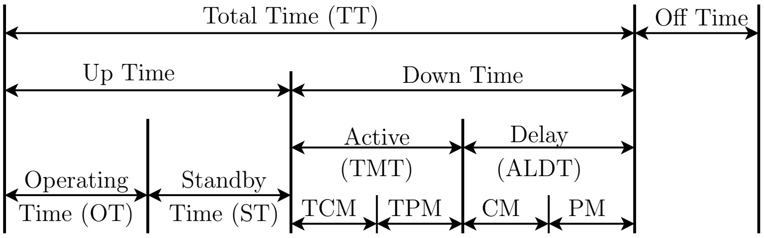

Figure B.1: Breakdown of total equipment time DoD 3235.1-H [78].

The basic mathematical definition of availability can be expressed as [78]

$$\text{Availability} = \text{A} = \frac{\text{Up Time}}{\text{TT}} = \frac{\text{Up Time}}{\text{Up Time} + \text{Down Time}} \tag{B.1}$$

Table B.2: Maintenance and availability: total equipment time breakdown.

Abbr.	Definition
TT	Total intended utilization period, total time.
TCM	Total corrective (unscheduled) maintenance time per specified period.
TPM	Total preventive (scheduled) maintenance time per specified period.
ALDT	Administrative and logistics down time spent waiting for parts, administrative processing, maintenance personnel, or transportation per specified period.
TMT	Total maintenance time = TCM + TPM.
TDT	Total down time =TMT + ALDT.
OT	Operating time (equipment in use).
ST	Standby time (not operating but assumed operable).
CM	Corrective maintenance
PM	Preventive maintenance
Off time	e.g. storage and transportation time

B.3 Vehicle Operation Cycle: Maintenance Operations

The diagram of vehicle operation cycle with an emphasis on maintenance operations, as shown in Figure B.2, is based on the FAA description of aircraft operation cycle in [131].

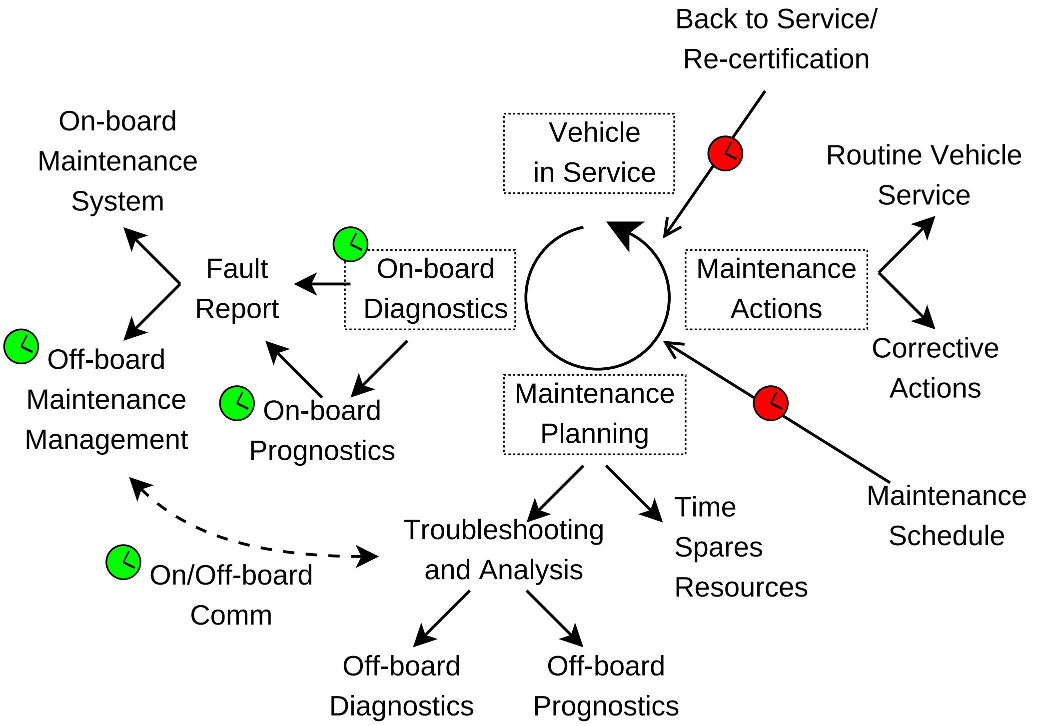

Figure B.2: Vehicle operation cycle: maintenance operations. The green dials indicate potential improvement of maintenance operations due to on-board IVHM System implementation, and the red dials indicate the potential delays.

B.4 Critical Systems: Hazard Categories

Table B.3: Hazard categories by FAA

Category	**Description**
No Effect	Failure conditions that would have no effect on safety; for example, Failure Conditions that would not affect the operational capability of the airplane or increase crew workload.
Minor	Failure conditions which would not significantly reduce airplane safety, and which involve crew actions that are well within their capabilities. Minor Failure Conditions may include, for example, a slight reduction in safety margins or functional capabilities, a slight increase in crew workload, such as routine flight plan changes, or some physical discomfort to passengers or cabin crew.
Major	Failure conditions which would reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example, a significant reduction in safety margins or functional capabilities, a significant increase in crew workload or in conditions impairing crew efficiency, or discomfort to the flightcrew, or physical distress to passengers or cabin crew, possibly including injuries.
Hazardous	Failure conditions which would reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be: a) A large reduction in safety margins or functional capabilities; b) Physical distress or excessive workload such that the flightcrew cannot be relied upon to perform their tasks accurately or completely; or c) Serious or fatal injury to a relatively small number of the occupants other than the flightcrew.
Catastrophic	Failure conditions which would result in multiple fatalities, usually with the loss of the airplane. (Note: A Catastrophic Failure Condition was defined in previous versions of the rule and the advisory material as a Failure Condition which would prevent continued safe flight and landing.)

Appendix C

MATLAB Implementation of the Optimisation Method

MATLAB Implementation of the Optimisation Method: Full Output Listing

The listing below is displayed to the user of partitioning optimisation MATLAB program each time the optimisation procedure is executed. It provides information about the program initial settings and results i.e. optimal system configuration, results of effectiveness measures and comparison between optimal system configuration $f(\hat{s})$ and the baseline configuration $f(s_1)$. Such listing is displayed in MATLAB command window and also stored into a text log file for future reference.

```
*************************************************************************
Optimal on/Off-board partitioning
  of IVHM system optimisation

Date: 03-May-2013 20:27:54

*************************************************************************
%-----------------------------------------------------------------------%
 On/Off-board partitioning optimisation settings
%-----------------------------------------------------------------------%
              N_sys: 9
       GenerateData: 1
       delete_files: 1
          xlsx_save: 0
      InputDataFile: 'CBA_Data'
    save_figure_ptr: 1
            LogFile: 'on'
       LogFile_name: 'Log_Optimal_Partitioning.txt'

%-----------------------------------------------------------------------%
 Results: Optimal On/Off-board partitioning
%-----------------------------------------------------------------------%

The optimal solution for 9 systems is:

 5 On-board IVHM systems:
System 1
System 4
System 6
System 7
System 9

 4 Off-board IVHM systems:
System 2
System 3
System 5
System 8

The optimal configuration is (see input data): 320
    'On'    'Off'    'Off'    'On'    'Off'    'On'    'On'    'Off'    'On'

Costs-Benefits Analysis resutls
- Costs:
Baseline:  4.859977
Partitioned:  4.875826
- Gains / Benefits:
```

```
Baseline:  3.755695
Partitioned:  9.784001
- Costs-benefits analysis (value of optimisation criterion)
Baseline:  -1.104282
Partitioned:  4.908175

Effectiveness of the optimal partitioning of IVHM system
1. Gain due to partitioning vs. baseline system
1.1 Optimal - Baseline:  = 6.012457

2. Optimal solution vs. mean value of non-optimal solutions
2.1 Optimal Gain:  = 4.908175
2.2 Average Gain:  = -1.021124
2.3 Optimal - Average Gain:  = 5.929299

3. Minimum gain: optimal vs. nonoptimal IVHM partitioning
3.1 Minimum Gain:  = 0.866041
3.2 Optimal vs. Minimum Gain [%]:  = 21 %

4. Maximum gain: optimal vs. nonoptimal IVHM partitioning
4.1 Maximum Gain:  = 12.118412
```