



AEROSPACE RECOMMENDED PRACTICE

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Guidelines for the Development of Architectures for Integrated Vehicle Health Management Systems

RATIONALE

This SAE Aerospace Recommended Practice (ARP) provides guidelines for development of the architecture for the design of an integrated vehicle health management (IVHM) system for aerospace platforms. The purpose of this document is to ensure that the architecture design covers the utilization of information responsive to the design requirements and to define and document an optimum architecture approach for an IVHM solution that is in line with the organization's business goals and objectives. Some efforts have tried to standardize the process of architecture development. For instance, ISO 13374 defined functional layers in building a CBM system. In addition, frameworks like DoD architecture framework (DoDAF) outline an architecture development process. This ARP incorporates these suggested standard practices into specific guidelines for IVHM. The guidelines are divided into sections that address each possible tier of the end to end architecture. The IVHM architecture may include: (1) The On-vehicle tier, which addresses the capture, processing, and packaging of on-board data; (2) the data transfer tier, which provides guidelines in the movement of data; (3) the at-vehicle tier, which includes maintenance support through data analysis and presentation equipment (such as a ground station or portable maintenance); and (4) the fleet data services and application tier, which includes a central, ground-based data center to provide processed data to the user community. Since each application of this tier is specific to a particular organization's operational use case, the various uses of the IVHM data by the user community are not addressed in this document.

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) provides guidance when creating integrated vehicle health management (IVHM) system architecture. IVHM covers a vehicle's monitoring and data processing functions inherent within its sub-systems, and the tools and processes used to manage and restore the vehicle health.

These guidelines are drawn from experience within both defense and commercial IVHM initiatives and implementations. The document identifies a step-by-step methodology to expose functional and non-functional requirements, mature the architecture and support organizational business goals and objectives.

2. APPLICABLE DOCUMENTS

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ARP4761	Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment
ARP6275	Determination of Costs and Benefits from Implementing an Integrated Vehicle Health Management System
ARP6407	IVHM Design Guidelines
ARP6883	Guidelines for Writing IVHM Requirements for Aerospace Systems
SAE JA6268	Design and Run-Time Information Exchange for Health-Ready Components

2.2 IEEE Publications

Available from IEEE Operations Center, 445 and 501 Hoes Lane, Piscataway, NJ 08854-4141, Tel: 732-981-0060, www.ieee.org.

IEEE STD 610.12 IEEE Standard Glossary of Software Engineering Terminology

2.3 RTCA Publications

Available from RTCA, Inc., 1150 18th Street, NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

RTCA DO-178C	Software Considerations in Airborne Systems and Equipment Certification
RTCA DO-254	Design Assurance Guidance for Airborne Electronic Hardware

2.4 U.S. Government Publications

Copies of these documents are available online at <https://quicksearch.dla.mil>.

Defense Acquisition University, "Systems Engineering Fundamentals"

The DoD Architecture Framework (DoDAF) and DoDAF Meta Model (DM2)

2.5 NASA Publications

NASA Technical Services, NASA STI Program STI Support Services, Mail Stop 148, NASA Langley Research Center, Hampton, VA 23681-2199, 757-864-9658, Fax: 757-864-6500, <http://ntrs.nasa.gov/>.

NASA Space Systems Engineering, "Trade Studies Module"

NASA Systems Engineering Handbook

2.6 U.K. Government Publications

Ministry of Defence Architectural Framework (MoDAF)

2.6.1 ISO Publications

Copies of these documents are available online at <https://webstore.ansi.org/>.

ISO 13374 Condition monitoring and diagnostics of machines - Data processing, communication and presentation

2.7 Other Publications

Carnegie Mellon University: Software Engineering Institute's System Architecture Tradeoff and Analysis Method (available at <https://resources.sei.cmu.edu/library/asset-view.cfm?assetid=513908>)

International Council on Systems Engineering (INCOSE): INCOSE Systems Engineering Body of Knowledge - Analysis and Selection between Alternative Solutions (available at <https://www.incose.org/>)

The Open Group Architectural Framework (TOGAF®) (available at <http://opengroup.org/togaf>)

MIMOSA OSA-CBM: Open System Architecture for Condition-Based Maintenance (available at <https://www.mimosa.org/mimosa-osa-cbm/>)

2.8 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.8.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

R-405 Integrated Vehicle Health Management: Perspectives on an Emerging Field

2.8.2 U.S. Government Publications

Copies of these documents are available online at <https://quicksearch.dla.mil>.

DoD Architecture Framework Version 1.5

The DoDAF Architecture Framework Version 2.02

2.8.3 NIST Publications

Available from NIST, 100 Bureau Drive, Stop 1070, Gaithersburg, MD 20899-1070, Tel: 301-975-6478, www.nist.gov.

FIPS 183 Integration Definition for Function Modeling (IDEF0)

2.8.4 ISO Publications

Copies of these documents are available online at <https://webstore.ansi.org/>.

ISO/IEC/IEEE 15288:2015 Systems and Software Engineering—System Life Cycle Processes

2.8.5 Other Publications

Allen, F. (1970). Control flow analysis. *SIGPLAN Notices* 5(7), pp. 1-19, doi: 10.1145/390013.808479.

Douglass, B. (1999). UML statecharts. *Embedded Systems Programming*, available at <https://www.embedded.com/uml-statecharts/>.

Gane, C. and Sarson, T. (1977). Structured systems analysis: Tools and techniques. *New York: Improved Systems Technologies*.

Lamm, J.G. and Weilkiens, T. (2010). Funktionale architekturen in SysML. In Maurer, M. and Schulze, S.-O. (eds.), *Tag des Systems Engineering*, pp. 109-118. Carl Hanser Verlag, München, Germany, November 2010. English translation by J. Lamm, available at https://www.oose.de/wp-content/uploads/2016/10/110427_TdSE2010_Lamm_Weilkiens_Functional_Architectures_English-1.pdf.

Taylor, R. (2012). Systems architecture processes, decisions, artifacts. *INCOSE Systems Architecture Seminar*, available at https://static1.squarespace.com/static/5cbc5f7b7980b3434f44ad6c/t/5cd86b1deb393159ba9db659/1557687071063/2012_03_31_SystemsArchitectureSeminar-Taylor.pdf.

Thompson, R., Colombi, J., Black, J., and Ayres, B.J. (2015). Model-based conceptual design optimization methods: Disaggregated weather system follow-on. *Journal of Spacecraft and Rockets* 52(4), doi: 10.2514/1.A33135, available at https://www.researchgate.net/publication/282518288_Model-Based_Conceptual_Design_Optimization_Methods_Disaggregated_Weather_System_Follow-On.

UK Ministry of Defense. (2010). The MODAF operational viewpoint. *UK Ministry of Defense*, available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/38711/20100426MODA_FOVViewpoint1_2_004U_1.pdf.

2.9 Acronyms and Abbreviations

A/C	Aircraft
ACARS	Aircraft Communications Addressing and Reporting System
ACMF	Aircraft condition monitoring function
AG	Advisory generation
BIT	Built-in test
BITE	Built-in test equipment
CAS	Crew alerting system
CBA	Cost benefit analysis
CBM	Condition based maintenance
CI	Configuration item

CMS	Central maintenance system
CONOPS	Concept of operations
D&C	Delays and cancellations
DA	Data acquisition
DAL	Design assurance level (as defined in RTCA DO-178C)
DB	Database
DFD	Data flow diagram
DM	Data manipulation
DoDAF	Department of Defense architecture framework
DTS	Data transfer system
EASA	European Aviation Safety Agency
EHM	Engine health monitoring
ERP	Enterprise resource planning
ESB	Enterprise service bus
FAA	Federal Aviation Administration
FFBD	Functional flow block diagram
FHA	Functional hazard assessment
HA	Health assessment
HRC	Health-ready component
I/O	Input/output
ICAS	Integrated crew alerting system
ICD	Interface control document
IVHM	Integrated vehicle health management
LGCU	Landing gear control unit
LGS	Landing gear system
LRU	Line replaceable unit
MBSE	Model-based systems engineering
MEL	Minimum equipment list
MoDAF	Ministry of Defense architecture framework

MTBF	Mean time between failure
MTTR	Mean time to repair
Nz, Ny, Nx	Load factors (in z, y, x directions)
OEM	Original equipment manufacturer
OIE	Operational information exchange
PA	Prognostic assessment
PMA	Portable maintenance aid
PSSA	Preliminary system safety assessment
PU	Processing unit
QFD	Quality function deployment
RF	Radio frequency
RUL	Remaining useful life
SD	State detection
SRD	Software requirements document
SysML	Systems Modeling Language
TLD	Time-limited dispatch
TOGAF	The Open Group architecture framework
USB	Universal serial bus
UUID	Universally unique identifier
WOW	Weight on wheels

3. INTRODUCTION

The recommended best practice and guidance provided in this ARP are strictly advisory in nature. They can be used with other IVHM ARPs and an organization's existing engineering design practices. There are situations where good design requires that these guidelines be extended or modified to exploit the vehicle's inherent design to realize the benefits of the particular IVHM system solution.

IEEE STD 610.12 defines architecture as, "...the structure of components, their relationships, their principles, and guidelines governing their design and evolution over time."

The system architecture considers physical components, functions, performance, technologies, cost, risk, constraints, boundaries, and internal and external interfaces that are all useful for documenting complex systems.

The SAE Integrated Vehicle Health Management Committee (HM-1) created documents to provide guidance on aspects of the IVHM development process (see 3.1). These documents utilize the system engineering activities outlined by the International Council on Systems Engineering (INCOSE) and the more specific IVHM systems engineering process described in SAE IVHM texts (see 2.1). In addition, the reader is directed to ISO 13374 for guidance on functional layers for health management systems.

The guidance provided in this document should help the practitioner to ensure that the architectural design addresses the system requirements, as well as defining and documenting an architecture for an IVHM solution that satisfies the organization's business goals and objectives. Since the IVHM practitioner may not have an extensive systems engineering background, some fundamentals of this discipline are repeated in an IVHM context. Systems engineers will likewise find IVHM-specific considerations which may not be obvious without prior IVHM experience.

3.1 The IVHM Development Process

IVHM system development starts, like most systems, by determining the organizational goals of the sponsoring and using communities. The requirements for the system evolve from these goals. The system architecture then provides a framework to govern the system design. The architecture must enable a detailed system design process to be completed. Together, these steps lead to a robust and efficient implementation that supports organizational goals and requirements for the planned life of the system. At each step, there are checks to ensure alignment with the constraints of previous steps. This leads to iterations in the process, where the design space is explored and new possibilities and constraints are revealed.

Other SAE Standards cover other portions of the development process. Organizational goals and business case are covered in ARP6275. Requirements development is addressed in ARP6883. These documents serve as the basic inputs to the architecture development process. Another potential input is covered in SAE JA6268, which covers health-ready components and systems. The concepts from this standard can help the IVHM architect standardize interfaces at various levels of the architecture. Finally, the architecture drives detail design as covered in ARP6407. Other IVHM standards (both current and future) may provide additional context.

3.2 IVHM Design Principles

There are four design principles to consider when developing an IVHM system for aerospace platforms:

1. Start with a systems view of the platform. This ensures that the solution incorporates the inherent design of the system, subsystem, vehicle interfaces, and data processing capabilities.
2. Integrate the inherent sub-system capabilities into an optimized solution. Unlike some platform capabilities, health management is not a self-contained, stand-alone function; at the platform level, it must satisfy numerous (often conflicting) sub-systems demands.
3. Address both monitoring and management needs. Health monitoring provides the data and information required to assess the health state of the overall system. Health management also encompasses the activities to restore it to a healthy state. This includes the resources and tools used to identify, manage, mitigate, and resolve actual and impending faults and failures.
4. Focus on data management. IVHM typically uses data processing technologies to exploit the inherent design features of a system in order to enhance safety and availability. The best IVHM solutions exploit automated data analysis and data transfer to maximize the value for the customer and user. Data management is therefore a critical issue to address during design.

3.3 System Architecture Overview

IVHM architecture usually begins with a systems view of the major tiers and their relationships (as shown in Figure 1):

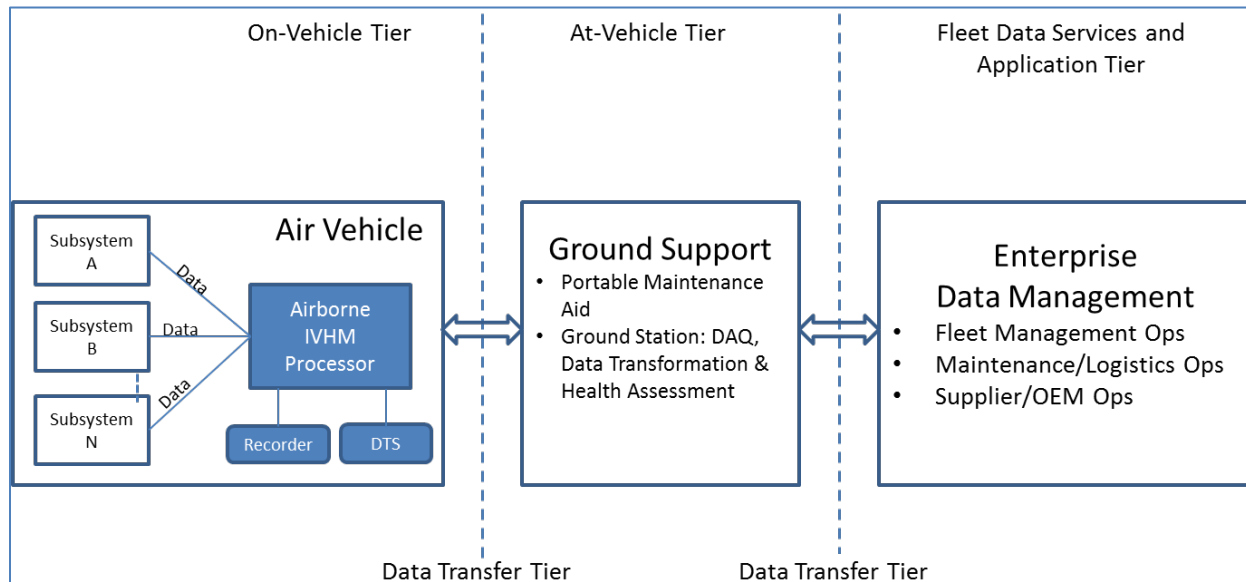


Figure 1 - General IVHM system architecture view

As shown in the diagram, the typical IVHM architecture will include:

- The on-vehicle tier: The capture, processing, and packaging of data on-board the vehicle being monitored.
- The at-vehicle tier: The maintenance support, through data analysis and presentation (such as a ground station or portable maintenance aid), necessary for effective line maintenance of the target vehicle.
- The fleet data services and application tier: Typically, a central, ground-based data center and the transformation, analysis and exchange, management, and archiving of the data to the user community. This is specific to an organization's needs so is not discussed in detail in this document.
- The data transfer tier: Specifications for the movement of data. Unlike the components, interfaces exist in multiple places (i.e., anywhere data crosses subsystem boundaries). This encompasses the uploading of algorithms to the air vehicle, transfer of collected data to a ground-based system for analysis, and transfer of aircraft data to a fleet data management system.

Each section of this ARP addresses one of the components of the end-to-end architecture. The IVHM architectural design should exploit existing health monitoring functions and accommodate existing infrastructure constraints, such as data acquisition, networks, data storage, processing capability, and throughput. These constraints may apply to both the vehicle and the off-board components.

3.4 Architecture Reference Model

A good architectural model will address the structure of components, their relationships and key principles within the systems architecture, and how they should be governed over time. This can include the organizational structure, business strategy, and the methods/tools employed to manage development (enterprise architecture).

From a systems architecture perspective, ISO 13374 recommends the use of the functional blocks shown in Table 1. These blocks are intended to aid in the development of condition based maintenance (CBM) systems.

Table 1 - ISO 13374 functional blocks - IVHM functional reference model

IVHM Functional Block	Description
Advisory generation (AG)	System functions provide actionable information to operational and maintenance personnel or external systems.
Prognostic assessment (PA)	System functions provide future state of health, performance life remaining, or remaining useful life (usage) indicators.
Health assessment (HA)	System functions provide information to determine the current state of health of equipment.
State detection (SD)	System functions evaluate equipment state conditions against normal operating profiles and generate normal or abnormal condition indicators.
Data manipulation (DM)	System functions process and transform the sensor data and health state information collected by the DA.
Data acquisition (DA)	System functions collect sensor data and health state information from equipment internal monitors, vehicle data bus, or data transfer system.

Using these functional blocks as the architecture reference model for IVHM provides a uniform reference for engineering analysis and definition of the architecture for any platform (new or legacy). Some platforms will already have on-board health monitoring capabilities (DA, DM, SD), thus may only require the health assessment (HA) and prognostics assessment (PA) functional layers and/or an enhancement to the advisory generation (AG) function within the vehicle or ground support system. Other vehicle components within the same platform may require new foundational layers. The IVHM architecture must address these technical variations.

This document incorporates these suggested standard practices into specific guidelines for developing IVHM system architectures. While ISO 13374 or the open systems architecture for condition-based maintenance (OSA-CBM; an implementation of ISO 13374 with a defined interface protocol) specification are not architecture standards, they provide a functional framework or reference model. This framework is used to characterize existing capabilities to expose functions that enable IVHM and define the optimum architecture.

In Table 1, the functional boundary of the core IVHM capability provides actionable information to operational users and external enterprise systems. For complete integration, an IVHM system requires functionality beyond this reference model. For example, the functionality must be associated with maintenance, logistics, and supply chain functions, such that together they provide full health management capability. These enterprise uses are discussed further in 4.11, but generally the IVHM architect has to understand the enterprise-specific functions that need to be added to the general reference model for their specific implementation.

From an enterprise architecture perspective, frameworks like The Open Group Architectural Framework (TOGAF), Department of Defense Architectural Framework (DoDAF) and Ministry of Defence Architectural Framework (MoDAF) provide support in the development of architecture. Enterprise architecture can be used to monitor progress, manage the operation of the IVHM system, implement changes and updates to a deployed IVHM system, and integrate and align the IVHM system with the business needs. This architectural framework bridges the gap between the ISO 13374 reference model and business needs. Figures 2 and 3 provide examples of how DoDAF and MoDAF can be used to document the structure of an organization and define how the organization realizes IVHM capabilities. In recent years, the enterprise community has worked towards merging these frameworks.

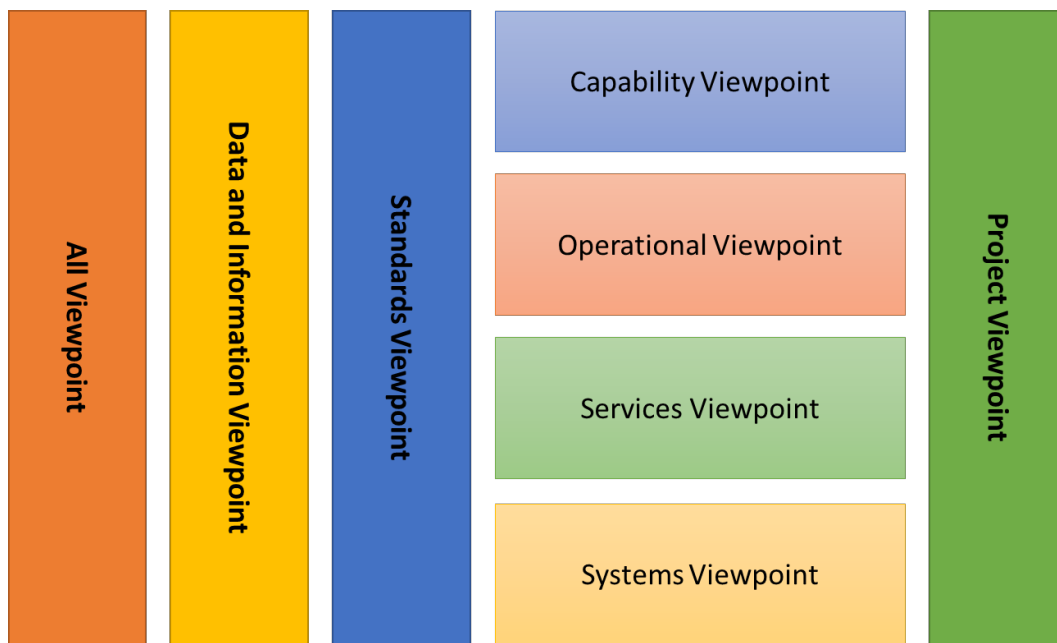


Figure 2 - DoDAF example

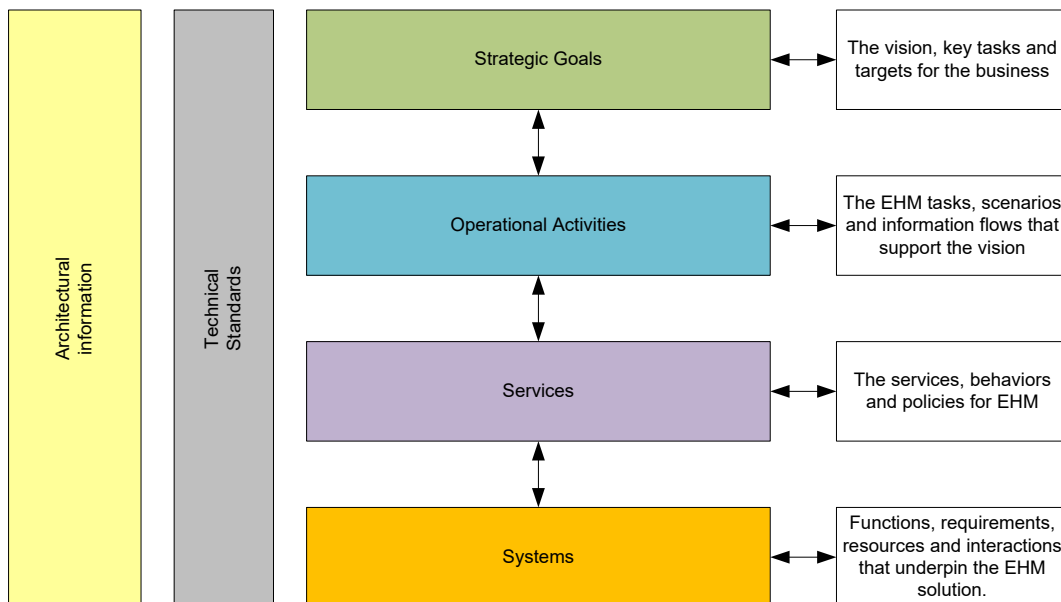


Figure 3 - MoDAF example

3.5 Operational User Considerations

The IVHM architecture should address the enterprise goals that are pertinent for managing the health of the vehicle, maintaining the vehicle functionality during the course of its mission and for successful achievement of the mission goals and sustainment of the vehicle during its life cycle. For commercial aircraft, the enterprise goals might include successful completion of the flight and avoidance of delays and cancellations. For military vehicles, the goal might be a successful completion of the mission. Architectural descriptions (models, data, context, and artifacts) should be a combination of a scenario-based and a function-based descriptions. A major objective of the description is to provide a uniform interpretation of the IVHM functions and operational results throughout the vehicle monitoring enterprise.

The architecture development should enumerate the information needed by the operational processes—capture and provide data to the organization entities (such as the supply chain) that require the information, provide data for tasks or activities performed by the organization, information that must be exchanged, the nature and type of information exchanges, the frequency of the exchange, and the tasks and activities that the information exchange supports. Several defined engineering processes provide methods for capturing this information exchange. Each process identifies several artifacts to describe the information. One example artifact is the operational information exchange (OIE) matrix, which defines the information exchange between the system functions (see 4.2).

4. ARCHITECTURE DEVELOPMENT PROCESS

A generic architectural development process for IVHM is presented herein. Table 2 provides an overview of the recommended architectural steps. The following steps are applicable to both a new design and implementation on a legacy platform. As stated earlier in this document, system requirements should be available at the start of the architecture development process. In addition to system requirements, the up-front development of a system safety analysis and functional hazard assessment, as it relates to IVHM functionality, is of paramount importance. The results of these analyses will establish the expectations for IVHM hardware and software development, with respect to development assurance levels (DALs). In the case of aerospace systems, they will guide the system architect through RTCA DO-178C for IVHM software and RTCA DO-254 for IVHM hardware. The results of these analyses will also influence safety-related architectural decisions, for example, the use of IVHM functional redundancy and partitioning.

Table 2 - Architecture development steps overview

Process	Inputs/Outputs	Activities
Step 1	Requirements Review	This step involves a review of the system requirements for completeness and appropriateness. A cleaned set of baseline requirements is the output of this step.
Step 2	Requirements Analysis	This step involves an in-depth analysis of the requirements prior to any architecture development. This analysis helps to expose conflicts that arise from requirement interactions and constraints.
Step 3	Define Logical Architecture Options	In this step, candidate logical architectures which may meet the requirements are defined. Enough options should be considered to encompass high-level architectural trade-offs (e.g., on-board versus off-board, centralized versus distributed).
Step 4	Constraints Analysis and Physical Architecture Options	This step involves identification of physical architecture options which may fit within the system constraints. This includes identification of components (hardware, software), users, and their relationships.
Step 5	Functional Requirements Allocation to Subsystems	This step involves assigning functions to physical architectures which can meet the overall system requirements. This includes decomposition and allocation of sub-functions specific to each of the candidate architectures, which may force changes to the architecture to meet functional or non-functional requirements.
Step 6	Architectural Design Evaluation/Validation	This process step provides a methodology for evaluating cost, weight, and performance to compare the options. The result of this step is selecting the final “best fit” architecture.
Step 7	Document	In this final step, the artifacts created in previous steps, along with the final, down-selected architecture description are stored as part of the architecture documentation package for future reference. In addition, specifications to flow-down requirements to lower-level system development are produced.

Table 3 shows this development process and some representative artifacts produced and updated in each step. These have been compiled from industry best practice to highlight architectural issues pertinent to the development of an IVHM system. The process assumes that requirements definition is complete since this is a critical process input.

Specific customer, organization, or vehicle programs may mandate their own architecture development process, method, tools, and artifacts. As such, some of these artifacts may be known locally by different names; however, the role and purpose should be broadly similar regardless of organizational differences. The recommended work artifacts can be generated using any particular design tools and practice used by the engineering organization. Regardless of the specific methods used, the IVHM system architect should document an architecture design plan which outlines which steps, artifacts, etc., are to be included in a particular project prior to starting the process. This will ensure process integrity. Such documentation can serve as the project's charter.

Table 3 - Architecture development process and artifacts

SECTION	ARTIFACTS	STEP 1	STEP 2	STEP 3	STEP 4	STEP 5	STEP 6	STEP 7
		Functional Requirements Review	Functional Requirements Analysis	Define Logical Architecture Options	Constraints Analysis and Phys. Arch. Options	Functional/(Requirements) Allocation to Subsystems	Architecture Design Eval/Validation	Documentation
4.1	System Boundary Diagram	I/C	U					feedback to requirements process
	CONOPS / Op Scenario Diag.	I/C	U					
	Constraints List	I/C	U		U			
	Requirements List	I/C	U					
	Function List	I/C	U					
4.2	Functional Hierarchy Diag.	I/C	U					
	Mode/State Transition Diagrams		C	U				
	Mode/State/Function Matrix		C	U				
	IE Matrix		C	U				
	Functional Flow Block Diagram		C	U				
4.3	Data/Control Flow Diagrams		C	U				
	Logical Arch. Diagrams			C				
4.4	Config. Item Lists				C	U		U
	Arch. Hierarchy Diagrams				C	U		U
4.5	Arch Flow/Interface Diagrams					C		U
	Allocation Table (CI Matrix)					C		U
	Requirement Traceability Matrix (physical allocation of requirements)					C		U
4.6	Trade Study Results						C	
4.7	System Architecture Documents							C
	Lower-Level Specifications							C
	Draft ICD's							C
	Approval Documentation							C
		I	Input	C	Create	U	Update	



The goal of this process is to define an IVHM system architecture that meets the stakeholder needs, exploits existing health monitoring functions and accommodates existing infrastructure constraints, such as data acquisition, networks, data storage, processing capability, and throughput, as well as defines the interfaces and integration needed for successful IVHM design and development. The goals are achieved by evaluating the system requirements against any existing capabilities and constraints, then following the process steps enumerated above. The following sections elaborate on each of the seven steps in the recommended methodology, including design tradeoffs and architectural considerations pertinent for IVHM design. Each subsection summarizes the main inputs and outputs at each step. Appendix A provides a worked example using a portion of these steps. Appendix B provides example artifacts to assist the reader.

4.1 Step 1: Requirements Review

4.1.1 Inputs and Outputs

Inputs: Target member systems will include propulsion, power, landing gear, structures, and avionics (list not comprehensive). Source documents which are useful in performing this step include the following:

- IVHM system requirements document (refer to ARP6883).
- IVHM system CONOPS.
- Aircraft-level certification documents, such as the functional hazard analysis (FHA).
- Target vehicle system/subsystem product specifications (including interface control documents, if available).
- Existing vehicle health management system description.
- Ground support system description.

4.1.2 Overall Goals

The primary purpose of this step is to review the stakeholder needs and objectives, which should be provided with associated concepts of operations (CONOPS). If this is not the case, developing stakeholders needs and objectives is strongly recommended as they will be used extensively in architectural development both to guide the architecture design and to support validation and verification activities. Use cases (as described in ARP6883) can also help the designer understand the operation of the IVHM system.

If the system requirements were developed to address high-priority mission critical subsystems, the review should focus on developing a good understanding of the stakeholder's needs and expectations for the IVHM capability and how those needs and expectations relate to the target IVHM system objectives. A preliminary system safety analysis (ARP4761) is particularly important for these systems, as well as for consideration of the effect of the design on future certification. This initial review should help in determining which subsystems in the aircraft will serve the most needs and deliver the most benefits when IVHM is implemented. The team needs to already have analysis results for each subsystem and components that will reasonably need some monitoring capability to identify all significant failure and degradation mechanisms so the proper and applicable monitoring capabilities are chosen.

The step should include creation of a systems view of the platform to allow the designer to explore the capabilities and limitations of any existing infrastructure. By definition, IVHM should focus on integration of the system, subsystem, vehicle interfaces, and data processing capabilities. The objective is for the development team to understand:

1. The vehicle inherent design and capabilities and how they relate to IVHM.
2. The existing vehicle health management functions.
3. Ground support system description current capability, operational, and sustainment strategies.
4. The aircraft-level certification approach (e.g., FHA) and the safety implications associated with the loss or malfunction of any IVHM functions.

4.1.3 User Community Needs and Objectives

The development team should build a detailed understanding of all the system users and how they intend to interact with the system. The architect must check that the user needs and system objectives map to specific non-functional performance requirements (including safety) described in the requirements document.

Part of the task in this step is to develop (or review) the system boundary diagram and stakeholder map. These will include all the stakeholders, their issues and provide a top-level summary of their interface to the IVHM system. It is tempting at this phase to expand the scope to cover the “nirvana” state of interconnectedness with multiple enterprise systems. The authors caution against over-burdening IVHM system development with too many external system integration tasks. A focus on core IVHM development first with a progressive integration approach (starting with only the minimal connections) is preferred to avoid creating a scope that may be too large to accomplish.

Figure 4 provides a generalized view of many possible stakeholders. Note that other stakeholders may also be present (e.g., training), and this figure is meant to be illustrative. Additionally, not all of the shown stakeholders need be considered in all systems (due to cost, complexity, and other considerations) as discussed in the previous paragraph. The diagrams show the goals and the metrics for the listed user communities. The specific user communities' goals, objectives, and process metrics for the IVHM system should be extracted from the requirements document and the CONOPS.

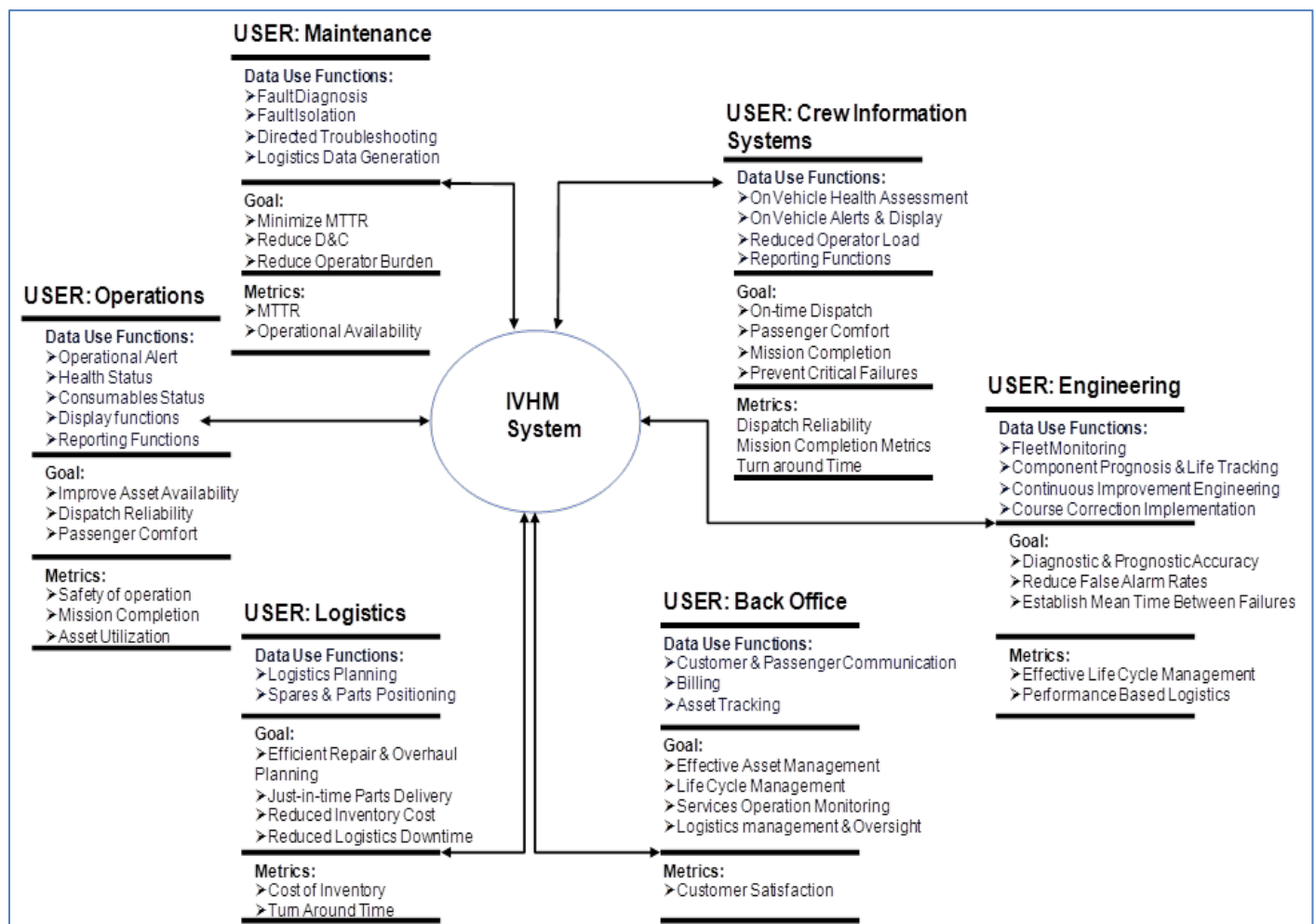


Figure 4 - System (boundary) diagram

The IVHM system architecture may incorporate the business information and related processes. These processes include maintenance information such as that used to create maintenance manuals for maintainers at both vehicle line maintenance and vehicle repair facilities. In addition, information required by logistics and the supply chain, to ensure the timely availability of parts, and information needed by the operational processes to meet the front office operational needs must also be addressed. This complexity drives the architect to develop use cases defined by the stakeholders across all business processes within the vehicle operational enterprise. Again, as previously stated, business information system integration complexity should not be underestimated. Therefore, carefully consider the business case of each of these interfaces prior to proceeding.

Key considerations which may have far-reaching effects on the architecture and therefore should be part of this assessment:

- **Criticality:** IVHM data may be required to support highly critical functions. Such areas will require special focus during the architecture development process. Possible impacts (to be developed in later steps) include hardware redundancy and software partitioning. The impacts of these applications should be well understood through a preliminary system safety assessment per ARP4761 prior to proceeding. Examples include:
 - Flight crew display—e.g., crew alerting system (CAS).
 - Maintenance credit—extending maintenance (and thus affecting airworthiness) using IVHM data.
 - Criticality by proximity/connectivity—in an integrated architecture, proximity/connectivity to critical data/systems may impose additional requirements.
- **Timeliness:** IVHM may be required to support time-critical functions. Examples include:
 - Autonomy—information is used in real-time to provide feedback to flight control and/or autonomous flight director functions.
 - Operations center—receiving data to make operational decisions such as contacting flight crew to change flight plans (e.g., to change destinations for convenience to address indicated health issues). Note that use of such an approach to meet safety objectives would be prohibited without airworthiness certification.
- **Data security/privacy:** Any of the users may have concerns here (even if not directly tied to a use case). There may also be regulatory requirements that apply.
- **Cross-organizational consideration:** the issues of data crossing multiple organization boundaries (from the aircraft integrator and suppliers and to the end users) adds significant complexity which may not be anticipated. Early coordination with all parties to drive agreements in this area is highly encouraged.

4.1.4 Inconsistencies and Constraints

The requirements review should identify inconsistencies in requirements and technical or process constraints related to the system, vehicle, and ground support system infrastructure. The technical and process constraints are usually known and are often contained in the vehicle product specifications. Other IVHM requirements are a result of decomposing the requirements from the top-level requirements contained in the vehicle specifications.

IVHM architectures which cover on-aircraft sensors and multiple off-board systems are particularly complex. The design may include integrating different data sources into one analysis system and providing the output of data to multiple end users. Since interfaces are usually the weakest link, the review must clearly identify the stakeholders and their data needs. Development of the interfaces will begin in Step 2.

Outputs: A set of baseline system requirements understood by the designer. This may include goals and metrics that can be used to evaluate the success of the system or verify its performance.

4.2 Step 2: Requirements Analysis

4.2.1 Inputs and Outputs

Inputs: This step involves detailed analysis and harmonization of the baselined functional requirements. Inputs to this step include the baselined requirements and artifacts developed by the IVHM development team in Step 1.

Outputs: Use cases, activity diagrams, and general descriptions of how the IVHM system will work in its representative environment. Artifacts can include:

- Baseline system requirement specification.
- Use case specification.
- Use case activity diagram.
- Sequence diagrams.
- Statechart diagrams.
- Operational information exchange (OIE) matrix.
- Functional flow block diagram.
- Mode/state transition diagrams.
- Mode/state/function matrix.
- Data/control flow diagrams.

4.2.2 Use Case Specification

Use cases, specified in non-technical language, provide a way to explore and understand the customer's requirements. Use cases can help to describe the functional needs, define the system boundaries, and identify important interfaces. They are also a valuable input into verification and validation activities and are often used to support user acceptance testing. The IVHM architect should have use cases associated with each user/stakeholder in the system boundary diagram. In cases where some of the architecture is defined by the customer or is constrained to reuse existing systems, use cases may be considered for interactions between the on-board and off-board subsystems.

A use case is a story of how the IVHM system and its actors collaborate to achieve a specific goal. This information is often captured in a step-by-step description of a particular system in use. The collective set of use cases should address as broad a range of customer needs as possible.

For more detailed development, the IVHM team should consider the development of activity diagrams. These are used to explore the behavior of the system in more detail, exposing key interfaces and interactions (including the sequence of events) that must occur for the system to operate to the user's satisfaction.

4.2.3 IVHM Data and Information Exchange Requirements

The focus when developing use cases is on the interactions between the system and its external environment (black box behavior). For an IVHM system, this external requirement can be other on-aircraft systems as well as external business systems. The data and information provide the critical link to both. IVHM cannot be achieved without a clear understanding of how the data is to be used to provide a benefit to the business and the data sources needed to reach this end goal. In fact, data integration and the exchange between disparate sources often provide the business case to justify the cost of a vehicle health monitoring system.

While the fusion of data sources to manage a business operation is beyond the scope of IVHM it is clear that health management has a critical role in the efficient operation of an enterprise. From a simple notification of a technical problem to the global management of spare parts inventory, the data and information exchanged between systems is fundamental when determining the optimal architectural solution. For this reason, during the requirements analysis phase, the interfaces to enterprise systems should be well defined and understood before any decision is made on the design of the lower level systems. The starting point is to consider how the data will benefit the business and then work towards an IVHM architecture that ensures this data is available to the enterprise elements that need the information. While this type of optimization may seem simplistic, it can result in significant cost savings. Where the development teams are not starting from a blank page, reaching back into the requirements process to identify revisions needed to ensure that the stakeholder use cases are properly represented, is a critical early phase activity.

The desire to fuse data sources is often tempered by the realities of implementation. While on-aircraft and at-aircraft systems may be in the control of the original equipment manufacturer (OEM) or system supplier (yielding uniform, controlled data sets), these external data sources often are neither controlled by the OEM nor uniform. This variety in data sources can result in significant complexity until broad standards are established. The responsibility of the IVHM architect is to mitigate the worst effects of this misalignment and to minimize the implications on the overall system goals.

4.2.4 Tier Consideration

In the early stages of development, the IVHM team should consider the fundamental structure of the architecture. For IVHM, there are usually four tiers (Figure 1):

1. On-vehicle.
2. At-vehicle.
3. Data transfer.
4. Fleet data services and application.

The tiers are specified in terms of physical separation. There are different options available to the IVHM team during development. An example of high-level physical architectures is shown in Figure 5.

- Option A: Vehicle-only (not-recommended).
- Option B: Extends the architecture to include at-vehicle equipment to transfer data but it does not include any fleet data services (not recommended). These are necessary to achieve integration. Many in-service systems stop at one of these levels.
- Options C to F: IVHM architectures that may or may not include the at-vehicle tier (though at-vehicle capability is recommended). Different combinations of data transfer (either serially or in parallel) are also shown.

Other options may be possible. Constraints may limit which options are available for a particular application. Not all tiers may need to be addressed during architectural development. At the very least, the IVHM team must consider the implications of the architecture on each tier.

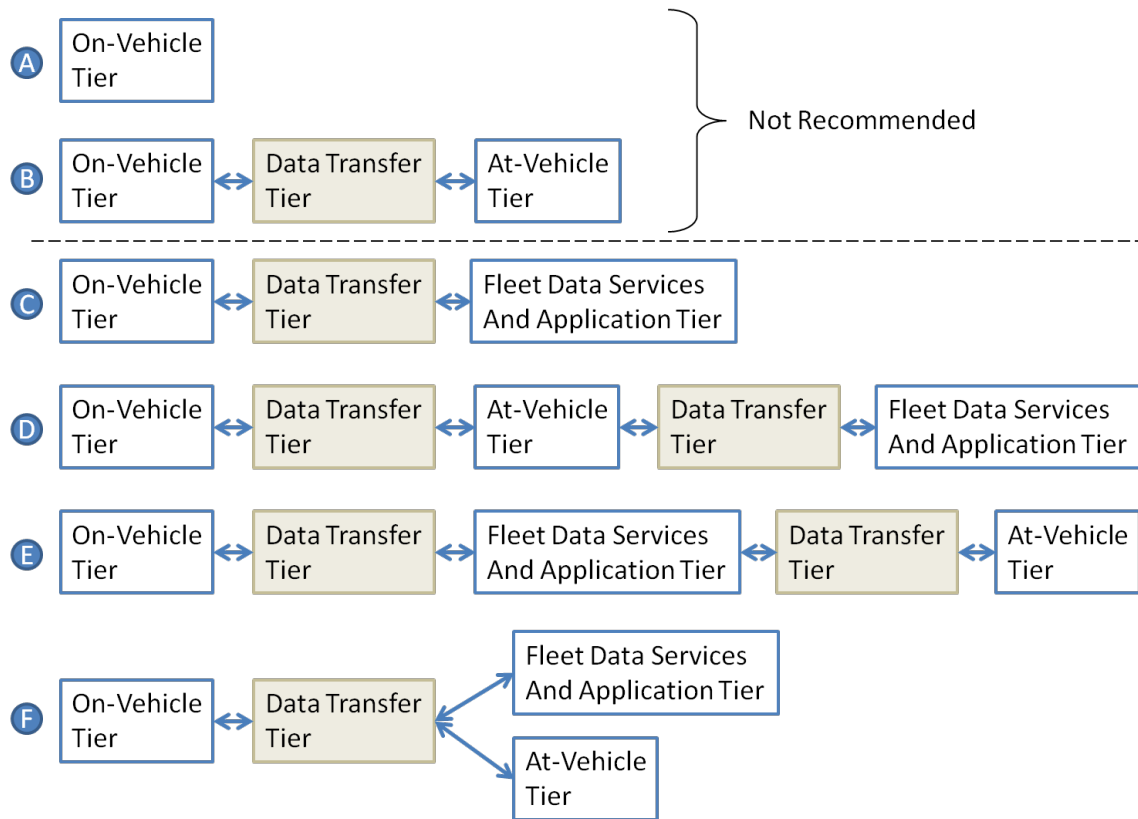


Figure 5 - Physical architecture options at the tier level

Within each tier, different physical architectures may exist which fit within the known constraints.

Consideration of tiers helps the design team to organize the development process and to manage the various requirements. Even if there is no requirement to develop a solution at one of these tiers, integration and alignment will mandate a review at each level. The requirements analysis should consider whether these tiers could place any constraints on the architectural solution. Constraints that will be examined in more detail in Step 4 when the physical architecture options are considered.

For IVHM development, the following aspects are worth considering:

4.2.4.1 On-Vehicle Tier

- Maximize re-use of existing data sources and interfaces. Wherever possible, architect the on-vehicle tier to maximize connectedness to other aircraft data sources to reduce the chance that the IVHM architecture will necessitate additional sensors and improve the overall business case.
- On-board versus off-board:
 - In general, data acquisition must be done in the on-vehicle tier. Other functions may be appropriate in other tiers.
 - Consider allocating functions to the on-vehicle tier when:
 - Timeliness is important (e.g., use for real-time decision making by flight crew or ground personnel).
 - Data transmission bandwidth is low (e.g., no way to send all the raw data off the aircraft post-flight).
 - Data storage capacity is low (processing of raw data “at the edge” is required to reduce data volume).

- Consider allocating functions to other tiers when:
 - Timeliness is less important.
 - Data transmission and storage resources on the vehicle are not a concern.
 - Capture of the raw data is important (e.g., to support development and validation of new algorithms - which is often overlooked).
- Distributed versus centralized:
 - An early design decision involves whether to push data acquisition and processing functions to remote modules throughout the system or the aircraft or whether to centralize data acquisition and processing in a centralized unit. This trade-off may look different to a system supplier than to an aircraft integrator. For the integrator, this may be answered by whether (a) aircraft systems are connected (physically or functionally), and (b) these systems already have health-ready capabilities. If so, the system is likely distributed (at some level) by default. For the system supplier, this trade-off may consider whether to have multiple data acquisition units tied to the aircraft, or one central data acquisition system with wires to each sensor. Obviously, for some small systems or components, distribution will not be practical.
 - Consider centralized architectures when:
 - The vehicle is small and the weight of wiring the sensors to the centralized unit(s) is minimal (as compared to the weight of distributed data acquisition units).
 - Access to data buses is minimal.
 - Re-use of existing centralized hardware is desired, and/or the cost of qualifying separate data acquisition modules is high.
 - Existing systems do not already report their own health status.
 - Consider distributed architectures when:
 - The vehicle is large, and weight may be excessive for running wires from each sensor to a central data acquisition module (as compared to the weight of the distributed data acquisition units).
 - Many health-ready (SAE JA6268) components or systems can report their own health.
 - There is ample ability for distributed data acquisition to tie into aircraft data buses.
 - Re-use of existing distributed hardware is desired.
- Shared versus dedicated resources (integrated versus federated):
 - This trade-off involves whether to host IVHM functions in dedicated (federated) hardware versus hosting IVHM functions in software hosted in shared (integrated) hardware. The latter is becoming increasingly common in new designs.
 - Consider dedicated resources when:
 - Designing a retrofit system; existing designs may have limited ability to add functions to hardware which was not designed for it.
 - Simplicity is desired.
 - Frequent updates are needed; changing software on shared resources may be more difficult than on systems that involve multiple functions and may require additional testing.