

CRANFIELD UNIVERSITY

ANDREW EDWARD HEATON

A Method to Support the Requirements Trade-Off of Integrated
Vehicle Health Management for Unmanned Aerial Systems

Integrated Vehicle Health Management
School of Applied Sciences

PhD
2011 - 2014

Supervisors: Ip-Shing Fan, Craig Lawson
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This thesis is submitted in partial fulfilment of the requirements for
the degree of Doctor of Philosophy

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Abstract

The digital revolution in the latter part of the twentieth century has resulted in the increased use and development of Cyber-Physical Systems. Two of which are Unmanned Aerial Systems (UAS) and Integrated Vehicle Health Management (IVHM). Both are relatively new areas of interest to academia, military, and commercial organisations.

Designing IVHM for a UAS is no easy task – the complexity inherent in UAS, with projects involving multiple partners/organisations; multiple stakeholders are also interested in the IVHM. IVHM needs to justify itself throughout the life of the UAS, and the lack of established knowledge makes it hard to know where to start. The establishment and analysis of requirements for IVHM on UAS is known to be important and costly – and for IVHM a complex one. There are multiple stakeholders to satisfy and ultimately the needs of the customer, all demanding different things from the IVHM, and with limited resources they need to be prioritised. There are also many hindrances to this: differences in language between stakeholders, customers failing to see the benefits, scheduling conflicts, no operational data.

The contribution to knowledge in this thesis is the IVHM Requirements Deployment (IVHM-RD) – a method for a designer of UAS IVHM to build a tool which can consolidate and evaluate the various stakeholder's requirements. When the tool is subsequently populated with knowledge from individual Subject Matter Experts (SMEs), it provides a prioritised set of IVHM requirements. The IVHM-RD has been tested on two design cases and generalised for the use with other designs. Analysis of the process has been conducted and in addition the results of the design cases have been analysed in three ways: how the results relate to each design case, comparison between the two cases, and how much the relationships between requirements are understood. A validation exercise has also been conducted to establish the legitimacy of the IVHM-RD process. This research is likely to have an impact on the elicitation and analysis of IVHM requirements for UAS – and the wider design process of IVHM. The IVHM-RD process should also prove of use to

designers of IVHM on other assets. The populations of the design cases also provide information which could be useful to other designer and future research.

Keywords:

Integrated Vehicle Health Management, IVHM, Unmanned Aerial Systems, UAS, Design, Requirements Analysis, Stakeholders

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Biography

Andrew gained his BSc in Aerospace Technology with Management in 2009 from the University of Hertfordshire – during which he spent his second year was spent on exchange at West Virginia University in the United States, and was a member of the UAS Team in his final year. He then went on to receive an MSc in Aerospace Engineering from Brunel University in 2010. During his PhD studies he was a finalist for the Royal Aeronautical Society UAS Group's Innovation Award at the 2012 conference.

Publications Related to PhD

Heaton, A. E., Fan, I. P., Lawson, C., McFeat, J. and Hill, J. (2012), "Assessing Vehicle Health Management Requirements for Unmanned Air Systems", Infotech@Aerospace 2012, 19 - 21 June 2012, Garden Grove, CA, AIAA.

Heaton, A. E., Fan, I., Lawson, C. and McFeat, J. (2012), "Integrated Vehicle Health Management and Unmanned Aviation [Poster]", First European Conference of the Prognostics and Health Management Society 2012, 3-5 June 2012, Dresden.

Heaton, A. E., Fan, I., Lawson, C. and McFeat, J. (2012), "A Business Case for IVHM on Commercial UAS [Presentation]", 2012 Royal Aeronautical Society's Unmanned Aircraft Systems Annual Conference, UAS Operations: Dependable, Effective, Efficient, 20 September 2012, London, Royal Aeronautical Society.

Heaton, A. E., Verma, R., Fan, I., Jennions, I. K., Lawson, C. and McFeat, J. (2013), "Defining Integrated Vehicle Health Management Requirements for Unmanned Aircraft Using a QFD Approach", Infotech@Aerospace 2013, 19-22 August 2013, Boston, MA.

Heaton, A. E., Fan, I., Lawson, C. and McFeat, J. (2014), "Health Monitoring Requirements for UAS [Presentation]", RPAS Today - Opportunities and Challenges, 10th-12th June 2014, London, Royal Aeronautical Society.

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Nomenclature

A	Availability
A_a	Achieved Availability
ACTD	Advanced Concept Technology Demonstration
A_i	Inherent Availability
AI-ESTATE	Artificial Intelligence Exchange and Service Tie to All Test Environments
A_o	Operational Availability
ASTRAEA	Autonomous Systems Technology Related Airborne Evaluation & Assessment
BLOS	Beyond Line of Sight
CAA	Civil Aviation Authority
CPS	Cyber-Physical System
CS	Control Station
DDD	Dull, Dirty, or Dangerous
DIKW	Data-Information-Knowledge-Wisdom
DoD	Department of Defense
EASA	European Aviation Safety Agency
EO/IR	Electro-Optical/Infrared
EHM	Engine Health Monitoring
EPSRC	Engineering and Physical Sciences Research Council
FH	Flight Hours
FH_{Sched}	Flight Hours Scheduled

FH _{Total}	Cumulative Fleet Flight Hours
FLAVIIR	Flapless Air Vehicle Integrated Industrial Research
FMECA	Failure Modes Effects and Criticality Analysis
ft	Feet
GCS	Ground Control Station
HALE	High Altitude Long Endurance
HM	Health Monitoring
HoQ	House of Quality
hrs	Hours
IAI	Israeli Aircraft Industries
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering
ISR	Intelligence, Surveillance, and Reconnaissance
IVHM	Integrated Vehicle Health Management
IVHM-RD	IVHM Requirement Deployment
KPI	Key Performance Indicators
kg	Kilogram
km	Kilometre
LOS	Line of Sight
\bar{M}	Mean Active Maintenance Time
m	Metre
MALE	Medium Altitude Long Endurance
MAV	Micro Aerial Vehicle

M_{ct}	Corrective Maintenance Time
MIMOSA	Machinery Information Management Open System Alliance
MMH/FH	Maintenance Man-Hours per Flight
MoD	Ministry of Defence
MR	Mishap Rate
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance
MTCR	Missile Technology Control Regime
MTD	Mean Down Time
MTTR	Mean Time to Repair
MUAV	Mini Unmanned Aerial Vehicle
$N_{ab,Mx}$	Number of Aborts Due to Maintenance Issues
NAV	Nano Aerial Vehicle
N_{ClassA}	Number of Class A Mishaps
N_{Cx}	Number of Cancellations
N_{Rep}	Number of Repair Activities
$N_{Sorties}$	Number of Sorties Launched
Obj	Objective
OEM	Original Equipment Manufacturer
OSA-CBM	Open Systems Architecture – Condition Based Maintenance
PSS	Product-Service System
PWC	Pair-Wise Comparison
QFD	Quality Function Deployment

R	Reliability
R_{Mission}	Mission Reliability
SE	Systems Engineering
SH	Stakeholders
SIMICA	Software Interface for Maintenance Information Collection and Analysis
SME	Subject Matter Expert
t	Time Interval
$T_{\text{Rep,Tot}}$	Sum Of The Repair Time
TUAS	Tactical Unmanned Aerial System
UA	Unmanned Aircraft
UA-P	Unmanned Aircraft Pilot
UAS	Unmanned Aerial Systems
UK	United Kingdom
US	United States of America
VLA	Very Light Aircraft
WCG	Weight Classification Group
λ	Incident Rate

1 Introduction

During the Digital Revolution in the latter part of the twentieth century the size and cost of producing many electronic components has fallen, resulting in the rising use of Cyber-Physical Systems (CPSs) – computation integrated with physical processes[1]. Two such ways in which CPS have manifested are: systems Health Monitoring (HM) technologies, where sensors are placed on a system to ascertain how well that system is functioning and if any failures are imminent. The second is, Unmanned Aerial Systems (UAS), where the human pilot for the aircraft has been located off-board the aircraft. UAS are Systems-of-Systems (SoS) consisting of elements, primarily the Unmanned Aircraft (UA) and the Control Station (CS) – all elements are needed to operate the UAS.

Integrated Vehicle Health Management (IVHM) is an extension of the HM technologies, bringing together the data and information for individual systems of a vehicle. This information can be then used to assess the health of the vehicle, and the health of the fleet which it operates in. The health information can be used to make informed operations and maintenance decisions.

1.1 Project Background

The funding for this project has been provided by the EPSRC's (Engineering and Physical Sciences Research Council) Industrial CASE PhD studentship with the industrial lead on the project being BAE Systems. BAE Systems is a partner in Cranfield University's IVHM Centre and has worked with the university on numerous projects, including the award winning FLAVIIR (Flapless Air Vehicle Integrated Industrial Research) project – which produced the Demon technology demonstrator UAS, with one of the demonstrated technologies being a vehicle health monitoring system. The PhD project was initially set up with a wide scope of looking into the design of IVHM for UAS. The scope of the project was subsequently refined to look at the requirements of the various Stakeholders (SH) investing in the IVHM of a UAS and how to take them into account in the design of the IVHM.

1.2 Introduction to UAS

The concept of controlled unmanned flight is just as old as manned. It was during the First World War which Lawrence Sperry and Glen Hammond Curtiss developed the Curtiss Sperry Aerial Torpedo – the first aircraft specifically designed for unmanned flight. It is these aerial torpedoes and the V-1s of the Second World War which are considered the ancestors of modern cruise missiles and today's UAS.

Developments in unmanned aviation continued to be made, primarily in military: target practice, reconnaissance, and decoys. The use of UAS by the US (United States of America) during the Vietnam War [2] and the Israeli Defence Force during the Lebanon War [2; 3] – proved that UAS could be used as effective tools of war.

During the late twentieth century the current interest in UAS started. The US Department of Defense (DoD) established the Advanced Concept Technology Demonstration (ACTD) programs, resulting in the well-known Northrop Grumman RQ-4 Global Hawk and the General Atomics MQ-1 Predator[2]. The Predator originally started out as a reconnaissance UAS, but during the Balkans War was fitted with Hellfire missiles and an laser targeter – giving it the ability to attack targets as soon as they were identified and not wait for a manned fighter to be dispatched[2]. After the 9/11 attacks in 2001, US Predator strikes on terrorist suspects became widespread, sparking the interest of the media, academics, and bringing unmanned aviation to the attention of the general public – starting an explosion of research and countries to start planning their integration into the uncontrolled airspace.

1.3 Introduction to IVHM

The task of maintenance used to be as simple as to fix something when it broke. Aircraft became more complex and the safety of passengers a concern and lead to the rise of planned maintenance, to remove and replace parts before they fail in order to keep the aircraft in a safe operational condition. With aircraft becoming larger and more complex reliability-centred maintenance was

developed, incorporating the reliability of components into maintenance practices.

The Digital Revolution coupled with a shift towards the responsibility of maintenance from the operator to the Original Equipment Manufacturer (OEM) and advances in the design and implementation of maintenance have led to a wide range of techniques tailored to specific challenges [4], such as engine health monitoring [5] and structural health monitoring [6], and avionics built-in-tests. IVHM makes use of these advances in technologies, integrating the HM from all the systems of the vehicle.

IVHM can be considered a Product-Service System (PSS); the product being the sensors, databases, etc. needed to gather information on the health of the vehicle and the service being the use of the health information to make decisions for that vehicle (or fleet). Although, as CPS these two may be entwined and cannot be separated in an easy manner, for example an automated response to a failure or fault could be programmed into the IVHM system. It is this blend of product and service which delivers the cost reduction, increased availability and safety over the life of the vehicle.

1.4 The Requirements Problem

IVHM is a relatively new concept and has only recently started to be fully explored[7] – leaving many challenges. One challenge of designing IVHM for a UAS is how to establish the requirements of the IVHM in order to maximize whole system availability, especially when a new product is being designed where there is no operational history, and also no records of maintenance and safety. At the start of the design of any product or service, requirements need to be established – the same is for IVHM. Requirements can be broadly defined as “a thing that is needed or wanted”[8].

The task of establishing requirements for IVHM, both as a service and product is a costly and time consuming task, but there are also costs in getting the requirements wrong. The importance of defining the requirements of IVHM, on any asset, is known and previous work has focussed on the flowing down of

higher level goals and requirements (e.g. have some form of prognostic assessment of the asset) of IVHM to more actionable ones a designer can strive to achieve (e.g. a prognostic window of X on system Y).

As with all design processes, the design of IVHM is still bound by the basic challenges of modern product development. They must attract and retain customers, be competitive in the market place, and satisfy the requirements of diverse global communities and governments[9]. These constraints include those related to the design process (e.g. budget, time) and because the IVHM is not designed in isolation it must also compete (e.g. could the weight used for IVHM be better used for more pay load or fuel?) and also collaborate with the rest of the design (e.g. an IVHM designer must work closely with designers of the systems they are to monitor) – both influencing and constraining the design of the IVHM.

Another barrier to implementing IVHM on a UAS is that the customer may fail to see the benefits of IVHM[10], and how these benefits relate to the purpose of the UAS. IVHM does not just have to satisfy the needs of the customer, but also the needs of various stakeholders as well, such as: marketing, operations, maintenance, personnel, logistics, suppliers – just to name a few, each having their own language around their needs and viewpoints of the IVHM. Also, the stakeholders will vary from one UAS to another. Even for the same UAS used by different organisations for different missions, the stakeholders could be different. This context, of the physical make-up of the UAS and how it is operated by an organisation for a specific purpose, means that there is no ideal IVHM[11], and that it must be tailored to the UAS it is to be implemented on.

The inherent complexity of UAS, due to the number of elements operating in a SoS, makes it hard to assess what the requirements of IVHM are when the design of a UAS is in its early stages and ill-defined. Also, due to the exploratory nature of some UAS designs the designers can sometimes overlook the through-life supportability of the UAS and focus on achieving mission requirements [12].

This paints a picture of a complex requirements problem with multiple stakeholders, who's needs to be satisfied by the IVHM. Also, with the IVHM design as a subsection of the overall UAS design, trade-off and compromises will have to be made, so establishing which aspect of IVHM are most important is essential. This leads to the question: How can a design determine the important aspects of IVHM for a UAS during its early design?

1.5 Aims & Objectives

1.5.1 Aims

The aims of the project are:

- Develop a method which supports the consideration and trade-off between the requirements and enablers of IVHM to aid the designer of the IVHM for a UAS.
- Develop a tool to correlate the relationship between the customer and mission requirements for a UAS and the requirements of the IVHM for that UAS.

1.5.2 Objectives

The objectives of the project to achieve the above aims are:

- 1) Establish the context which will influence the design of IVHM for UAS.
- 2) Develop a method to relate the stakeholder and mission requirements of a UAS to requirements of the IVHM for that UAS.
- 3) Develop a process to prioritise the requirements and enablers of the IVHM, which can:
 - a) Efficiently solicit the opinions of stakeholders.
 - b) Establish the reliability of the opinions of the stakeholders.
- 4) Apply techniques to UAS design cases.
- 5) Develop a generalised process which can be used in other design cases.

Figure 1-1 provides a simplified view of how the wider research domain which was the starting point of the project (investigating the design of IVHM for UAS) relates to the gap in the knowledge and how the objectives go to filling that gap.

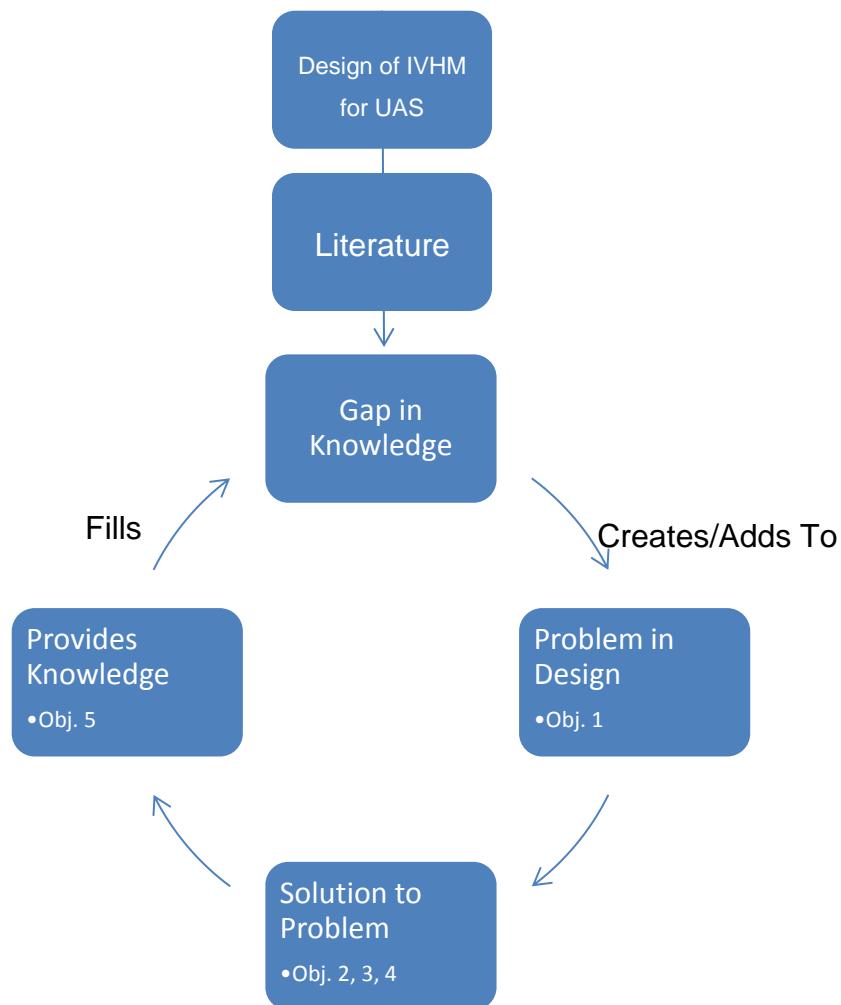


Figure 1-1 Objectives in Relation for Knowledge

1.6 Contribution to Knowledge Summary

This thesis presents a method (The IVHM Requirement Deployment Process) in which a designer of IVHM for a UAS can use to create a tool to capture and analyse the requirements of stakeholders in the IVHM and how they influence the IVHM requirements so that trade-offs can be made. The process also takes into account the context in which the UAS is being used (the operator, the mission, etc.) and fact that a UAS is a System-of-Systems with each element having different maintenance needs.

The process guides the designer in the creation of a tool to link the customer's requirements through multiple stakeholder groups to the IVHM requirements,

and the enablers of those requirements – for a specific UAS. The tool can then be populated with the knowledge of Subject Matter Experts (SMEs), from the different stakeholder groups, in such a way that will give an indication of the agreement between SMEs and the validity of the results. The populated tool then produces ranked sets of IVHM requirements and enablers based on the context of the design and the requirements of the stakeholders – bringing the aspects of IVHM that will best support the UAS in its operation. In addition to the ranked sets of requirements, information on relationships can between requirements is captured as well as the degree of agreement between the SMEs.

This information can then be used to make informed design decisions and focus further development of the IVHM (flow higher level requirements down to more actionable ones, influence simulations, etc.), when there is little known about the details of the design of the UAS. The IVHM-RD has been validated with the input of SMEs.

1.7 Chapter Summaries

The thesis is organised into the following chapters:

- **Literature Review**
This chapter reviews the literature providing the foundation of the project. Literature is split into the domains of: UAS design, IVHM design, UAS health, IVHM design for UAS, requirements analysis, and IVHM requirements. Finally, the gap research is identified.
- **Research Methodology**
This chapter sets out the methodology used for the research and offers the purpose and reasoning for each stage.
- **IVHM in the Context of Unmanned Aviation**
This chapter explores the factors which influence the design of IVHM for UAS. It also develops the design cases being used in the thesis.
- **Development of the IVHM-RD**
This chapter details the development of the IVHM-RD (IVHM Requirements Deployment) for the design cases.

- **Population of the IVHM-RD**

This chapter details the population of the IVHM-RD for the design cases. It also provides an analysis of the results from the populated IVHM-RDs.

- **Analysis of the IVHM-RD**

This chapter looks at the whole IVHM-RD process, based on their development and use. It first analyses the tool, then the population, and finally, provides insight on how the IVHM-RD could be applied to other design cases.

- **Validation**

This chapter details the validation process for the research.

- **Discussion & Conclusion**

This chapter provides a summary of the thesis and a discussion on the IVHM-RD and its impacts. It then presents the future work.

2 Literature Review

The literature for this project spans several subject areas, primarily UAS, IVHM, and design (of both UAS and IVHM). This chapter reports the literature related to the background domains. Additional literature is used in the setting of the context (Chapter 4) development of the IVHM-RD (Chapter 5) and its population (Chapter 6) and is reported in the relevant chapters to avoid duplication.

This chapter is split into seven sections. The first section reviews the current state of UAS design and the laws and regulation affecting it. This builds up and understanding of the stakeholders to UAS and some of the current issues with UAS which relate to the project. The second section reviews the design of IVHM. This establishes the state of the art in IVHM and related methods. The third section reviews how the health of UAS can be measured. The fourth section focusses on the design of IVHM for UAS. The fifth section reviews requirements analysis methods. The sixth section reviews the requirements of IVHM. Finally, the literature is summarised and the research gap developed.

2.1 UAS Design

As the UA part of a UAS are still aircraft they generally follow the same design procedure as their relevant manned counterparts, albeit with alterations due to the pilot(s) being located off board. The main change in the design of a UA is that there is no need to be able to accommodate humans (unless it is being designed as transport): no space provision made and no need for life support equipment. This shifts the pilot to a different location called the Control Station (CS), the CS can take any shape or form (an office in a build, another aircraft, back of a truck). Additionally there is a need for good communications between the UA and CS to ensure inflight control; and contingencies should communication between the two be lost.

Many aircraft design techniques used on UAS (more specifically the UA) can be adapted or derived from established sources, such as Roskam[13] and Stinton[14], taking into account the nuances of UAS. Recently with the growing

demand for UAS several books were published that specialised in the design of UAS, such as Austin[15] and Gundloch[16].

2.1.1 System Elements

Although the exact composition of a UAS varies from one to the next there are elements which are more common than others:

- Unmanned Aircraft (UA)
- Control Station (CS)
- Humans
- Pilot (UA-P)
- Controller
- Maintenance Personnel
- Launchers
- Recovery Equipment
- Storage and Transportation

The UA and CS (along with the pilots) make up a UAS in its most basic form. A generic architecture for this type of UAS can be seen in Figure 2-1, which was developed as part of the ASTRAEA programme (and the colour coding relates to)[17]. It shows the sub-systems in a UA and ground control station (GCS) and the interactions between them. Also, there can be a duplication of some elements within a UAS; the Predator UAS has two CS: one local (to where the UA is operating) to minimise delay during take-off and landing and another during the rest of its flight (cruise, loiter, etc.).

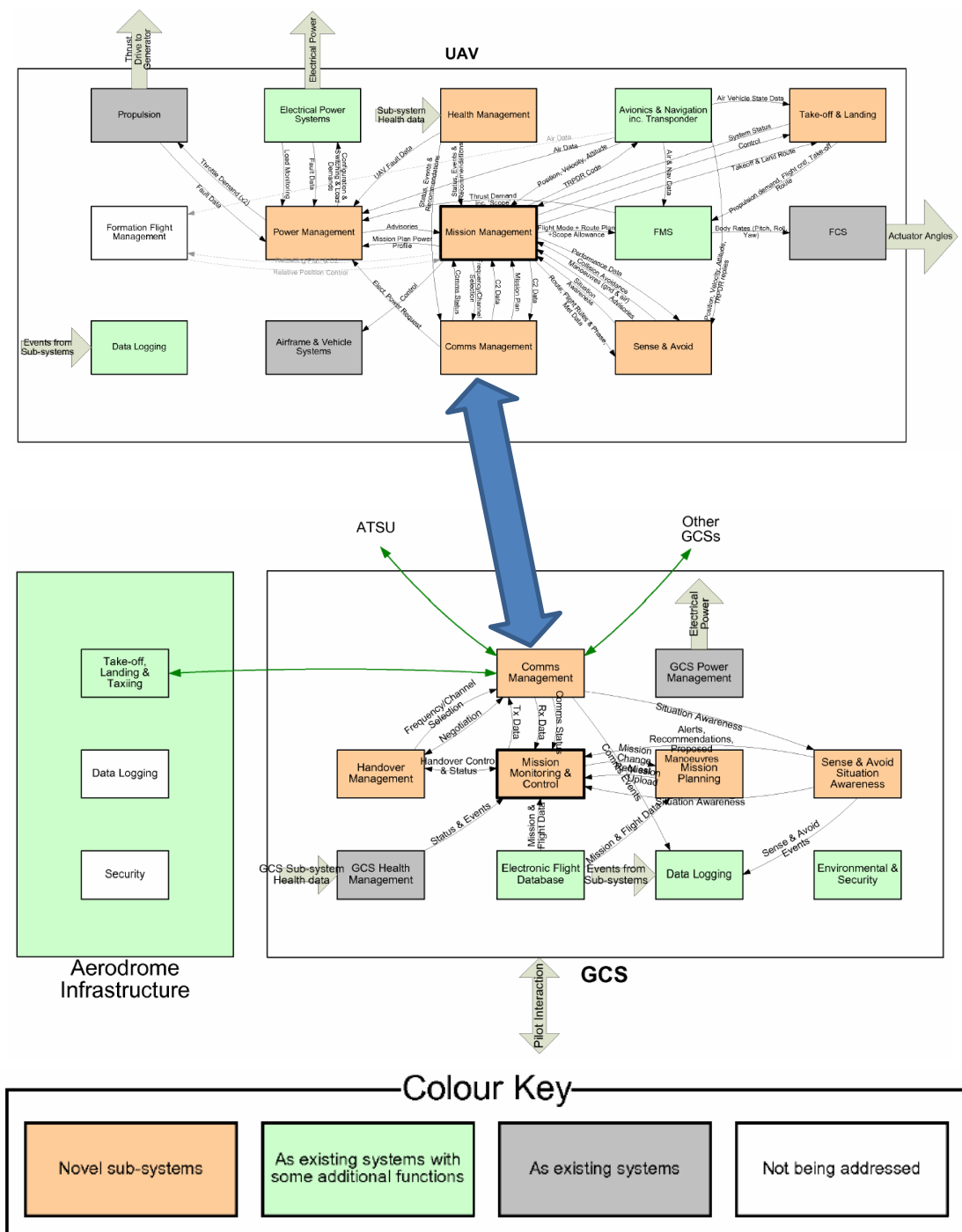


Figure 2-1 Generic UAS Architecture[17]

2.1.2 Modular Design

One of the claimed advantages UAS is seen to have over manned aircraft is that it is possible for them to be highly modular[15]. Essentially a UA is made up of several interchangeable modules containing sub-systems (e.g. sensor

payloads, power plants) allowing quick reconfiguration and flexibility. However this is not currently the case for UA in current operation, they are highly integrated as with manned aircraft. The UAS level does offer modularity; elements of the UAS can be swapped around – e.g. a CS could be used to fly one Predator one day, then a different one the next. Regulations are currently not clear on the regulation of modularity in UAS – although they will probably be wary of certifying a highly modular UA. The modular nature of the UAS will have an effect on how IVHM will have to be designed and implemented.

2.1.3 The ‘Equivalency’ to Manned Aviation

A fundamental concept in unmanned aviation is the safety equivalent to manned aviation. This often manifests itself in two ways: first, the safety of unmanned aviation should be equivalent to manned aviation and second, that the piloting ability should be equivalent to manned (regardless of the level of automation/autonomy). However the idea of equivalency is not defined clearly, even in current regulations, and is open to debate as to just how one view what is ‘equivalent’ in a given capacity and just how to prove it.

2.1.4 Systems Engineering

INCOSE (International Council on Systems Engineering) defines Systems Engineering (SE) as “...an interdisciplinary approach and means to enable the realization of successful systems”[18]. SE is built upon systems theory and is often used for complex products, which can have emergent behaviour. SE is a holistic approach and looks at how elements within a system sit within the larger context and focusses on the iterative process to provide better understanding and minimise undesirable outcomes. This approach to thinking is well suited for UAS, as it is a SoS, but also the UAS having to operate in national airspace. It is also suited to IVHM, which interacts with many systems within the UAS (e.g. propulsion, structures) and many aspects of the organisation which is operating the UAS (and again still has to sit in the wider scope of regulations).

2.1.5 Laws & Regulation

The various laws and regulations that apply to UAS vary from country to country and the sector in which they are to be used (e.g. military, commercial, etc.), and in many cases have not been finalised. In general currently they are derived from the regulations and laws (national and international) which are applied to equivalent size manned aircraft or model aircraft (or a combination of regulations), and have restrictions placed on where they are allowed to fly and what types of operations they are allowed to conduct. The comparison to the already existing regulatory infrastructure highlights the areas which need to be investigated (both in defining the laws and regulations, and the technologies needed) in order to allow UAS to be safely operated in unrestricted airspace with other air traffic.

2.1.5.1 International

Due to the global nature of the aviation industry (particularly in passenger and cargo sectors) several international treaties and organisations have been established in order to standardise the industry, and are often applicable (if only in part) to UAS[19]. Additionally there are several efforts around the world trying to establish rules and regulations for UAS and facilitate their integration into non-segregated airspace[20-23].

The Convention on International Civil Aviation was signed on 7th December 1944 in Chicago (known as the Chicago Convention) and has been revised a number of times since. It sets out the conventions and standards to which signatories must comply with in order to facilitate civil international air travel, without resorting to individual agreements between States. The convention only covers civil aviation and any civil UAS must abide by the applicable Articles and Annexes. The most prominent being Article 8 (below), meaning that any UAS flying from one State to another must have permission to do so, and that both States have the infrastructure to accommodate that UAS safely into civil airspace.

“Article 8 Pilotless aircraft

No aircraft capable of being flown without a pilot shall be flown without a pilot over the territory of a contracting State without special authorization by that State and in accordance with the terms of such authorization. Each contracting State undertakes to insure that the flight of such aircraft without a pilot in regions open to civil aircraft shall be so controlled as to obviate danger to civil aircraft.” [24]

The International Telecommunications Union (ITU) at the 2012 World Radiocommunications Conference has allocated a frequency of 5.030 – 5.091 MHz to UAS for their command and control, for both terrestrial and satellite use. The ITU has made no mention of dedicated frequencies for the data or telemetry from UAS[25]. In the UK there are currently no allocated frequencies for UAS, but commonly used ones are 35MHz, 868MHz and 2.4GHz. Applications to use a frequency must be submitted to Ofcom (who is responsible for the allocation of frequencies within the UK) or the CAA for bands that they have taken responsibility for on behalf of Ofcom[26].

2.1.5.2 European

The European Aviation Safety Agency (EASA) is the responsible body for the regulation of civilian aircraft in the European Union and as such is responsible to the regulation of UAS, although it delegates the regulatory responsibility of UAS under 150kg to the national regulators. The European Commission had produced a roadmap for the integration of UAS into European airspace[27-30]. This roadmap indicates that significant research is needed into contingency measures, which is where they place health monitoring technologies.

2.1.5.3 UK

Depending on the intended use and weight of the UAS, the task of regulation and certification can fall to different bodies. Figure 2-2 (below) shows the current decision process for deciding which body is responsible for the regulation of any UAS for use in the UK; the three bodies are the EASA, the UK CAA and the UK Ministry of Defence.

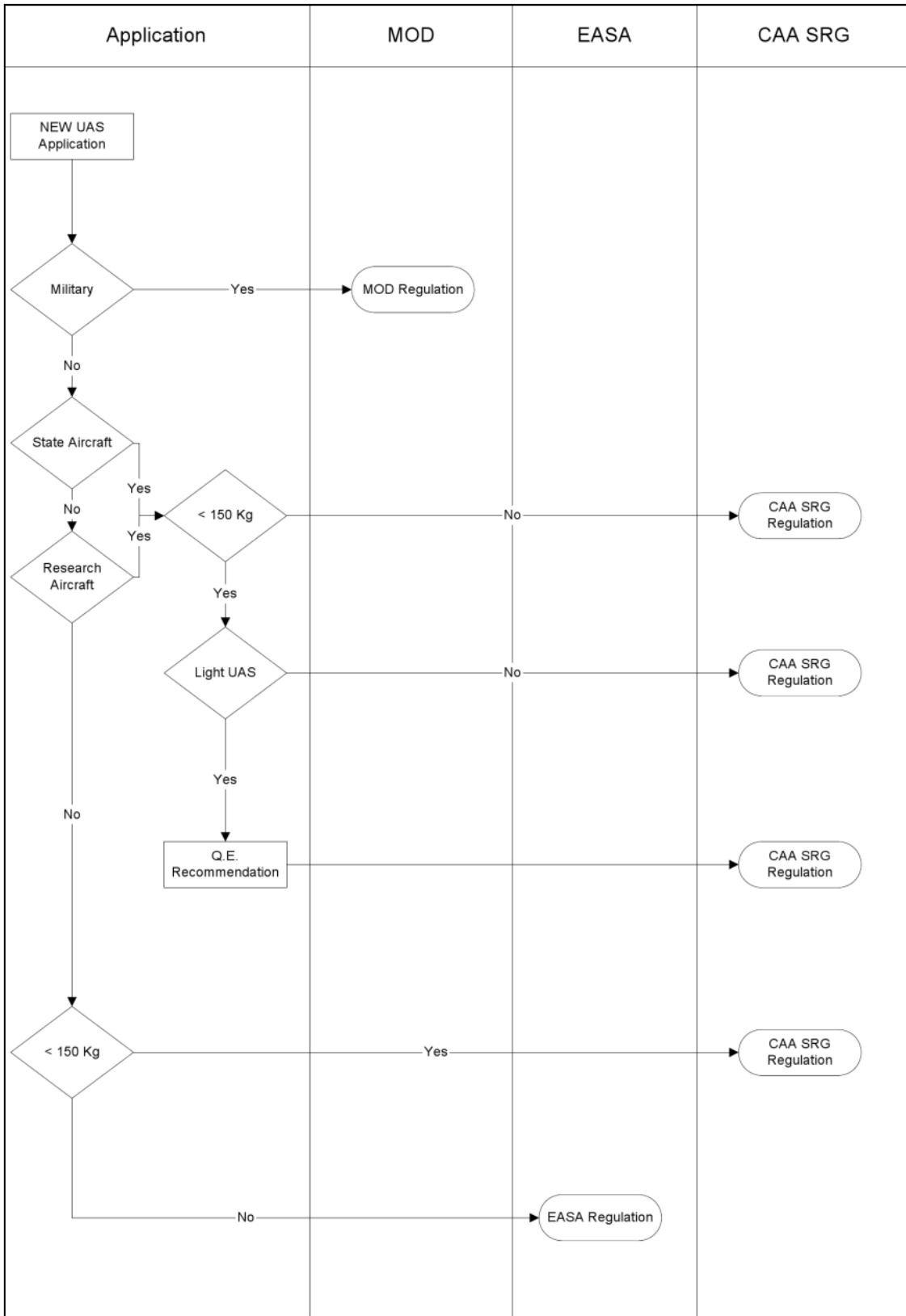


Figure 2-2 UAS Regulation Decision Map [26]

Civil Aviation

As well as the relevant international laws and regulations civil UAS are subject to the Civil Aviation Act 1982[31]. The Civil Aviation Authority (CAA) as the UK's regulatory body has produced *CAP 722 Unmanned Aircraft System Operations in UK Airspace – Guidance* [26] and two papers [32; 33], for the purpose of regulating and certifying UAS.

CAP 722 Unmanned Aircraft System Operations in UK Airspace – Guidance is the document produced by the CAA in order to assist companies and organisations who are developing UAS to meet the required airworthiness and operational standards in order to gain certification. As the title of the document suggests it is only 'guidance' and states that "not all areas of UAS operations have been addressed"[26]. It is a temporary document intended to allow innovation and testing of UAS before the standards have been finalised and issues with the full integration of UAS into the general airspace are fully resolved. CAP 722 focuses on ensuring that designers and operators of UAS are following established design and operational principles and rules developed in manned aviation.

Expert groups are considered by the CAA to be experts in their fields. The Large Model Association (LMA) is one such expert group set up in 1982 to represent the views of people who fly large model aircraft [34] and are experts in their field [33]. Due to the similarities between large model aircraft and UASs (i.e. size and lack of pilot on-board) and the lack of an established and recognised body of expertise in UASs the CAA looks to the LMA, or other learned bodies (such as university's aeronautical department) to assist in the certification of UASs [33].

The CAA is looking for a body to be established with the same or higher level of competence as the LMA that can give assurances that a particular UAS has met a given design and build quality and successfully completed a flight test programme without incident or modification [33]. The LMA are reluctant to help with the certification of UASs, especially for commercial use, because they see themselves as a group for people who use model aircraft for recreation.

In addition to CAP 722 the CAA has produced two papers to aid those designing UAS and guide them towards the appropriate existing standards (for manned aircraft).

Aircraft Airworthiness Certification Standards For Civil UAVs. This paper uses the kinetic energy of UAS on impact with the ground in two crash cases in order to find the equivalent manned aircraft specifications. The first crash case is an *“Unpremeditated Descent Scenario - A failure (or a combination of failures) occurs which results in the inability to maintain a safe altitude above the surface. (e.g. loss of power, WAT limits, etc).”*[32] The second crash case is *“Loss of control scenario - A failure (or a combination of failures) which results in loss of control and may lead to an impact at high velocity.”*[32] The paper then gives the appropriate velocities to use in each case and for different types of UAS (aeroplanes, rotorcraft and airships/balloons). Once the kinetic energy for each crash case is calculated the designer of a UAS can use the charts in the paper to determine the equivalent manned regulations. This may lead to two different regulations being indicated by the different design cases, when this happens the paper suggests that mixing the two regulations is possible – this could require a high level of judgement and it may be best to consult the CAA before pressing on with the design in order to avoid costly mistakes later if the regulations need to change.

UK CAA Policy for Light UAV Systems. The UK Light UAS Systems Policy is designed to get lighter UAS (generally below 150kg, but not all UASs under 150kg will qualify for the policy) into regular operation if they can show equivalence in terms of safety to existing model aircraft (and meet the conditions of the policy)[33]. As with the previous CAA paper (above) the paper makes use of kinetic energy, but this time sets a maximum at 95 KJ (calculated with a velocity of $1.4V_{max}$) and for those aircraft over 80 kg must prove that the aerodynamic drag must be sufficient to stop impact energy of the UAS exceeding 95 KJ[33]. This creates a trade-off between the weight and speed of the UAS if the designer wishes to operate under the policy.

Military Aviation

The UK Ministry of Defence has published *Defence Standard (DEF STAN) 00-970: Design and Airworthiness Requirements for Service Aircraft*. This standard covers all aircraft for military service, not just UASs, and it is divided into parts[35]:

- *Part 1* – *Fixed Wing*
- *Part 3* – *Small Type Aeroplanes*
- *Part 5* – *Large Type Aeroplanes*
- *Part 7* – *Rotorcraft*
- *Part 9* – *UAVS*
- *Part 11* – *Engines*
- *Part 13* – *Military Common Fit Equipment*
- *Part 15* – *Items with no specific military requirements*

Part 9 covers UAV Systems (the current preferred term used by the UK Military[26]), it does not differentiate on what the purpose of the UAS (e.g. target drone, surveillance) and also does not currently cover unmanned dirigibles and manned aircraft which have subsequently been converted to operate without a pilot on-board. Other parts of the DEF STAN 00-970 may still apply (e.g. Part 11), including other DEF STAN documents, as well as other standards/requirements documents, such as NATO STANAG 4671 to which it constantly refers to [35].

Compliance with DEF STAN 00-970 will not in itself guarantee acceptance by the UK Military, as it sets out only the basic requirements, and that terms stated in the contract must be met[16]. The CAA's CAP 722 also makes provisions for UASs intended for use within the UK Military, including contractor owned prototypes[8].

2.1.6 Autonomy & Automation

The autonomy of a UAS refers to how much decision making is taken away from the pilot/operator and given to UAS, using sophisticated computer programming. Although UASs are often referred to as autonomous, semi-autonomous, or not autonomous (and sometimes automatic), these terms often have ambiguity in their meaning[36]. Recently ICAO have decided that

autonomy (for civilian UAS at least) means completely autonomous with no human interaction[20].

Many ways have been established for defining the autonomy level of a UAS, and they do not always map directly from one to another. DoD has established ten levels of autonomy, they are[37]:

1. Remotely Guided.
2. Real Time Health/Diagnosis.
3. Adapt to Failures & Flight Conditions.
4. On-board Route Re-plan.
5. Group Co-ordination.
6. Group Tactical Re-Plan.
7. Group Tactical Goals.
8. Distributed Control.
9. Group Strategic Goals.
10. Fully Autonomous Swarms.

Another way of classifying the autonomy level is the PACT levels of Automation (Figure 2-3).

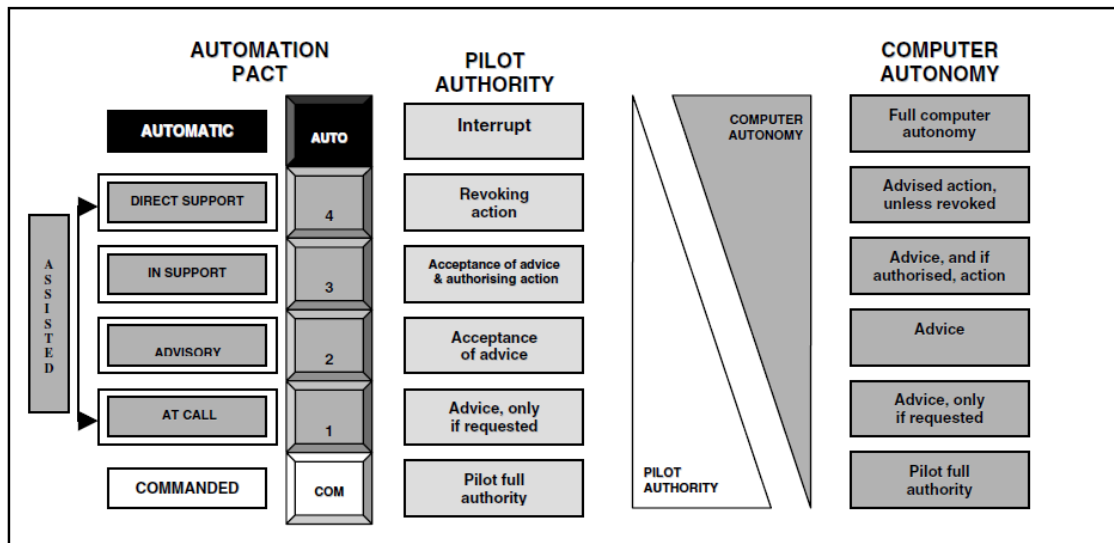


Figure 2-3 PACT Levels of Automation [38]

An alternative way to think about the autonomy of a UAS is to consider how the pilot interacts with the UAS. There are three main ways a pilot can control a UAS: direct control, management by consent, and management by exception[39].

Selecting an autonomy level for a UA often depends on the use of the UA (as not all uses would warrant autonomy) and the company's technology capability. Some of the most advanced UAs in operation to date (e.g. Global Hawk) only fall between levels two and three (on the DoD scale), indicating that there is considerable work needed before higher levels can be achieved.

2.1.7 UAS Classifications

Although UAS can be described by their configuration of the UA (e.g. fixed wing, co-axial rotorcraft) these are not always useful, especially when comparing two or more UAS's suitability for a particular mission, as the configuration tends to be driven by the requirements[15]. This may result in two aircraft with dissimilar configurations being suited for the same role (e.g. crop spraying could be carried out by either a fixed wing UA or rotorcraft UA), therefore it is best to use the type of configuration as a detail of the UAS rather than a defining character.

There are currently several different ways in classifying UAS into groups, depending on the preference of the body grouping them. Some of these different ways are described below. These classifications are not necessarily mutually exclusive, as a UAS can be accurately described by a combination of them (i.e. the role the UAS is to perform and the range it is to perform it at).

2.1.7.1 Mass

Dividing UAS into different mass bands (based on the mass of the UA, not the whole UAS) is probably the simplest way of grouping UAS. This method is currently in use with the CAA, which splits UAS into the weight categories (i.e. mass in the context present of the earth's gravitational field) for the purpose of regulation and the MoD, which splits them into three classes. Figure 2-4 shows the MoD UAS weigh classes (and categories) and their CAA equivalent. One problem that may arise from this classification is that the weight categories may be subject to change, for whatever reason (e.g. change in the regulations for UAS), and the resulting reshuffling of UASs into different bands may cause confusion.

Class	Category	Normal Employment	Normal Operating Altitude	Normal Mission Radius	Civil Category (UK CAA)	Example Platform
Class I <150 kg	MICRO < 2 kg	Tactical Platoon, Section, Individual (single operator)	Up to 200ft AGL	5 km (Line of Sight (LOS))	Weight Classification Group (WCG) 1 Small Unmanned Aircraft (<20 kg)	Black Widow
	MINI 2-20 ¹³ kg	Tactical Sub-Unit (manual launch)	Up to 3000ft AGL	25 km (LOS)		Scan Eagle, Skylark, Raven, DH3
	SMALL > 20 kg	Tactical Unit (employs launch system)	Up to 5000ft AGL	50 km (LOS)	WCG 2 Light Unmanned Aircraft (20><150 kg)	Luna, Hermes 90
Class II 150–600kg	TACTICAL	Tactical Formation	Up to 10,000ft AGL	200 km (LOS)	WCG 3 UAV (>150 kg)	Sperwer, Iview 250, Aerostar, Watchkeeper
Class III >600 kg	Medium Altitude, Long Endurance (MALE) ¹⁴	Operational/ Theatre	Up to 45,000ft AGL	Unlimited (BLOS)		Reaper, Heron, Hermes 900
	High Altitude, Long Endurance (HALE)	Strategic/ National	Up to 65,000ft AGL	Unlimited (BLOS)		Global Hawk
	Strike/ Combat	Strategic/ National	Up to 65,000ft AGL	Unlimited (BLOS)		

Figure 2-4 MoD UAS Classes [36]

2.1.7.2 Roles

A useful way of presenting how UASs are currently being used (and possible future uses) is in what roles they will carry out, rather than stating particular mission types (e.g. surveillance, crop spraying). Presenting UAS applications in this way allows the advantages to be seen in non-mission specific terms.

Traditionally UASs have only sought to take on DDD (Dull, Dirty, or Dangerous) jobs[15; 40; 41], because they are mainly military roles and benefit from removing humans from the aircraft, but there are other roles in which UAS are well suited[15], some of these roles are listed below. It must be noted that a UAS may cover more than one of these roles for any given mission (e.g. a surveillance mission is considered to be dull, but also in many cases has the need of being covert). Currently the majority of UASs used are military, and the civilian market (globally) is predicted to emerge in this decade, initially in roles/missions similar to military ones (e.g. surveillance by a boarder control agency)[41].

- *Dull Roles* – Jobs deemed tedious or boring, e.g. surveillance, crop monitoring. These jobs tend to last over 24 hours[15; 41] (the main dull job currently being military surveillance), and using a UAS allows for one

crew to relief another without the UAS needing to land for this to happen[15].

- *Dirty Roles* – Jobs with environmental factors which could endanger the health of humans, e.g. NBC (nuclear, biological, and chemical) monitoring, crop spraying.
- *Dangerous Roles* – Jobs where there is danger of being shot at, primarily military roles, but also possibly some law enforcement ones as well.
- *Covert Roles*.
- *Research Roles*.
- *Environmental Roles*.
- *Economic Roles* – Could be based initial costs, operating costs, or life-cycle costs. Also, lack of labour force could – as with Japanese agricultural industry, where due to dwindling rural populations, helicopter like UAs have been used for crop spraying since the 1960s[2; 15; 42]

2.1.7.3 Range & Endurance

Classifying UAS by range and endurance is quite a useful method, as the weight of a UA will limit the amount of fuel on-board, and the amount of fuel will affect range and endurance of the UA, this method of classifying can be linked to weigh base method (and thus to what regulations are to be used) as is the case in Figure 2-4. There are three main groups for this method, they are as follows:

- Long Endurance, Long Range – Designed to generally fly beyond line-of-sight (BLOS) (but may not always be the case) for prolonged periods of time (over 24 hours[15]). This group is generally broken down into two sub-groups based on the operating altitude, they are:
 - *High Altitude Long Endurance* (HALE) UAS operate over 15,000 m altitudes and their operations can be global in scale[15]. They are suited to reconnaissance and surveillance roles.
 - *Medium Altitude Long Endurance* (MALE) UAS operate between 5000 – 15,000 m[15] and their operational range is over 500 km but less than HALE UASs[15]. They too are suited to surveillance and reconnaissance roles, but the lower altitude at which they operate allows other roles such as the case with Predator being equipped with air-to-ground missiles to provide a strike capability.

- *Medium Range & Tactical* – Medium Range or Tactical UAS generally operate in the range of 100 – 300 km[15]. Their endurance vary somewhat, but tend to be under 24 hours.
- *Close Range & Battlefield* – These UASs tend to be designed to be used in visual line-of-sight (LOS) for ranges up to 100 km[15]. This group has the widest set of operational areas (e.g. surveillance, crop spraying, NBC monitoring) and their endurances also vary and can last from a few minutes to hours. There are three sub-groups (although not all UASs in this group will fit into the sub-groups), they are:
 - *Mini Unmanned Aerial Vehicle* (MUAV, MiniUAV) have a mass of less than 20 kg, have range up to ~30 km, and may or may not be hand launched.[15]
 - *Micro Aerial Vehicle* (MAV) or MicroUAV tend to have wing span of around 150 mm or less and are intended for use in urban environments[15].
 - *Nano Aerial Vehicle* (NAV) are about the size of insects or seeds[15].

2.1.8 UAS Design Summary

- There is a lack of regulations for UAS. CAP 722 is the UK CAA current regulation for UAS, but the regulations are still under development and currently “guidance” to people. There are many throughout the world working on regulations for UAS and it can be assumed that there will be a time of consolidation for the civilian regulations throughout the world (only once regulations have established).
- UAS should be ‘equivalently’ safe as manned aircraft, but the exact definition what ‘equivalently’ means has not been defined. The idea that UAS should be “equivalent” to manned aircraft is somewhat established, and not given any special rules for integration into the same airspace as other air users. The exact meaning of ‘equivalent’ is up for debate: some say that it means that the accident rate should be the same as manned aircraft (approximately 0.01 per 100,000 hours for large airliners[43]); others argue that as in manned aviation safety regulations are mainly to protect those on-board the aircraft (crew and passengers) and that a

crash or a UA does not necessarily endanger human life, but is dependent on where it is being operated, so a UAS not operating over human populations could have a higher permissible accident rate.

- Designing UAS currently is somewhat like building on shifting sands – regulations are forever changing – posing a problem for any manufacturers of UAS and their sub-systems (such as IVHM systems) as there is uncertainty as to what the future may hold, but this is an excellent environment for research into UAS because of the flexibility of the current regulations.
- There is a lack of standardised groupings for UAS. Some UAS by their mass, some by kinetic energy, some by their mission, some type/configuration (e.g. fixed wing, quad-rotor), some by endurance and flight level (e.g. MALE, HALE). Even if two organisations are using the same measure for grouping, their groups may be different e.g. UK Military and Civilian groupings by mass are different.
- The need for health monitoring of UAS is recognised as being important in the European roadmap – although it is as a contingency measure, and not a maintenance approach.
- Autonomy often has different meanings to different people.
- Modular design and “integrated” vehicle health management system sound incompatible, but might be achievable. If standardised interfaces (both for software and physical connectors) for IVHM sub-systems could be established (for the UAS, but ideally for the IVHM industry) then a ‘plug in and play’ IVHM element could be designed into each module (e.g. sensor package).
- There could be interference from other radio/communications sources that may affect IVHM data transmitted from the UA to the CS. There are no frequencies for UAS allocated in the UK and the various associated signals needed.
- There are security issues to consider when using IVHM. IVHM could possibly be a ‘back door’ to gain control of the UAS. There are also

concerns about the ownership of the IVHM data, and controlling access to it.

- The cost advantages (e.g. reduced fuel costs due to a smaller aircraft, no life-support systems or space accommodation need for humans on board) proclaimed for some time before the current generation of UAS had been in operation have not borne out. With the inclusion of the sensors and communications needed to fly many of the current military UAS, the need to buy ground control stations, and any other associated equipment, UAS are often more expensive to purchase than their manned equivalent. The saving is proposed to be made in the operational costs over the UAS's life time. The life time savings have yet to be proven on the current generation of military UAS, as there is little to compare. In some uses of UAS, both military and civilian, there are no manned equivalent. The cost factors usually include the initial purchase costs; the cost in retraining people to operate the UAS; etc. Many current UASs need two (or more) people to operate them, where it could be done by a single person in manned aircraft. With so many counter-arguments against the savings UAS suggests, there is a strong motive to develop technologies that can reduce the operating costs of UAS, such as IVHM.

2.2 IVHM Design

Starting in the 1970's aircraft have become larger and increasingly complex, the cost of having an aircraft unavailable or underutilised became a problem. The concept of reliability-centred maintenance was developed, incorporating the reliability of components into maintenance practices to make maintenance more cost effective. It was at this time that NASA proposed IVHM as a concept[7].

The digital revolution of the late 20th century (bringing with it sensors and the ability to store, sort, and access data from around the world) coupled with a shift of maintenance responsibility to the Original Equipment Manufacturer (OEM) from the operator brought interest in IVHM. IVHM could provide an approach to

mitigate the increasingly prohibitive costs of maintaining complex aircraft and running underutilised aircraft.

Although initially started in the aerospace domain, the concept of IVHM could be applied to other vehicles (e.g. trains) and assets (e.g. power plants). IVHM is also referred to as integrated systems health management, prognostic health management, health and usage monitoring and has been adopted (in some form) by Rolls-Royce, Mann Trucks, Caterpillar, General Electric, Boeing, BAE Systems.

IVHM can be considered a Product-Service System (PSS): a product (the physical items needed e.g. sensors, databases, networks) and service (the management of the health of the UAS and the fleet of UASs) integrated as one to deliver value [44; 45] to an asset through its life – shifting the responsibilities from the user to the supplier of the IVHM (which may or may not be the original manufacturer).

The designer of IVHM for a UAS is still bound by the fundamental challenges of modern product development: they must attract and retain customers, be competitive in the market place, and satisfy the requirements of diverse global communities and governments [9]. Maintenance can often be overlooked during the design of a UAS[12], and this not helped by there being a lack of tools to address the design of maintenance[46].

2.2.1 Goals of IVHM

IVHM sets out to achieve a number of high-level goals: reduce cost, increase availability and safety; which when broadly stated like this can apply to almost any asset. The cost-benefit analysis is to decide whether adding IVHM capabilities to an asset is worth it over the life-cycle of the asset. It is well known that the majority of an asset's life-cycle cost is fixed during its design [47; 48], so for IVHM to have the biggest impact on those costs then it must be considered right from the start.

2.2.2 Features of IVHM

To achieve the above IVHM goals, there are many different features which can be employed. The following are some summarised from literature:

- Diagnostics Analysis
- Prognostics Analysis
- Vehicle Health Assessment
- Fleet Health Assessment
- Fault Management
- Fault Isolation
- Integrated Logistics

The optimal mix of these various features of IVHM will depend on the context of the UAS, and which of them best support the mission/use of the UAS, and the requirements of its stakeholders.

2.2.3 Stakeholders of IVHM

As IVHM needs to be integrated into not just the product, but also the organisation operating the UAS, there are multiple stakeholders who have vested interest in the IVHM. Who exactly the stakeholders are will be dependent on many things, but there are common ones, such as: the customers (could be internal or external to a company, intermediate or final), the organisation/business operating the UAS, the maintainer of the UAS, the manufacture of the UAS, sub-contractors. Perhaps the most important stakeholder is the final customer of the UAS, as the ones who will ultimately be purchasing the UAS (or the services of a UAS), but they do not always see the benefits of IVHM[10].

2.2.4 Technologies of IVHM

There are some key technologies for implementing IVHM which are common across different systems[49].

2.2.4.1 Sensors

Sensors are necessary for an IVHM system. They are used to gather key performance indicators, which can be used to assess the health of the system they are attached to. The sensors used may or may not be smart. Smart

sensors refer to the ability to combine some filtering and analogue to digital data conversion techniques with the sensors.

2.2.4.2 Diagnostics & Prognostics

Diagnostics are used to detect failures and anomalies, using algorithms, then isolate the location of the fault if possible. Prognostics are used to detect degradation in performance and predict or forecast the time before the system fails – allowing maintenance to take place before the failure. Both use the key performance indicators picked up by the sensors, although prognostics may use different ones from diagnostics on the same system.

2.2.4.3 Networks & Databases

Networks and databases allow the health information to be sent where it is needed, whether to operations or maintenance – allowing them to make the appropriate informed decisions. Databases allow a history to be built up about a fleet of vehicles and are used to understand their behaviour in operation.

2.2.4.4 Computer Reasoning

This is the computing hardware running the diagnostic or prognostic algorithms. With many sub-systems being monitored by an IVHM system there needs to be some sort of vehicle level reasoning. The vehicle level reasoning needs to be able to determine what is causing a degradation in the vehicle and what may be the symptoms of this failure (e.g. failure in the fuel system will have effects on propulsions and power).

There is a considerable amount of research into different aspects of health monitoring systems and the technology needed. These primarily focus on a specific aspect of IVHM and they should be considered as solutions in design process and not drivers for it e.g. you assess what you need from a prognostic algorithm then see if any current ones meet them (or if development is needed).

2.2.5 Sub-Disciplines

IVHM can be seen as an overarching subject which encompasses many different sets of technologies and health monitoring techniques. Advances in the

design and implementation of maintenance have led to a wide range of techniques (using the technologies mentioned above) tailored to specific challenges [4], such as engine health monitoring (EHM)[5], structural health monitoring [6], and avionics built-in-tests. IVHM takes these different technologies (each with their specialised applications to systems/sub-systems) and brings them together with the intention of integrating the separate health monitoring for systems (or sub-systems, components, etc.).

With IVHM intending to bring the health monitoring of a UAS's systems into one health system, this could provide a source of contention with subcontractors who wish to provide their own health monitoring service to the sub-systems they provide. For example an engine manufacturer (supplying the engines to a UAS design) may wish to offer its own EHM service, separate from the IVHM service provided by the manufacturer of the UAS. This sort of inter organisational politics is beyond the scope of this thesis, but such situations could have an impact on the design of IVHM for a UAS.

2.2.6 Standards

Standardisation could help reduce costs with similar systems[50] and could ease the integration of health monitoring systems from different suppliers into the IVHM for the UAS (and the fleet). IEEE has established the AI-ESTATE (Artificial Intelligence Exchange and Service Tie to All Test Environments) and SIMICA (Software Interface for Maintenance Information Collection and Analysis) standards which can be applied to IVHM[50].

OSA-CBM (Open Systems Architecture – Condition Based Maintenance) was developed by an industry led team partially funded by the US Navy. It is a standard architecture for moving information in a condition-based maintenance system[51] – it covers the format and communication health information. OSA-CBM is an implementation of ISO 13,374. OSA-CBM is split into seven levels:

1. Data Acquisition
2. Data Manipulation
3. State Detection
4. Health Assessment
5. Prognosis Assessment
6. Decision Support
7. Presentation

The introduction and widespread adoption of open standards for IVHM would allow suppliers to sell compatible systems and parts to a wide range of customers. Open standards also support the idea of an open platform for IVHM[49].

2.2.7 IVHM Design Summary

- There are many individual technologies being developed related to IVHM and health monitoring of systems (sensor systems, prognostic algorithms etc.). They are often being developed on their own e.g. a prognostic algorithm will be developed and compared to other algorithms with a limited set of parameters (e.g. computing time, accuracy). There is not currently a set of universal parameters which different health monitoring systems can be compared, although one has been suggested. There is not often consideration on how that system might be integrated with other health monitoring systems or the rest of the vehicle (although this is not really expected), making it hard for a designer to choose the best components, algorithms, systems etc. A set (or sets) of standards addressing IVHM (and related technologies) would be useful for the designer. MIMOSA OSA-CBM is one such standard, which is a “standard architecture for moving information in a condition-based maintenance system”[52], allowing a designer to know exactly what information and the format they will get from any one component or sub-system. Further developments (and the adoption by industry) of standards should increase competition in the supply chain, lowering the cost of technology – making IVHM cheaper to implement, allowing greater savings in the lifecycle costs of a UAS.

- There is a lack of regulations and standards for IVHM. Coupled with the current flexibility in UAS regulations, IVHM on UAS could be feasible, but again regulations could change – limiting the long term viability of any particular IVHM design on a UAS.
- Designing an IVHM system for a UAS is like designing any other. The design process for an IVHM system can follow established design engineering processes/methodologies (e.g. systems engineering). This means existing tools designed for other applications in engineering design could be adapted for use when designing IVHM.

2.3 UAS Health

The idea of health is taken from the field of medicine. Just as with humans the ‘healthy’ state will vary from one asset to another asset, to bring this into a UAS context: a healthy state for a quad-copter UA will not be the same for fixed wing UA[53]. This variation in what is healthy is also true between two of the same UA, due to the variations which result from the manufacturing processes. This results in there being no ideal IVHM for all UAS[11].

2.3.1 Failures

In order to fully make use of current health monitoring technologies and techniques there must be an understanding of which systems are problematic to UAS in general (e.g. unreliable, take a long time to maintain) and therefore need monitoring. One way of identifying problematic systems is to look at the causes of system failures for UAS fleets in operation, such as the ones shown in Figure 2-5.

US Military UAV Fleet (194,000 hrs)

IAI UAV Fleet (100,000 hrs)

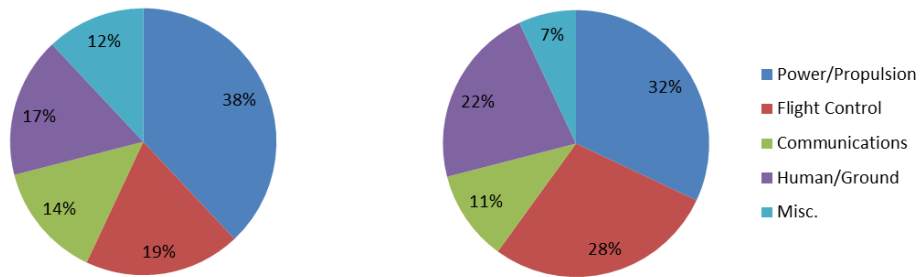


Figure 2-5 Average source of system failures for US Military and IAI UAS Fleets[37]

These show the systems failures for the US Military and Israeli Aircraft Industries (IAI) and both identify power/propulsion systems and flight control systems as the main sources of failure. This indicates a good place to start but there are problems using these charts. They account for the average of a whole fleet of UASs; containing UASs of different sizes and various missions. If we take a closer look at some of the different types of UASs from the US Military fleet (Table 2-1) we can see that there can be drastic differences between different types of UASs in the fleet (e.g. Shadow RQ-7 and Pioneer RQ-2B), or even between two configurations of the same UAS type (e.g. Predator RQ-1A and Predator MQ-1B). With the large variations between individual UASs the information on system failures for the fleet can only provide low fidelity guidance for a designer at the early stages of designing a health monitoring systems as to which systems require more attention. More detailed information on system failures would be useful, but due to the current UAS operations, mainly military and surveillance, this information will be hard to come by in the public domain, and even if gained there may be conditions attached due to security issues.

Table 2-1 Summary of UAS Failures [37]

UAS		Power/ Propulsion	Flight Control	Comms.	Human/ Ground	Misc.
Predator	RQ-1A	23%	39%	11%	16%	11%
	MQ-1B	53%	23%	10%	2%	12%
Pioneer	RQ-2A	29%	29%	19%	18%	5%
	RQ-2B	51%	15%	13%	19%	2%
Hunter	RQ-5A	38%	5%	31%	7%	19%
Shadow	RQ-7	38%	0%	0%	38%	24%

2.3.2 Reliability

Reliability and availability tend to increase over time; as the operators (UAS-p, maintenance crews etc.) progress along the learning curve getting used to the UAS and the design of UAS evolves and improves due to the identification of problem parts (or design faults). Table 2-2 shows that these improvements can be drastic as is the case with the Predator and Pioneer.

Table 2-2 Summary of DoD Reliability Findings[37]

UAS			MTBF (hrs)	Availability	Reliability	Mishap Rate per 100,000 hrs (Series)	Mishap Rate per 100,000 hrs (Model)
Predator	RQ-1A	Requirement	-	-	-	-	20
		Actual	32	40%	74%	43	
	MQ-1B	Requirement	40	80%	70%	-	
		Actual	55.1	93%	89%	17	
Pioneer	RQ-2A	Requirement	25	93%	84%	-	281
		Actual	9.1	74%	80%	363	
	RQ-2B	Requirement	25	93%	84%	-	
		Actual	28.6	78%	95%	179	
Hunter Pre-1996	RQ-5	Requirement	10	85%	74%	-	47
		Actual	-	-	-	255	
Hunter Post-1996	RQ-5	Requirement	10	85%	74%	n/a	
		Actual	21.2	99%	97%	24	
Shadow	RQ-7	Actual	-	85%	98.80%	191	191

The reliability (R) of a UAS can be expressed by:

Equation 2-1 [16]

$$R = e^{-\lambda \cdot t}$$

$\lambda = \text{incident rate}, t = \text{time interval}$

The incident rate is the inverse of the mean time between failures (MTBF), MTBF can be expressed by:

Equation 2-2 [16]

$$MTBF = \frac{1}{\lambda} = -\frac{t}{\ln(R)}$$

MTBF can also be expressed using the number of flight hours (FH), aborts due to maintenance issues ($N_{Ab,Mx}$), and the number of cancellations (N_{Cx}):

Equation 2-3 [16]

$$MTBF = \frac{FH}{N_{Ad,Mx} + N_{Cx}}$$

The mishap rate (MR) can be expressed by:

Equation 2-4 [16]

$$MR = \frac{N_{ClassA}}{FH_{Total}} \cdot 100,000$$

N_{ClassA} = Number of Class A Mishaps¹, FH_{Total} = cumulative fleet flight hours

The mission reliability ($R_{Mission}$) can be expressed by:

Equation 2-5 [16]

$$R_{Mission} = 1 - \frac{N_{Ab,Mx}}{N_{Sorties}}$$

$N_{Sorties}$ = number of sorties launched

2.3.3 Availability

There are different ways in which availability of a UAS can be expressed, in general form it is the ratio of up time (time where the UAS is available for use) and total time (up time and down time). One driver to improve availability is the inclusion of the availability target into a contract by the customer (as in Table 2-2). The exact penalties for not meeting such a target will usually be financial in nature (either the customer will pay less for the equipment or there will be more development to improve the availability to the required standard).

The inherent availability (A_i) can be expressed by:

¹ A Class A mishap is one that causes significant damage or loss of the UA.

Equation 2-6 [16]

$$A_i = \frac{MTBF}{MTBF + \bar{M}_{ct}}$$

M_{ct} = corrective maintenance time

The achieved availability (A_a) can be expressed by:

Equation 2-7 [16]

$$A_a = \frac{MTBM}{MTBM + \bar{M}}$$

$MTBM$ = mean time between maintenace, \bar{M} = mean active maintenace time

The operational availability (A_o) can be expressed by:

Equation 2-8 [16]

$$A_o = \frac{MTBM}{MTBM + MDT}$$

MDT = mean down time

The availability of a UAS based on number of flight hours flown and scheduled can be expressed by:

Equation 2-9 [16]

$$A = \frac{FH}{FH_{Sched}}$$

2.3.4 Maintainability

The maintainability of the UAS is the ease with which the UAS can be maintained. One measure is to determine the maintenance man-hours per flight hour (MMH/FH) [16]. The mean time to repair is another measure of determining maintainability and can be expressed by:

Equation 2-10 [16]

$$MTTR = \frac{T_{Rep,Tot}}{N_{Rep}}$$

$T_{Rep,Tot}$ = sum of the repair time, N_{Rep} = number of repair activities

2.3.4.1 Repair Levels

There are typically four levels of repair; their exact meaning is dependent on the UAS's use and operational context (e.g. civil, military), and in some cases the levels may be in the same physical location[54]. Often the repair level is self-evident but there are cases where it may be unclear as to what level the maintenance is best conducted. It is therefore best to conduct a LORA (level of repair analysis) exercise to determine the most cost-effective repair level for that maintenance action over the life-cycle of the UAS. Generally speaking the higher the repair level the longer the repair time (often due to transit time), and this is usually traded off against the cost of storing parts or equipment at the lower levels in the LORA.

First Line – Maintenance actions which can be carried out in situ at the site of UAS operations.

Second Line – Maintenance actions which need a workshop of some kind, generally with specialist equipment.

Third Line – Maintenance actions which must be conducted at the operator's main facility, generally due to the need for specialist equipment and the location of parts.

Fourth Line – Maintenance actions which must be carried out by the manufacturer or contractor.

2.3.5 Life-Time Support

Many of the technologies and procedures associated with unmanned aviation are novel (e.g. autonomous flight) and when developing a new UAS it is often the case that these novel technologies have little to no consideration for the through life consequences of design decisions. This is usually the result of the

way the projects to develop these new UAS were initiated; they are just to demonstrate the new technology or capability.

The Predator was funded in such a way. It was an advanced concept technology demonstration (ACTD) project for the DoD and subsequently made the transition into military service[12; 40]. ACTD projects are designed to demonstrate new capability to the DoD and rapidly incorporate the new capability into operation. As such the first generation Predator A (RQ-1) designed as an ISR (Intelligence, Surveillance, and Reconnaissance) platform did not go through the traditional assessment of the support and logistical requirements. Without the necessary data logisticians have problems trying to allocate the appropriate resources[12].

Adding to the complicity of the logistical situation is that the design of the Predator has not stayed static, evolving into different variants being produced with different systems from the original. Most notable is the Predator B (MQ-1) which has the added capacity to carry and fire weapons. The situation gets more complex with each variant being produced in blocks; and each block having a slightly different systems from the next[12].

This lack of consideration for the support of a UAS, coupled with the limited idea of how the new capability might be fully utilised and subsequent re-designed, only causes confusion and adds cost to the logistics; having to maintain tools, parts and training for several variations of a design. It is now obvious with hindsight that supportability of a UAS must be meaningfully considered from its conception, or risk having logistical problems later.

2.3.6 UAS Health Summary

- There is a lack of readily available detailed information as to UAS causes of failures and crashes. Although there is some information in the literature about causes of failure in UAS, they are only averages for military fleets (the USA and those produced by IAI) with somewhat large undetailed groupings (Figure 2-5). The way UAS are grouped, coupled with the fact that from one UAS to the next they may vary significantly

from the averages (as highlighted in Table 2-1), make these figures only useful for a low fidelity insight early on in the design. It would be prudent to consider each UAS to be an individual case or a smaller sub group (based on size, mission, operating condition etc.) than to consider IVHM systems for all UAS types and sizes. Working from specific design cases (where data is available or assumptions can be made) and then trying to draw generalisations for a sub-set (or the whole scope of UAS if possible) would be more practicable.

- It can be hard for a new UAS designer (especially for less conventional UASs and ones incorporating the latest technology) to know what their system failure pattern may be.

2.4 IVHM Design for UAS

There are different sources that look into the design of health monitoring systems[11; 55-61], but do not specifically look at the design of health monitoring systems for unmanned aviation. They can be useful, but may miss some of the unique aspects of a UAS.

There are two papers that specifically discuss designing health monitoring systems for UAS, both from industry: one from General Atomics and the other from PHM Technology and Agent Orientated Software (AOS). Both point out the need to capture the functional failures of the UAS and assess the impacts of failures using Failure Modes Effects and Criticality Analysis (FMECA). They reflect more what is currently being done in their respective companies rather than what may be the best solution for UAS generally.

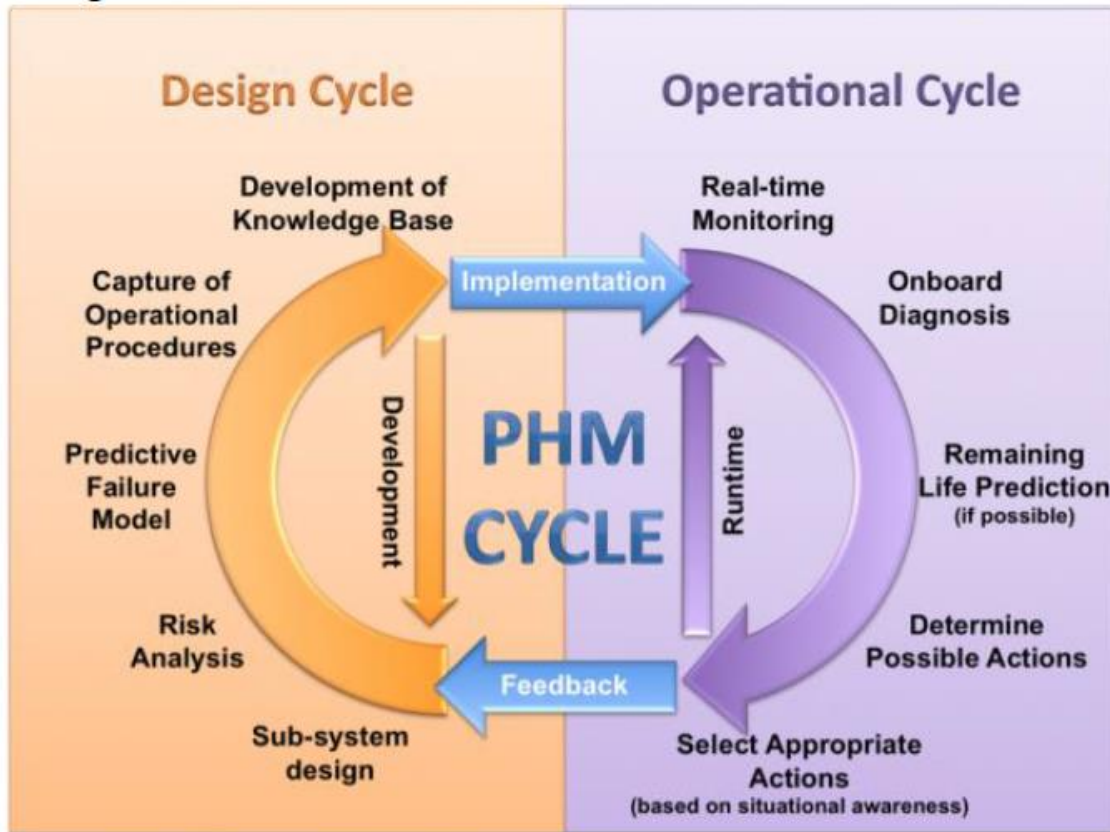


Figure 2-6 PHM Technology and AOS Methodology[62]

The PHM Technology and AOS have developed the PHM Cycle[62], Figure 2-6. The PHM Cycle is split into two stages, the Design Cycle: which an iterative process of analysis techniques to develop a knowledge base (causes of failures, FMECA, interaction between failures, expected functional and hardware reliability of the system) before the system is in operation. The Operational Cycle is what happens in the system in operation and describes the process that health information is gathered, addressed and presented to the user, which could be a human (e.g. pilot of the UAS) or UAS's artificial intelligence. The PHM Cycle also makes it possible for the Operational Cycle to feed back into the Design Cycle to allow future upgrades.

The General Atomics approach to designing a health monitoring system is much more a linear one as opposed to the PHM Cycle. It starts with the gathering of documents and information from other areas of design that might be relevant to the health monitoring system, the assessment of the information

and the performing new analyses that need to be performed. Then the functional failure modes and their effects of the systems in the UAS are captured. The consequences of the failures are assessed, including their criticality and how the failures propagate, and costs. The final step is to implement proactive maintenance tasks based on the analysis conducted.

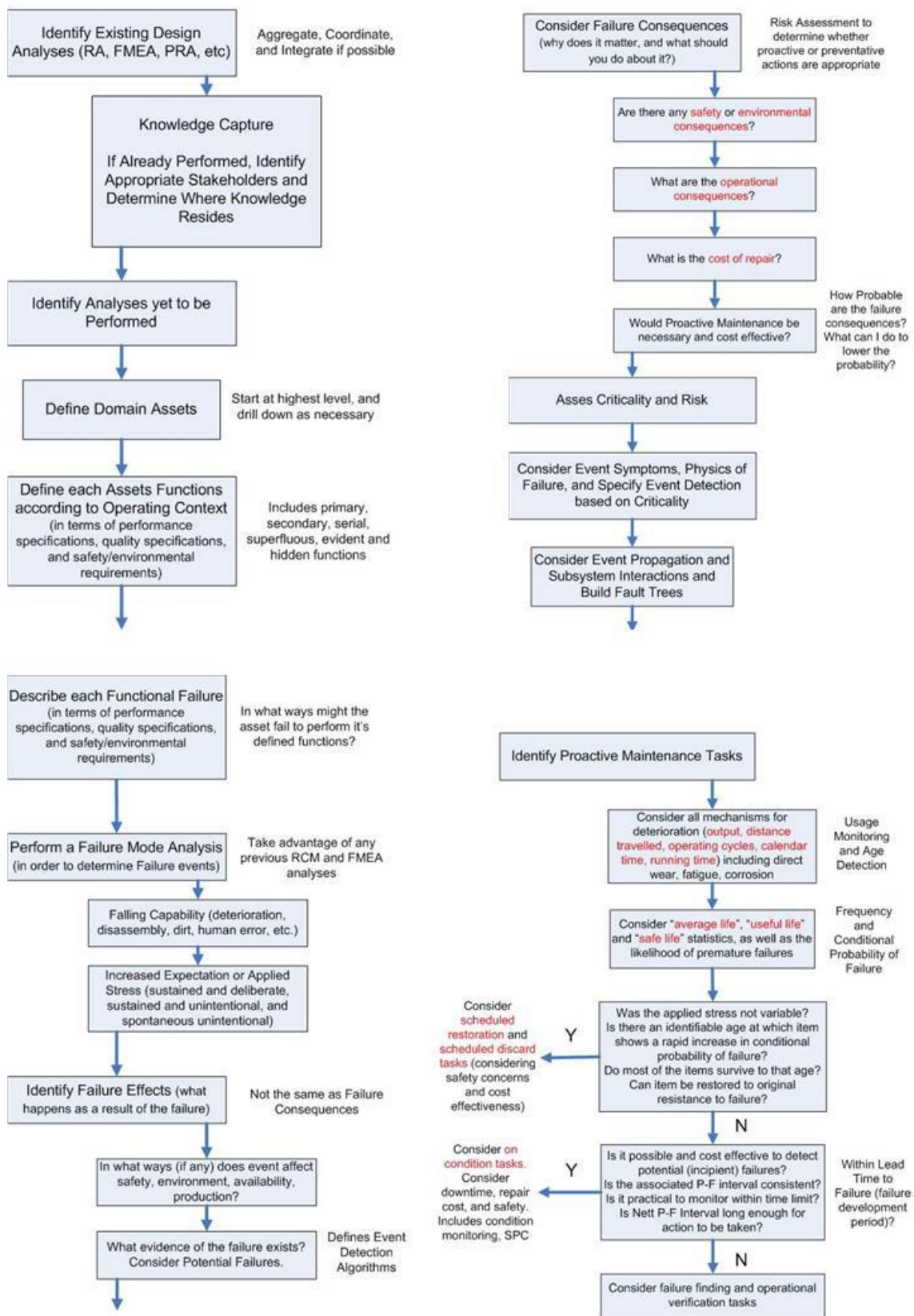


Figure 2-7 General Atomic Methodology[63]

2.4.1 IVHM Design for UAS Summary

- Design methodologies for IVHM (or similar systems) often do not define each step in detail. They give a good overview of the whole process of designing a health monitoring system but they do not specify how to conduct each step in sufficient detail for others to duplicate.
- There is little academic research into designing IVHM for UAS looking at the whole vehicle (UA), let alone the whole UAS. Some design methodologies for IVHM (or similar systems) are proposed by companies and as such may not show the 'best way' of designing an IVHM system, but more what they are doing inside the company, and also to show that they are using the latest technology (to advertise their technological prowess). Although they may be implemented in industry they may not be founded with enough theoretical insight (they may contain little referencing). Other academic work may focus on the monitoring the health of a sub-system of a UA and not mention why monitoring that system is important to the overall vehicle health.

2.5 Requirements Analysis

The establishment and analysis of IVHM requirements is costly and important [64]. Requirements analysis is a part of the SE process where needs of a product are established, analysed, documented, validated, and managed. Requirements analysis can be split into three main tasks[65]: requirements elicitation, requirements analysis, and requirement specification.

2.5.1 Requirements elicitation

Requirements elicitation (also known as requirements gathering) is the process of systematically collecting or extracting the requirements of customer, users, and stakeholders.

2.5.2 Requirements Analysis

Requirements analysis is determining whether the stated requirements from the elicitation are clear, complete, consistent, unambiguous, and resolving conflicts.

2.5.3 Requirement Specification

Requirements specification is process of creating the product specification.

2.5.4 Requirements Tools & Techniques

There are various techniques and tools to help accomplish the above tasks.

2.5.4.1 Parametric Analysis

Parametric analysis is used to identify where a product sits in the market[66]. Parameters (e.g. weigh, cost) are cross-plotted against each other to produce a chart to establish strong patterns. Several hundred plots may be generated for a design but few will be useful and fewer significant[66]. Parametric plots are often used to establish initial estimates in aircraft design[13; 14; 16; 67]. Though with IVHM being relatively new, with the understanding of it still growing and little publicly available information on design it (and also UAS) might not be of particular use at this time.

2.5.4.2 Needs Analysis

Needs analysis is used to establish the Voice of the Customer (VoC)[66]. It is a structured approach to establish the needs of the customer through various methods, including: interviews, questionnaires, reports, market data, reactions to products, official opinions.

2.5.4.3 Matrix Analysis

Matrix analysis compares features of comparable products (to the one being designed), on the vertical axis, and the comparable products on the horizontal axis of a matrix[66]. The matrix is then completed with to show which product incorporate the listed features.

2.5.4.4 Quality Function Deployment

Quality Function Deployment (QFD) tries to capture the qualitative knowledge of people's experience using different forms. Development of QFD started in Japan in the 1960s throughout the design and manufacture of a product [68]. QFD has two interrelated objectives: 1. convert the customers' needs into

design requirements; 2. deploy the design requirements to production activities to establish control points [69].

Since its creation QFD has been used and developed by many organisations and its use has spread around the world [70]; QFD is used to support Total Quality Management (TQM) and ISO 9000 activities [69]. The traditional QFD follows a four phase process (Figure 2-8) which carries the VoC into the product design and production through four Houses of Quality (HoQs) [70].

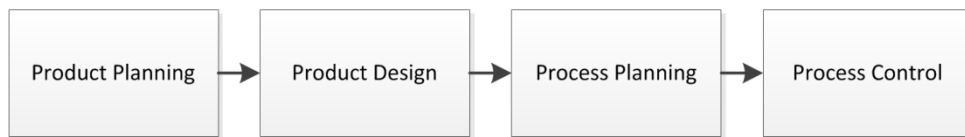


Figure 2-8 QFD Process

QFD makes use of various interlinked forms, most prominent is the HoQ. Several HoQs can also be lined together to cover the whole design and production process (Figure 2-8). The HoQ drawn in Figure 2-9 illustrates the basic parts of HoQ, called rooms, the core element is a relationship matrix (much like matrix analysis above). There are different additional rooms such as the correlation matrix where requirement can be assessed as to whether they support one another.

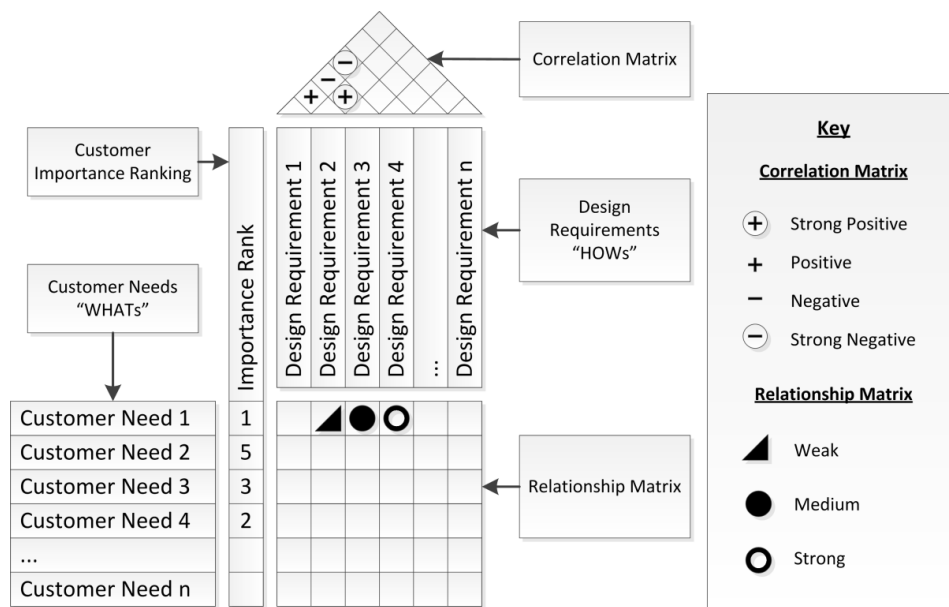


Figure 2-9 Basic Product Planning House of Quality

Another commonly used form in QFD is the Pairwise Comparison (PWC). It is typically used at the start of a QFD to establish the importance rankings for the customer needs. The matrix is formed with the customer needs as both the rows and columns. They are compared with one another and which one is more important to the customer is decided. The amount of times a need is chosen to be more important, compared to the rest of the customer needs depicts its importance rank.

QFD has been proposed for use in the IVHM design process [64; 71], but little detail of how it should be implemented is given.

Van de Poel [72] has identified some problems with the QFD method, with the main focus on the product planning HoQ, which is apt as most QFD are stopped after this point [70].

1. *“Customer demands are product dependent”* – customers are usually unable to voice their demands on products they do not know or have little experience with.
2. *“Customer demands cannot always be represented by a linear additive value function”*.
3. *“Individual customer preferences cannot be aggregated into a collective customer preference ordering without violating a number of reasonable conditions”*
4. *“The correlation between customer demand and engineering characteristics is not always non-negative and constant”*.
5. *“The relative importance of customer demands cannot be uniformly translated into a relative importance of the engineering characteristics”*.
6. *“The meaning of target values is unclear or disputable”*.

Martins & Aspinwall [73] surveyed several UK companies as to their experience with QFD and shows that the top problems (the rest can be seen in Table 2-3) concerning the implementation of QFD are: that it is time consuming, lack of knowledge, and lack of commitment.

Table 2-3 The main problems encountered with QFD [73]

<i>Problem</i>	<i>Percentage</i>
Time – Consuming	16.7
Lack of Knowledge	16.7
Lack of Commitment in the Groups	14.3
Lack of Commitment at the Top	14.3
Difficulty with VoC	9.5
Lack of Resources	7.1
Completing Matrices	7.1
Difficulty in Comparing with Competitors	4.8
Working in Teams	4.8
Not Obtaining Results	2.4
Costs	0.0
Training	0.0
Planning	0.0

2.5.4.5 IBM Rational Doors®

Rational Doors® is a proprietary software for requirements management from IBM®. It offers users the ability to optimize requirements communication, capture, analyse, collaborate, trace, and verify throughout an organisation and supply chain[74].

2.5.4.6 Kansei Engineering

Various psychological factors (e.g. personality, motivations) influence how customers interpret a product. Kansei engineering is used to translate the customers feeling of a product into particular design elements[65]. One such factor which could influence the customers feelings about IVHM is not always seeing the benefits to the customer[10].

2.5.4.7 Knowledge Recovery

Knowledge recovery re-uses knowledge from historical data as a means to facilitate the requirements elicitation process[65]. Again, with IVHM and UAS being relatively new and unused (compared to manned aircraft) this is not very

useful to establishing requirements for IVHM – but could prove useful for future effort.

2.5.5 Requirements Analysis Summary

QFD stands out as a technique which could be useful to deal with the IVHM UAS problem – albeit with alterations. QFD has many advantages that will make it a useful approach when trying to ascertain the IVHM requirements for a UAS:

- QFD has a history of being used in the design of complex products and services[69; 70] – and is well suited for designing PSS, such as IVHM and dealing with the inherent complexity of a UAS.
- QFD has been mentioned as useful to the IVHM design process[64; 71].
- QFD could be used for requirements elicitation, requirements analysis, and requirement specification.
- QFD is customer orientated[70] – and should allow the customer to see the benefits of IVHM, something which is not always obvious to them[10].
- QFD can store, organize, and convey a large amount of information[70] – considering the needs of all stakeholders for a UAS through-out its life will generate a large amount of information.
- QFD allows decisions to be based on data gathered and allows traceability back to the data[70] – using the expert opinions of the stakeholder groups provides qualitative data during the early stages of design, allowing design to make decisions based on previous experience and knowledge, and tracing design decisions back to qualitative data they are based on.

2.6 IVHM Requirements

For the high-level goals of IVHM to be reached, requirements need to be set, identifying both the functional and non-functional aspects of the IVHM. Though there are differences, which must be taken into account, there are commonalities between requirements, systems, sub-systems [49].

The range of technologies and techniques available to IVHM to achieve these goals is numerous: diagnostics, prognostics, etc. Each having their own sub-set of technologies and techniques which can be used (e.g. prognostics could be data-drive, model-model-drive, or a hybrid, each subsequently needing different technologies to implement the prognostic capability). It is the challenge of the designer to choose the best IVHM solution for the UA, given that it is working in a fleet and organisation – based on the requirements they have been given. High-level IVHM requirements can be broken down into both functional and non-functional requirements [75]. The establishment of these requirements is costly [64], but standardisation could help reduce costs with similar systems [50]. IVHM is also expected to have provision for in-service updates [62; 76] – to optimise it once real operational data has been gathered.

Previous works looking into the requirements of IVHM have been focussed on the flowing of higher-level requirements (system level goals, e.g. safety, maintainability) to lower-level requirements (e.g. false positive rate, false negative rate) [77] and provide set of metrics to assess whether certain aspects are being met [78; 79]. Although the need to understand the context and ascertain which aspects of IVHM are more important to meet the needs of the stakeholders is understood [75; 80] there is still a lack of methods for gathering and sorting the various opinions of different stakeholders to IVHM.

2.6.1 Types of Requirements

Requirements can be broken down into categories in several different ways. A useful way of breaking down requirements is into functional requirements and non-functional requirements. Functional requirements define the functions of a system, or its sub-systems and components i.e. what the system must do. In the case of IVHM functional requirements are along the lines of: the IVHM must perform diagnostic analysis for the UA.

Non-functional requirements specify criteria that can be used to judge the operation of a system, rather than specific behaviours defined by the functional requirements. In the case of IVHM non-functional requirements are along the lines of: the IVHM must be reliable.

2.6.2 Typical IVHM Requirements

The following is list of generalised IVHM requirements summarised from the literature and is not a definite list:

- The IVHM shall monitor 'A' (e.g. the structure) on/of system 'X' (e.g. the landing gear).
 - This sort of requirement can be flowed down to the sub-systems.
 - Tolerances can also be specified.
- The IVHM shall perform fault detection.
- The IVHM shall perform fault isolation.
- The IVHM shall assess the severity of a fault.
- The IVHM shall assess the impact of a fault on the sub-system/system/vehicle.
- The IVHM shall detect degradation.
 - In normal use.
 - In the case of a fault.
- The IVHM shall detect anomalies.
- The IVHM shall predict future performance.
- The IVHM shall predict future faults.
 - Could be for the vehicle, or the fleet.
- The IVHM shall report the fault to the pilot.
 - Could also report the fault to maintenance personnel
- The IVHM shall the operating conditions.
- The IVHM shall report detect abnormal operating conditions.
- The IVHM shall assess the health of the fleet.
- The IVHM shall transfer 'X' data/information to 'Y' in 'Z' time.
 - Could be within the vehicle or from it (e.g. to the fleet database).
 - Could be information of the stage of the fuel system to the flight control computer, which parts and equipment for maintenance crews to prep, etc.
- Health data/information will be stored for 'X' amount of time.
- The IVHM shall record 'X' (e.g. hard landings) events.

2.6.3 Challenges of Requirements Analysis

There are several challenges inherent when conducting requirements analysis. Customer requirements are often ambiguous and imprecise due to the linguistic origins – with different departments (engineering, marketing, etc.) using different terminology[65]. Requirements can conflict with one another[65]. Customers do not always know what they want from a new product[72]. Requirements at the start of a project are often ambiguous and mature during the project[18]. These challenges are just as applicable to IVHM requirement as any other design.

2.7 Literature Summary & Gap Identification

2.7.1 General Findings & Gaps

The following are some of the general findings from the literature review:

- The idea of unmanned flight is just as old as that as manned, but until the late 20th Century the technologies available to earlier pioneers fell short of their ambitions. The technologies involved in the current successes with unmanned aerial vehicles/systems are much the same that enabled IVHM today, i.e. the advances in sensors, processors that are more powerful, networking technologies, and databases. Advances in these areas, as well as the fall in cost, reduction in size, of the components (driven often by other market areas e.g. the mobile phone industry) has allowed many people and organisations (companies, universities etc.) to experiment with them, improving programming and algorithms (autonomy, automation and flight control in the case of UAS; and diagnostic and prognostics in the case of IVHM).
- Both IVHM and UAS can be seen as disruptive innovations: disrupting existing markets (sale of spare parts for the case of IVHM and power line inspection for the case of UAS) as well as creating new ones (enabling availability based contracting for IVHM and environment monitoring UAS). With both the IVHM and UAS industries still developing business models, it would be advantages for UAS manufacturer/operator to think

of including IVHM now, as opposed to developing their business without IVHM, then making the shift later to include it.

- IVHM could be used to enhance some advantages of UAS.
 - Autonomy and Flight Control – IVHM could provide another set of information that the UAS's autonomy/mission planning/flight control computer could use.
 - Long Endurance Missions – IVHM could allow a UAS to stay up for as long as possible, only coming down when a maintenance action is necessary (or if fuel is needed) e.g. solar powered for pseudo-satellite dirigibles.
 - Dirty and Dangerous Roles – If being sent into a contaminated area (e.g. bio-chemical, radiation) IVHM could account for the time and level of contamination the UAS in the area allowing evaluation of any effects it might have on the life of systems. Additionally, although not strictly in the remit of IVHM, the IVHM system could send information on the contamination of the UAS (not in the environment it is sent into) to the ground crew so they can take the appropriate action when it lands (e.g. HAZMAT suits worn by ground crew, decontamination showers).

2.7.2 Focused Findings & Gaps

The following findings establish the gap in the current state of knowledge in which this thesis poses to contribute to.

- UAS is a vast term covering many different types of aircraft, which can be arranged in varying combinations into a SoS.
- IVHM has a wide range of stakeholders. The final customer of the UAS, the business/organisation operating it, operations staff scheduling flights, maintenance, etc. all have different requirements of the UAS, which will need to feed down to the IVHM design.
- UAS are Systems of Systems and all parts are needed to fly them – IVHM systems should be considered on all parts.

- IVHM design is not always treated as part of the overall design of an asset. Some IVHM solutions are applied as fixes to a particular problem. IVHM designs methods often do not make much reference to the overall design of the asset.
- The context of the IVHM is important. Who the stakeholders are, what the UAS elements are, failure rates, regulations, etc. are all dependent on the context of the UAS.
- Designers/manufacturers of UAS need to consider IVHM (and the through-life support in general) early in the design.
- Customers often fail to see the benefit of IVHM to them.
- Customers of a new product do not always know what they want. As IVHM and UAS are both still being established, there is little operational understanding of what aspects of IVHM will best support a UAS in its operation.
- The importance of establishing the requirement for any product is known and is true for IVHM. The need to establish the requirements of IVHM for an asset is often stated, the details in how to establish them are not clearly set out.
- There are existing tools and techniques for gathering and sorting requirements and each tool will bring its own pros and cons.

These findings from the literature point to there being a complex requirements problem, as there are many stakeholders to be satisfied by the IVHM, and the IVHM design dependent on the context of the UAS it is to be applied to. The need for a designer to understand those requirements is clear, and to know which is most important to best appease the stakeholders and support the UAS in its operation (to achieve the goals of IVHM: increase availability, increase safety, and reduce cost). Figure 2-10 maps the out how topics within this review relate to each other, and whether there is have a positive (+), negative (-), or neutral (0) effect. Starting at the bottom left, it relates the quality of IVHM design to customer satisfaction at the top. However there is currently no clearly defined way for a designer to analyse the different stakeholder viewpoints and need of the IVHM. Trade-offs will have to be made during the design of the UAS, so

having a clear understanding of the order of importance for the requirements will be of advantage to the designer of the IVHM for the said UAS. It is from these finding which the aims and objectives of the project (page 25) have been drawn from.

3 Research Methodology

This chapter sets out the methodology used for the research and offers the purpose and reasoning for each stage. These steps detail the major actions taken during the project, how they relate to achieving the objectives of the project, and reference where in the thesis the work conducted during them is contained.

From the literature review in the previous chapter it is clear that a relativistic approach to the research would be best suited to the problem[81-83] – as opposed to a positivistic one. With the many different influencing factors on IVHM design (the vehicle, the technology available, cost, the operator, etc.), the current situation of the regulations for UAS, and the vast range of sizes and configurations of UAS, it is only prudent to assume that the research will be accurate when all these factors are considered as a whole.

A holistic approach to solving the problem is needed for several reasons. First, the nature of UAS. As UAS are SoS, according to systems theory, emergent behaviour is to be expected – which the reductive nature of positivism does not cater to. Further to UAS being SoS, they are also operating within environments (the organisation operating the UAS, the national air system, etc.), as is the IVHM which – again with emergent behaviours.

Second, the nature of stakeholder requirements, which come from people or organisations with interest in the IVHM. Different UAS designs/uses will have different stakeholders and thus different requirements. Additionally, the requirements are coming from people (or the organisations which are made up of people) and will be subjective.

Third, the subjective nature of system health. At some point the health of a the UAS (or fleet, system, etc.) will need to be assessed (whether by a human or through algorithms). Judging the health of a UAS will be based on information provided by the IVHM (as well as other maintenance activities and records). Whether a UAS can be considered healthy will be dependent on its current/intended use and who is assessing the UAS. For example, a UAS

suffering a failure in flight could be assessed as healthy to continue its current mission, but unhealthy for any future missions. But this is not limited to missions, it can be applied to different contexts (e.g. operation planning, maintenance, leasing/financing) and viewpoints of stakeholders. Some may argue that the 'true' health of the UAS is only being perceived (by sensors, algorithms, humans, etc.) through the context, and could lead to a post-positivism approach, others could argue that the health of the UAS is only relevant when it is considered alongside the use of the UAS, leading to relativism.

With the many types and classifications of UAS, and there is no ideal IVHM, a case study based strategy is used in the research. In order to achieve the aims of the research specific cases need to be explored. From comparing and contrasting these cases to one another, generalisations can be drawn – which will be of use beyond the specific cases.

An overview of the steps taken in the research is presented below (Figure 3-1). The project took an experiential approach to conducting the research. Steps one to three build up the definition and understanding of the problem. Steps four and five develop and apply the IVHM-RD for specific cases. Finally, steps six and seven, reflect on the use of the tool based on the experience with the design cases.

Although presented in a linear fashion of one task leading onto another, some tasks continue throughout the project (e.g. literature was read throughout the project) and there are iterations between steps, details of such will be given in the following explanations of the steps below.

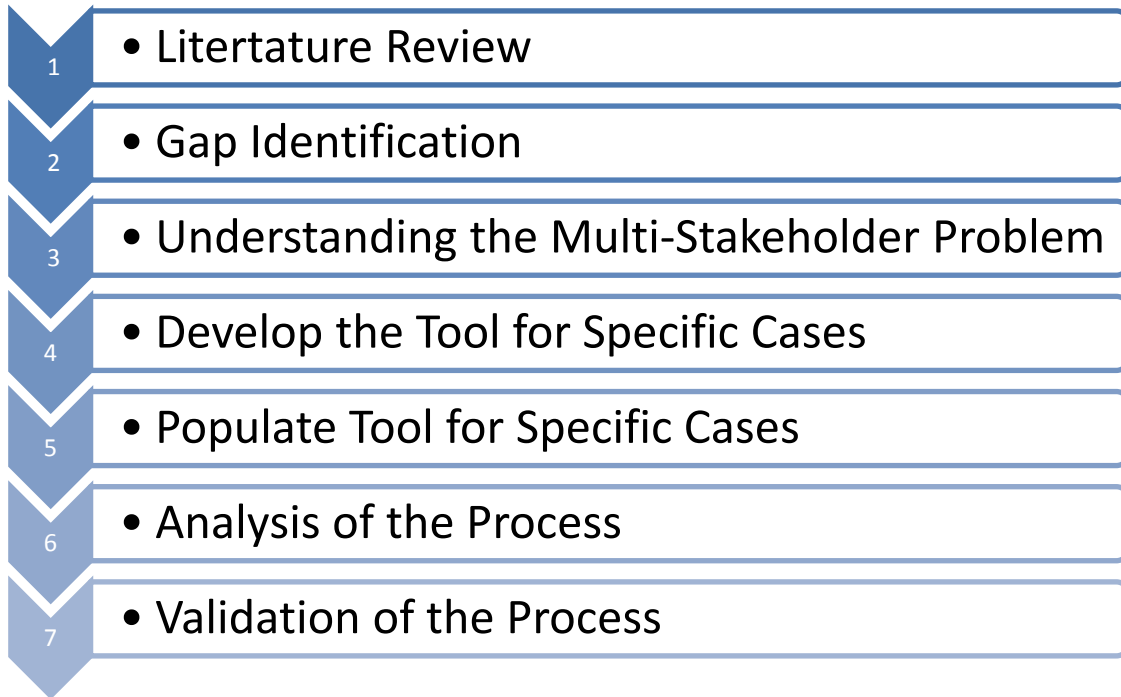


Figure 3-1 Overview of the Research Methodology

3.1 Literature Review

This stage works towards achieving objective one and provide the current state of knowledge. In order to establish where the research sits in the wider subject area and identify current understanding, a review of the literature was conducted. This review had two main phases.

The first phase was the scoping of the project and the definition of the problem. This part of the review looked at available literature to initially establish the area of interest (the complex requirements problem) within the domain (designing IVHM for UAS), then looked in depth at areas of interest to establish the current state of knowledge.

Second was investigating the nature of the problem and possible ways of solving the problems identified in from the gaps in the knowledge way in which is useful to designers of IVHM for UAS.

The process of reviewing available literature and adding it to the review continued throughout the project as new material was published or came to light.

3.2 Gap Identification

This stage is used to establish the gaps in the current knowledge around designing IVHM for UAS and set out the aims and objectives of the project. BAE Systems provided the area of interest for the project based on the lack of knowledge within industry around the design of IVHM for UAS. From this starting point literature was assessed to find specific gaps for which the project can contribute to the understanding of the subject. These gaps in the knowledge have been identified previously in the Literature Review chapter (page 71) and the aims and objectives which resulted from the identification of gaps in the current knowledge are presented in the Introduction (page 23).

3.3 Building the Context for the IVHM

This stage works towards objectives one. During this stage an understanding of the multi-stakeholder problem was developed. It was impossible to explore all the possible combinations of UA type, UAS elements, operating organisations, etc. It was therefore necessary to select design cases to apply the tool. These cases need to be representative of real designs for UAS. These design cases will provide the context to the IVHM being designed for a UAS, through which the complex requirement problem can be explored.

The design cases developed for the project were a persistent UAS and the Demon UAS – both covering different issues that a designer will currently face. The Persistent UAS represents the next generation of UASs, which is being designed and is of similar scale to some current military UAS. The Demon UAS represents the current generation of UASs, which have been produced (constraining the available weight and space for any IVHM on the UA) and is conveniently located at Cranfield University. The IVHM in the Context of Unmanned Aviation chapter (page 83) describes how IVHM sits in the context of unmanned aviation and how the design cases were developed.

3.4 Develop Tool for Specific Cases

This stage works towards objectives two, three, and four. An assessment of established requirements tool was done to find out which tool would be best suited to solve the problems identified.

The selection of the appropriate tool for development was a qualitative one based on the literature for the tools and also the understanding of the multi-stakeholder problem when designing IVHM for UAS. It is worth noting that the selection of any one tool brings both its benefits and drawbacks. The assessment of the tools considered is found previously in the Literature Review chapter, and a more detailed reasoning of the chosen tool (QFD) is presented in the Chapter 5 .

During this stage of the research it was necessary to develop the IVHM-RD tool for the two representative problems in order to see how the developed tool would impact the design of IVHM on the particular UAS.

3.5 Populate Tools for Design Cases

This stage works towards objectives two, three, and four. Once the tools for both design cases were developed they needed to be populated with data by relevant SMEs. During this stage SMEs were sent the IVHM-RD and asked to fill out the forms. The details of the population for the design cases can be found in the Chapter 6.

Populating the tools provided valuable information on the IVHM-RD in three ways. First, it provided information which will be useful to the design of IVHM in both design cases. Second, it provided information on the effectiveness of the IVHM-RD tool in use and to the method of population itself. Third, it provided an opportunity to capture the knowledge contained within BAE Systems and the other IVHM Centre partners.

The during the population of the IVHM-RD forms steps were needed to ensure that the results gathered are representative. To achieve this it was also necessary to develop a set of metrics to judge the reliability of the population.

Cranfield University has guidelines to ensure that research is conducted ethically when dealing with human participants. These guidelines were followed during the project and the necessary approval was sought when populating the IVHM-RD, from the ethics committee.

3.6 Analysis of the Process

This stage works towards objectives one to five. The analysis of the process can be divided into two parts. The first part is to look at the tools and populations for the design cases and the generic process. It evaluated the process noting the differences between the two implementations of the IVHM-RD on the design cases, and also the IVHM-RD process's merits and where it can be improved upon.

The second part looked at the results of the population of the design cases. First, looking at the results and posing what impact they will have on those specific cases. Second, comparing the results of both cases to each other (and to a third case, of a manned fast jet) in order to see what the cases have in common and also their differences they have in the ranking of their IVHM requirements and enablers. The analysis of the populated IVHM-RDs for the design cases prove that it is able to capture the context and reflect it in the IVHM requirements, and that the tool provides useful information to the IVHM designers.

The analysis of the IVHM-RD process (tool, population, and results) is found in the Chapter 7.

3.7 Validation of the Process

This stage goes towards confirming the achievements of the objectives. To fully achieve the objectives set out in the introduction of this thesis, the outputs of the research must be of use to designers of the IVHM for any UAS (not just for design cases presented in this thesis). The validation of the IVHM-RD works towards instilling a level of confidence of the process, to the effect that it is of use to the designer of IVHM for a UAS. The details of the validation process are described in the Validation chapter.

4 IVHM in the Context of Unmanned Aviation

There are many factors which have influence over the IVHM for a UAS, these factors constitute the context in which the tool must fit. The context will vary from UAS to UAS, mission to mission, organisation to organisation, etc. These factors may also influence how much IVHM (which could be in terms of features, weight assigned, development cost, etc.) is included in a UAS design – if any at all². This chapter looks at how these different factors affect the trade-off decisions in the design of IVHM for UAS.

This chapter is split into eight sections. The first section looks at the tool requirements needed to support the trade-off of IVHM requirements. The second section looks at stakeholders. The third section looks at what makes the context for this project. The fourth section looks at how the mission and configuration of the UAS will affect the development of the tool. The fifth section looks at how IVHM requirements are developed. The sixth section looks at the characteristics of the tool. The seventh section details the design cases used in the project. The eighth is a summary.

4.1 Trade-Off Tool Requirements

Developing a tool which will fulfil the aims of this project will have to meet a set of requirements derived from the project objectives (page 25):

- i. The tool must establish the context which will influence the design of IVHM for UAS;
- ii. Relate the stakeholders and mission requirements to the IVHM requirements;
- iii. Prioritise the requirements and enablers;
- iv. Efficiently solicit the opinions of various stakeholders;
- v. Establish the reliability of the opinions of the stakeholders.

² It is possible that the costs of implementing the IVHM would outweigh the benefits.

4.2 What Makes up the Context?

Figure 4-1 shows how the context is provided to the IVHM requirements. The design cases provide information on the elements (UA, CS, etc.) for the UAS, and also the context to which will affect the IVHM requirements. In addition to these there will be enablers which will support the design of any IVHM.

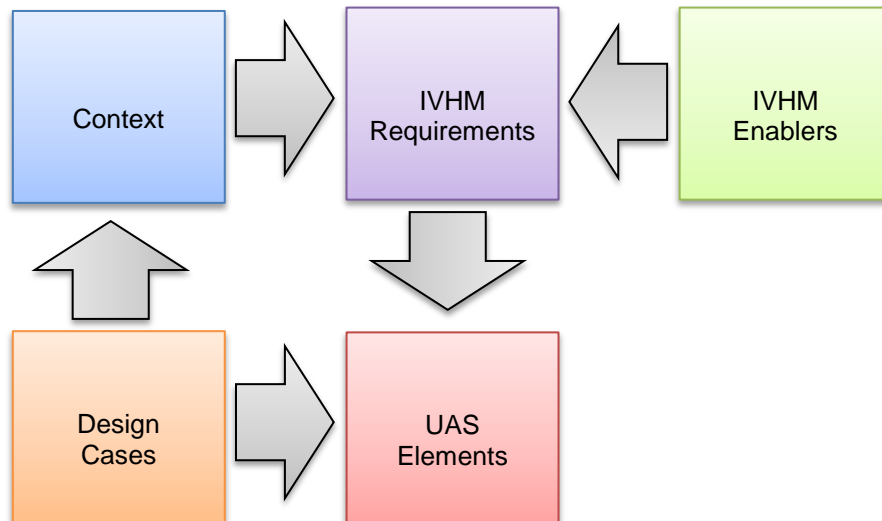


Figure 4-1 Context applied to IVHM requirements

4.3 Who are the Stakeholders?

Although the stakeholders to each implementation of IVHM on a UAS will be different from design to design, mission to mission, and organisation to organisation. With the propensity of IVHM to interact with all the systems within a UAS, there is a wide range of stakeholders which include[80]:

“

- *Maintenance personnel and management (e.g. line, overhaul, [Maintenance, Repair, and Overhaul] personnel)*
- *Operator (e.g. the airline, USAF, etc., if not the owner)*
- *Crew (the actual operator such as the pilot)*
- *Fleet manager (e.g. mission commander)*
- *Owner (e.g. airline/lease company/USAF)*
- *Regulatory authorities (e.g. airworthiness, certification)*
- *General public*
- *Health Management (HM) system integrator (e.g. third party IVHM provider)*
- *Original Equipment Manufacturer (OEM, e.g. Internal integrated engineering teams developing the product)”*

A UAS could have any combination of the above generic stakeholders (and possibly more). However, there are three core groups of stakeholders which will be interested in the IVHM. These groups are customers, the businesses, and the users (of the IVHM).

4.3.1 Customers

The customer (or customers) is a relative term. It can refer to the end customer of the UAS (the organisation purchasing the UAS or a service which uses the UAS) but could also apply to manufacturer of a UAS if the IVHM design is sub contracted, or one design department to another within the same company. Clearly understanding who the customer and what their needs are is necessary. IVHM has a supportive role providing information to the maintenance and operations of a UAS. The need to link the IVHM's supportive role to the needs of the customer is necessary for them to see if IVHM is of value to them – something which is not always the case[10]. Knowing what the customer wants and how IVHM relates to those wants is the first step of justifying why IVHM should be included on a design.

4.3.2 Businesses

Just as with the customer, the business (or businesses) is relative (and for the military is not totally apt). There can be several businesses involved with the IVHM for a UAS e.g. manufacturers (including sub-contractors), suppliers, UAS operators. Again, understanding the needs and wants of each business involved, and relating the IVHM to them, can show how IVHM can reach different business objectives e.g. transitioning to availability based contracts.

4.3.3 Users

The users of IVHM are also a diverse collection of people, depending where they are in the operations and maintenance chain. A front line maintainer will need to know different information than those further back in the chain. Likewise, the pilot will also need to know different information from the IVHM. Additionally, the UAS itself can also be considered a user of the IVHM, with the flight control/management for the UA making decisions based on information

provided by the IVHM. The key to all users of the IVHM is to provide them with the right information at the right time.

4.4 UAS Mission and UA Configuration

The mission of the UAS is used to determine its elements needed and the configuration of the UA. The mission and configuration will determine which systems and sub-systems are needed, and how critical they are for the UAS to complete its mission. The designer of the IVHM then has to design the IVHM to support the UAS's mission by providing health data accordingly.

However, the lack of use of UAS (compared to manned aircraft) limits the information on the reliability of UAS (and their systems) and what the impact the mission will have on those systems' health. But it is known that the different elements will comprise of different systems, thus need different maintenance regimes and techniques – resulting different needs from the IVHM. This will have an impact in the development of the tool. The tool will need have enough elements to cover the missions and configurations of the UAS being designed and be flexible in order to adapt to other UAS designs (different missions and configurations).

4.5 Developing Requirements for IVHM

Each stakeholder group will have their own sets of requirements for the UAS, which will relate to the IVHM in varying degrees, as well as to other stakeholders. For example, a customer for a UAS will be concerned with the total cost ownership, as will the business manufacturing the UAS (which could use it as a selling point). A reduction in maintenance costs is the goal of IVHM (thus reducing the ownership costs of the UAS). It is clear to see that IVHM could help the UAS reduce its total cost of ownership – but the details have not been defined.

As mentioned in the literature review (page 68) there is little detail in how to explore how stakeholder requirements of the UAS relate to the various IVHM tools and techniques. Each design case will have a unique set of requirements which can be related to generalised set of requirements for IVHM, comprising of

features which are common across IVHM implementations. These stakeholder requirements are what will be used in the tool to prioritise the IVHM requirements, thus establishing which IVHM requirements best support the requirements of the UAS and its stakeholders.

Just as there can be a generalise set of requirements for IVHM there can be a generated set of IVHM enablers to support those requirements.

The development of both stakeholder requirements, IVHM requirements and enablers is covered in Chapter 5.

4.6 Tool Characteristics

4.6.1 Positioning in the Overall Design Process

When developing the tool consideration needs to be give as to where it will be positioned in the design process. The tool is to be considered to be used in the early stages of the design of IVHM for a UAS, which for a new design should be at the start of the overall design. This is when the stakeholders requirements, the mission of the UAS, its elements and configuration are defined. The intention is the tool to consolidate and prioritise the requirements of the stakeholders and relate them to the requirements of the IVHM, and then assess what would help enable that those IVHM requirements.

4.6.2 Time and Cost

There is going to be a cost associated with using the tool in the design process, this can be equated the time. The time taken to complete the tool can be split into three main sections: the time taken to adapt the tool to the UAS being designed, the time taken to populate the tool, and the time to analyse the results. Population involves valuable SME time.

Minimising time (and thus cost) has obvious benefits. However, there will be a trade-off to be made, mainly in the effort to adapt the tool to the specific UAS in question (i.e. how much of the context needs to be present/captured in the tool) and the time taken to populate it. The more of the context is included in the tool the more information will be needed to populate it.

4.6.3 Elicitation of Group Opinion

The tool will need to elicit the options of individuals in the various stakeholder groups.

4.7 Design Case Creation

When designing the IVHM for any asset the first major influencing factor to the design is whether the IVHM is to be implemented on a new design or a legacy design (an asset which has already been design, produced, and entered service). The two UAS design cases are selected to be in different stages of their life-cycle. One at the start of the design process (the persistent UAS design case) and one part way through its operational life (the Demon UAS design case).



Figure 4-2 Basic Representation of Stages in a UAS's Life

Although in theory IVHM could be considered at any stage during the life of a UAS, currently HM technologies tend to be considered during in the operation of UAS – as lessons are learned about the UAS and where adding HM might of benefit to solve a specific problem. It is also conceivable that IVHM will be considered at the end of the UAS's life to stave off withdrawal during a major overhaul, as is the case with aging manned aircraft but few UAS are even approaching this stage. Also, the problem of whether or not adding IVHM to a UAS in operation is beneficial is a different problem entirely, and a digression from the focus of this thesis. For the Demon design case adding of IVHM will be justified qualitatively, but there will be no quantitative analysis (e.g. cost benefit analysis).

The other stage in a UAS's life that IVHM is considered is during its design – this is the case for the next generation of UAS, HM technologies have been

seen in solving some problems in the current generation so are considered. The design stage itself can be subdivided, as has been described above. The case studies used in the research are built around these classifications. Summaries of each design case are presented below and more information can be found in the Appendix A.

4.7.1 Persistent UAS

This design case represents the next generation of UAS. The Persistent UAS has been created as a plausible concept. It is a civilian commercial farm monitoring UAS which monitors the condition/health of vegetation, the condition and use farm land, and location/movement of animals over a prolonged period of time (forty eight hours). This mission is essentially an observation mission. Currently these types of prolonged observation mission are carried out by military MALE (medium altitude long endurance) UAS (such as Predator and Global Hawk), this is in part due to the relatively new technology involved and the fact that the civilian regulations are still being developed. The Persistent UAS is in the early stages of its design. It has a conventional configuration, high aspect monoplane wings of fifteen meters and weights 1,175 kilograms, and is equipped with an electro-optical/infrared (EO/IR) camera for the purpose of monitoring vegetation (primarily farm crops). The elements of the persistent UAS are: the UA, a CS, a storage box for the UA, and a truck to transport everything.

The UAS is owned, manufactured, and operated by one company (Company X) and offers a flight/data service to another company or organisation (Organisation Y) – it does not sell the UAS for others to operate. For example, government Organisation Y contacts Company X to conduct flights over farms to confirm that the minimum environmental standards are met for receiving farm subsidies. The Persistent UAS is to be considered as part of a fleet (consisting of just the persistent UAS and no other types of UAS).

Any IVHM implemented on the Persistent UAS must support its farm monitoring mission as part of a business – and should be considered on all elements of the UAS. The IVHM must compete with other aspects of the UAS design (e.g.

weight and power for IVHM could also be used for extra fuel or payload) and justify itself.

4.7.2 Persistent UAS Stakeholders

This section identifies the primary and secondary stakeholders to the IVHM on the Persistent UAS. Each stakeholder is assigned a number, which they will be referred to in this report.

4.7.2.1 Primary

The primary stakeholders who have direct involvement/interest in the Demon UAS are:

1. Customer of the Service (Organisation Y)
2. Company X (owner, manufacture, and operator)

4.7.2.2 Secondary

The secondary stakeholders who have an interest in the project are:

3. Regulators
4. Other Aerospace Users
5. The General Public

4.7.2.3 Stakeholder Analysis

The stakeholders have been arranged by their level of interest and potential impact on the project (Figure 4-5) in the following categories:

- A. High interest and low impact
- B. High interest and high impact
- C. Low interest and low impact
- D. Low interest and high impact

	Low Impact	High Impact
High Interest	A 1	B 2
Low Interest	C 4 5	D 3

Figure 4-3 Stakeholder Impact and Interest for the Persistent UAS

4.7.3 Demon UAS

This design case represent the current generation of UAS. The Demon UAS was built by Cranfield University as part of the FLAVIIR (Flapless Air Vehicle Integrated Industrial Research) project. The FLAVIIR was a five-year collaboration, ending in June 2009, between ten UK universities³, BAE Systems, and the Engineering and Physical Sciences Research Council (EPSRC). The project was set two challenges[84]:

- Challenge 1: To develop technologies for a low cost, maintenance free UA without conventional control surfaces and without performance penalty.
- Challenge 2: Significantly research impact through effective academic/industry management and exploitation of large scale integrated academic research.

³ Cranfield University, Imperial College of Science, Technology and Medicine, The University of Leicester, The University of Liverpool, The University of Manchester, The University of Nottingham, The University of Southampton, The University of Wales Swansea, Warwick University, and The University of York.



Figure 4-4 The Demon in Flight

The Demon UA was developed as the flying technology demonstrator aircraft (a research aircraft) for FLAVIIR and incorporated many of the technologies developed from the project. The Demon has a novel blended wing body configuration constructed using composite materials, is approximately three meters long and weighs eighty kilograms. A gas turbine provides power and thrust vectoring capabilities. The Demon can use novel fluidic control devices, fed by compressed air powered by an auxiliary gas turbine; the metallic-grey fluidic control devices can be seen on the trailing edge in Figure 4-4. Since the conclusion of the FLAVIIR, the Demon UAS has been used as a publicity tool at various events by both BAE Systems and Cranfield University. Although its original mission had been accomplished, Demon has been designed with a level of flexibility so that it may be used for new research projects after the FLAVIIR[85].

The idea of adding IVHM to the Demon is in keeping with the first challenge of the FLAVIIR project, and Demon does have some HM technologies on-board already (monitoring the landing gear and electrical currents), but these are included as part of its role as a technology demonstrator and it is not clear whether or not they would form part of an overall IVHM system based on requirements of its current use as research aircraft (post the FLAVIIR project). As a research UA the Demon is only flown as and when an experiment is needed and all the proper preparations have been made (e.g. research goals established installing the experimental equipment, flight approval from the CAA, safety assessments).

Any IVHM implemented on the Demon UAS will need to support its role as a research aircraft (be flexible enough to accommodate its changing nature). It must also meet the physical constraints of it being a build UA (e.g. spatial, weight).

4.7.4 Demon UAS Stakeholders

This section identifies the primary and secondary stakeholders of IVHM on the Demon UAS. Each stakeholder is assigned a number, which they will be referred to in this report.

4.7.4.1 Primary

The primary stakeholders who have direct involvement/interest in the Demon UAS are:

1. Cranfield University
2. IVHM Centre
3. BAE Systems
4. EPSRC

4.7.4.2 Secondary

The secondary stakeholders who have an interest in the project are:

5. FLAVIIR Universities
6. Academia
7. ASTRAEA Project
8. Regulators
9. Other Aerospace Users
10. The General Public

4.7.4.3 Stakeholder Analysis

The stakeholders have been arranged by their level of interest and potential impact on the project (Figure 4-5) in the following categories:

- E. High interest and low impact
- F. High interest and high impact
- G. Low interest and low impact

H. Low interest and high impact

	Low Impact	High Impact
High Interest	A	B
	5	1
		2
		3
Low Interest	C	D
	6	4
	9	7
	10	8

Figure 4-5 Stakeholder Impact and Interest for the Demon UAS

4.7.5 Design Cases Comparison Summary

Table 4-1 A Summarised Comparison of the Design Cases

	Demon UAS	Persistent UAS
Airframe	Blended wing body	Conventional configuration
	Diamond shaped wings, single tail with rudder	High aspect monoplane wings
	Aspect Ratio: 2.047	Aspect Ratio: 30
	Wing Span: 2.53 m	Wing Span: 15 m
	Wing Area: 3.13 m ²	Wing Area: 7.5 m ²
	Conventional Wheeled Landing Gear	Conventional Wheeled Landing Gear
Power Plant	One Turbojet	Two Turboprops
Performance	Speeds: 70 – 150 knot	Speeds: 40 – 210 knot
	Endurance: 20 min	Endurance: 48 hr
	Ceiling: Within Line of Sight	Ceiling: 20,000 ft
	Range: Within Line of Sight	Range: 300 km (max)

4.8 Context Summary

This research argues that the context will affect what IVHM is best for a particular UAS. The two design cases will provide the context needed for the trade-off tool to be developed. They are representative of two different points in the current UAS spectrum, each with their own stakeholders.

5 Development of the IVHM-RD

This chapter reports on the development of the IVHM Requirements Deployment (IVHM-RD) tool. The tool development has two aspects: first, the generic research done to establish the architecture and elements that cover a comprehensive range of IVHM for UAS design problems; and second, the process to make a case specific requirements analysis. The chapter is split into three sections; the first section is on the tool and its development. The second section is on the adaptation of the tool to the design cases. The final section is on the generalised process and how it can be used in the design of IVHM in other UAS.

Although presented in this thesis in a linear fashion this was not entirely the case. The tool portion of the IVHM-RD was developed alongside with its application to the design cases. This led to one (or both) of the design cases informing the general tool, which subsequently fed back into the applied IVHM-RDs in an iterative fashion.

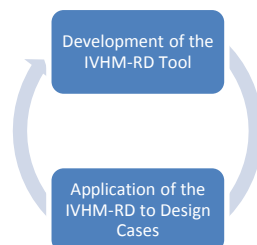


Figure 5-1 Iterative Nature of Developing the IVHM-RD

5.1 Development of the Tool

As stated in the literature review there are several tools and techniques which have been developed to capture and analyse requirements. QFD (Quality Function Deployment) provides a good starting point (as stated in the Literature Review chapter, page 72). However, it will need to be adapted in order to be able to solve the problem being investigated.

Unlike QFD the IVHM-RD's propose is not to relate the VoC through the design and production of the IVHM for the UAS (i.e. the product/service). The propose

of the IVHM-RD is to relate the viewpoints of the stakeholders involved to the IVHM – more specifically to relate the requirements of the stakeholders to the requirements and enablers of the IVHM so that they can be ranked in terms of importance. This a fundamental change in the use, although the IVHM-RD uses components of QFD they are used to achieve a different purpose – which align with achieving the aims of the project (page 25).

5.1.1 Requirements

As previously mentioned, requirements at the start of a project are often ambiguous[18], there can be little operational use of the UAS – subsequently what issues IVHM could help with (e.g. problem systems, problem components, common failure models) and the evidence to assess the scope of the problem (e.g. actual component failure rate, actual costing on maintenance).

There are limitations to the number of requirements to be included in the IVHM-RD. The more requirements there are the greater detail in which the amount of detail can be captured within the IVHM-RD, but this will increase the amount of time needed for its completion. There could also be overlap in requirements between stakeholders. Grouping stakeholders with similar requirements has advantages in reducing these overlapping, reducing the number of HoQ needed. The exact grouping will be subject to the context. There are three general categories which requirements can be grouped into: stakeholder requirements sets, IVHM requirements set, IVHM enablers set.

5.1.1.1 Stakeholder Requirements Sets

These sets represent the requirements of the various stakeholders. The stakeholders are grouped together in order to reduce the number of HoQ needed in the IVHM-RD and better control the requirements. Grouping requirements into sets which represent different stakeholder will be dependent on the UAS (i.e. the context). This said there are commonalities between stakeholders which can be used to form these groups.

One such way is using the organisational structure. For instance those in the maintenance department will have different jobs performing different roles, but their requirements will be centred on the maintenance of the UAS.

There is also a need to consider the elements within the UAS. With all elements in the UAS needed for operation there is potential advantages to adding IVHM to all, but each element will have different maintenance needs (i.e. the maintenance activities, tool, skills, etc. for the UA are different to those needed for the CS)., and thus different IVHM needed.

5.1.1.2 IVHM Requirements Set

The set contains the requirements of the IVHM. These are the common capability of IVHM which could be applicable to any implementation of IVHM (they are not specific to UAS). A common set of IVHM requirements created in this project has been used for both design cases:

- Performance Indicators
- Sensitivity
- Conditioning of Data
- Store Data
- Transfer Data within the Vehicle
- Transfer Data from the Vehicle
- Diagnostics Analysis
- Prognostics Analysis
- Fleet Analysis
- Response to the IVHM
- Management of Spare Parts
- Reconfigure IVHM in Service

The IVHM requirements are collated from literature and the expertise within the IVHM Centre, ensuring each requirement was sufficiently different from each other. Once the initial set of IVHM requirements (with definitions) was established they went through several iterations of refinement, with additional

input from BAE Systems: in the wording of the requirements (and definitions) and which requirements should be included in the set.

A common set is used for two main reasons. First, it allows the results of the population of the IVHM to be compared. With little use of UAS, there is little knowledge on the differences between the requirements for IVHM between missions and types of UAS. Although the stakeholders for both design cases are different (thus have different requirements and a structure for the IVHM-RD, see below) having the same set of IVHM requirements allows direct comparison in the relative rankings and order of the IVHM requirements – this comparison will be discussed in more detail in the Chapter 6 (page 136). Second, as previously mentioned there are commonalities between IVHM even when implemented on different systems. These common aspects could be present in any IVHM, but the relative benefits to that particular asset (in this case UAS) will be different. It is through the IVHM-RD process, which takes into account the requirements of the stakeholders and context of the UAS, which will allow this generic set to be ranked in order of importance to a specific design and operation.

5.1.1.3 IVHM Enablers Set

The difference between the IVHM enablers and the IVHM requirements is that enablers are not required by the IVHM but are there to help implement (i.e. enable) the IVHM. These enablers were also created in the same way as the IVHM requirements, and are used in both design cases – which allows further comparison of the results. The enablers are:

- Degradation Traceability
- Detectability of Impending Failure
- Performance Monitoring
- Standard Data Format
- Availability of Communications
- Accuracy and Precision of Captured Data
- Availability and Accuracy of Historical Maintenance Data
- Availability and Accuracy of Operational Data

- Availability and Accuracy of Failure Data
- Failure Mode Knowledge
- Maintenance Staff Availability
- Flexibility of Schedules

5.1.2 Forms Used

QFD offers a variety of different forms for different purposes. The IVHM-RD makes use of two of these forms to rank sets of requirements; these are the Pairwise Comparison (PWC) and the House of Quality (HoQ). Both forms are used to compare two requirements against each other, albeit in different manners which leads them to provide different roles within the IVHM-RD tool.

The PWC is used to compare all the requirements within a set and establish a ranked order. Working down the columns each requirement is compared to the requirement below the diagonal and assessed as to which of the two is more important. Comparisons above the diagonal are the mirror of the comparisons below and do not need to be considered. The columns are then summed to make the raw scores for the requirements, which can then be normalized into an importance rank.

	Req. 1	Req. 2	Req. 3	Req. 4
Req. 1						
Req. 2						
Req. 3						
Req. 4						
...						
...						
Raw Score						
Importance Rank						

Figure 5-2 IVHM-RD Pairwise Comparison Form

The HoQ is used to establish the relationships between two sets of requirements, using the importance rankings of the requirements set present in

the rows to influence the scores. The requirements which form the rows of the HoQ are taken from the PWC or the previous HoQ – along with the importance ranks which have been calculated for them. These are then compared with the requirements in the columns to ascertain what the relationship is between the requirements from the different sets. This is normally done using natural language (e.g. a weak, medium, strong relationship) which is then converted into a numerical value (e.g. 1,3,9), the scale and conversion used in the IVHM-RD is discussed below. The sum product of the relationship values of the column and the importance ranks of the rows is then used to calculate raw score for the column. From the raw score the raw percentage, percentage of the maximum value, and a normalised importance rank can be calculated for each column.

	Importance Rank						
		Req. A	Req. B	Req. C	Req. D
Req. 1							
Req. 2							
Req. 3							
Req. 4							
...							
...							
	Raw Score						
	Raw %						
	% of Max.						
	Importance Rank						

Figure 5-3 IVHM-RD House of Quality Form

5.1.2.1 Unused Forms

There are various other tools, with different functions, which are part of QFD which have not been used in the IVHM-RD. These forms have not been used as they are not necessary for the aim of the project. Likewise, there are various ‘rooms’ for the HoQ which have not been included, most notably the ‘roof’, the planning matrix, and targets matrix. These have not been included because

they are not important to the core objectives of the IVHM-RD. More information on the unused forms and rooms can be found in the Future Work section of the Conclusion.

5.1.3 IVHM-RD Structure & Flow

The simplest way to relate the stakeholder requirement to the IVHM requirements would be to use just a single HoQ, such as in Figure 5-4, although there would still be the need for a PWC, to compare the stakeholder requirements, and a second HoQ to relate the IVHM requirements to the IVHM enablers.

		IVHM Requirements					
		1	2	⋮	⋮	⋮	n
SH 1	1						
	2						
SH 2	...						
	...						
...	...						
	...						
...	...						
	...						
SH n	...						
	n						

Figure 5-4 One Single House of Quality

However, this is not best suited to the problem at hand. Having all the stakeholders represented one HoQ creates some problems. First, the HoQ relationship matrix can become very large. Although this will capture how all stakeholder requirements will interact with those of the IVHM (giving a very complete picture) it will take considerable time and effort to populate the form, and may stretch the attention span of the people participating in the data gathering.

Second, the PWC comparison needed to establish the initial ranking would be as large. This would take a long time to complete. Also anyone filling in the PWC would have to have knowledge of all the stakeholders and their

requirements in order to judge which one could be considered more important than another.

Third, is that not all stakeholders will see how their requirements will relate to the IVHM, such is the case with customers[10]. Fourth, the HoQ may be trying to deal with a set of stakeholders which is too diverse.

To engage the stakeholders as requirements capture participants, IVHM-RD split the tool into several HoQs where the different stakeholder groups are paired, and then chained in a logical fashion. This splitting of the HoQ into smaller HoQs make them targeted at the relevant stakeholders.

The IVHM-RD takes into consideration the needs of customer/mission and different aspects of the operation of the UAS and reflects this in the structure of the forms and how they flow into each other – ultimately linking the customer to the IVHM. Below is the general structure and flow for a commercial UA (the issue of the UA being part of the UAS is addressed later in adaptation for the persistent UAS, Section 5.2, page 107)

5.1.3.1 General Structure & Flow for a Commercial UA

The IVHM-RD is split into a single PWC of the Customer Requirements that feeds into a linked series of HoQs. Each HoQ represents different aspects of operating an asset. For the civilian UA being operated as business they are:

- Business House,
- Operations House,
- Maintenance House,
- IVHM House, and
- IVHM Enablers House.

In each house two sets of requirements are compared to each other to establish their relationships. The requirement set that form the columns of one HoQ form the rows of the next, and an importance ranking generated for that set of requirements using the relationship matrix. Figure 5-5 shows the linking of the PWC and the five HoQs and how the information flows from one HoQ to the

next. The flow from the customer requirements, through the HoQs, to the IVHM requirements and enablers allows the knowledge of captured in the forms to be presented in a way where the customer can be linked to the IVHM.

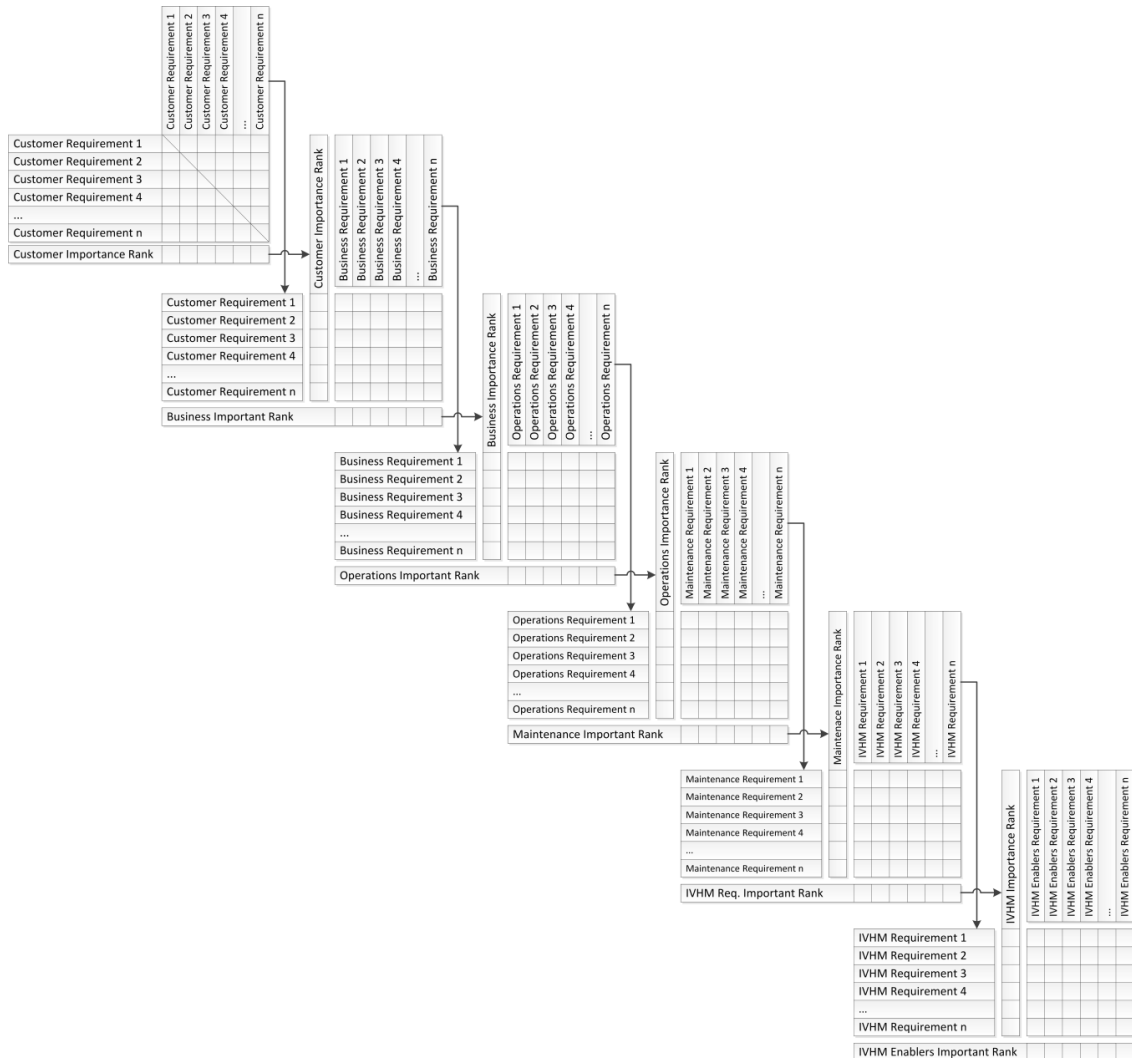


Figure 5-5 Linked HoQs of the IVHM Requirements QFD Process

5.1.3.2 Customer Requirements PWC

This is where the customer/mission requirements are compared with each other to establish the importance ranking of each individual customer requirement. Customer requirements can be based on anything the customer desires and what the mission demands of the UAS. These are often high level requirements and relate to cost, safety, functionality needed to conduct missions, ease of use etc. – all the requirements should be established with the customer of the UAS.

5.1.3.3 Business House

In this HoQ the customer requirements from the PWC are assessed against the business requirements (requirements that relate to use of the UAS as business asset) the relationships established and a numerical value established. Then new importance rankings for the business requirements are calculated and then normalised.

5.1.3.4 Operations House

In this HoQ the Business Requirements from the Business House are assessed against the Operations Requirements (requirements that relate to operation of the UAS), the relationships established and a numerical value established. Then Operations Importance Rankings are calculated from the raw scores and then normalised.

5.1.3.5 Maintenance Houses

In this HoQ the Operations Requirements from the last house are assessed against the Maintenance Requirements of the UAS (requirements that relate to the maintenance of the UAS), the relationships established and a numerical value established. Then Maintenance Importance Rankings are calculated from the raw scores and then normalised.

At this point, a different Maintenance Houses would be needed for each element of the UAS, given the different engineering nature of the elements. The design cases focus on the UA element. The UA is focussed on for the following reasons: it is the part of the UAS which flies, giving any failure more impact (e.g. loss of an expensive aircraft/sensors, public perception); it is one element common to all UAS; creation and population of the forms for the UAS will be sufficient for proof of concept; and SMEs who volunteer for the population will not appreciate filling in multiple similar forms.

5.1.3.6 IVHM Requirements House

In this HoQ the Maintenance Requirements are assessed against the IVHM Requirements (requirements that relate to the IVHM on-board the UA), the relationships established and a numerical value established. Then IVHM

Importance Rankings are calculated from the raw scores then and then normalised.

5.1.3.7 IVHM Enablers House

In this HoQ the IVHM requirements are assessed against the IVHM enablers, the relationships established and a numerical value established. Then IVHM Enablers Importance Rankings are calculated from the raw scores and then normalised.

5.2 Design Case Adaptation

5.2.1 Persistent UAS Adaptation

5.2.1.1 Requirements Sets for the Persistent UAS

The key references for establishing the costs for UAS undertaking a crop monitoring commercial enterprise was from work reported in [16; 86; 87]. From these sources the requirement headings were created for each requirement set (Costs, Business Requirements, Operations Requirements, Maintenance Requirements) within the IVHM Centre. Rigorous deliberations were carried out so that each heading are mutually independent of each other; e.g. aircraft availability was used to cover the general concept of availability rather than creating headings for inherent availability, achieved availability, and operational availability.

A summarised table (Table 5-1) containing the headings and which sets they form into, and a table containing all the requirements, organised into their sets with definitions, can be seen in the Appendix B.

Table 5-1 Persistent UAS Requirement Headings in Stakeholder Groupings

<i>Costs</i>	<i>Business Requirements</i>	<i>Operations Requirements</i>	<i>Maintenance Requirements</i>	<i>IVHM Requirements</i>	<i>IVHM Enablers</i>
Transportation of the Aircraft	Aircraft Availability	System Downtime	Availability of Spares	Performance Indicators	Degradation Traceability
Use of Facilities at Destination	Quality of Design Documentation	Platform Reliability	Fault Detection Rate	Sensitivity	Detectability of Impending Failure
Deployment of Personnel	Quality of Operational Documentation	Mission Success Rate	False Positives Rate	Conditioning of Data	Performance Monitoring
Aircrew	Quality of Maintenance Documentation	Demand of Personnel	False Negatives Rate	Store Data	Standard Data Format
Mission Planning	System Ease of Operation	Deployability	Repair Reliability	Transfer Data within the Vehicle	Availability of Communications
Fuel	Total Cost of Operation	Operational Readiness	Mean Time Between Removals	Transfer Data from the Vehicle	Accuracy and Precision of Captured Data
Consumables (excl. Fuel)	Safety		Mean Time To Replace	Diagnostics Analysis	Availability and Accuracy of Historical Maintenance Data
Depreciation of the asset	Marketing		Average Turnaround Time	Prognostics Analysis	Availability and Accuracy of Operational Data
Insurance			Mean Time To Diagnose	Fleet Analysis	Availability and Accuracy of Failure Data
Communications			Personnel Required	Response to the IVHM	Failure Mode Knowledge
Ground Equipment			Auxiliary Equipment Required	Management of Spare Parts	Maintenance Staff Availability
Maintenance Facilities				Reconfigure IVHM in Service	Flexibility of Schedules
Acquisition of Parts					
Delivery and Storage of Parts					
Maintenance Labour					

5.2.1.2 Persistent UAS IVHM-RD Structure & Flow

The UAS comprise of more than just the aircraft, and any IVHM design must take this into account. The crop monitoring UAS comprises of four main parts: the aircraft itself (UA), the control station (CS), a box for storage of the UA, and a truck to transport all the parts. All the aforementioned parts act as a SoS and are all are needed for the successful operation of the UAS. When the customer is considering the hiring the services from the crop monitoring UAS they will be looking at whole costs and benefits associated with the UAS. The customer will compare what is being offered to what is available from other companies. Other services may use different UAS, aerial photography from manned light aircraft, satellite imagery, etc., or the customer may even consider buying their own UAS. The customer is interested in the data and its analysis, not the platform or method in which it is gathered. This fact is reflected in the IVHM-RD: the Customer Requirements consider the UAS as a single entity. Again the way in which the crop monitoring UAS is operated (a pilot-UA ratio of one to one and all four parts of the UAS needed) and the business is run (one complete UAS hired out per mission) see the UAS as single entity. This results in IVHM-RD having one pair-wise comparison, one Business House, and one Operations House – all dealing with the UAS as single entity. However, when we come to consider the Maintenance Requirements of the UAS things become more complex. Each part of the UAS will have different maintenance issues, procedures, expertise, and tools. The way the IVHM-RD process accounts for the different maintenance needs of the various parts of the UAS is to split into different streams. The one Operations House (for the whole UAS) feeds into four Maintenance Houses. These four Maintenance Houses then lead into four IVHM Requirements Houses and finally into four IVHM Enablers Houses. Figure 5-6 shows the whole IVHM-RD for the crop monitoring UAS.

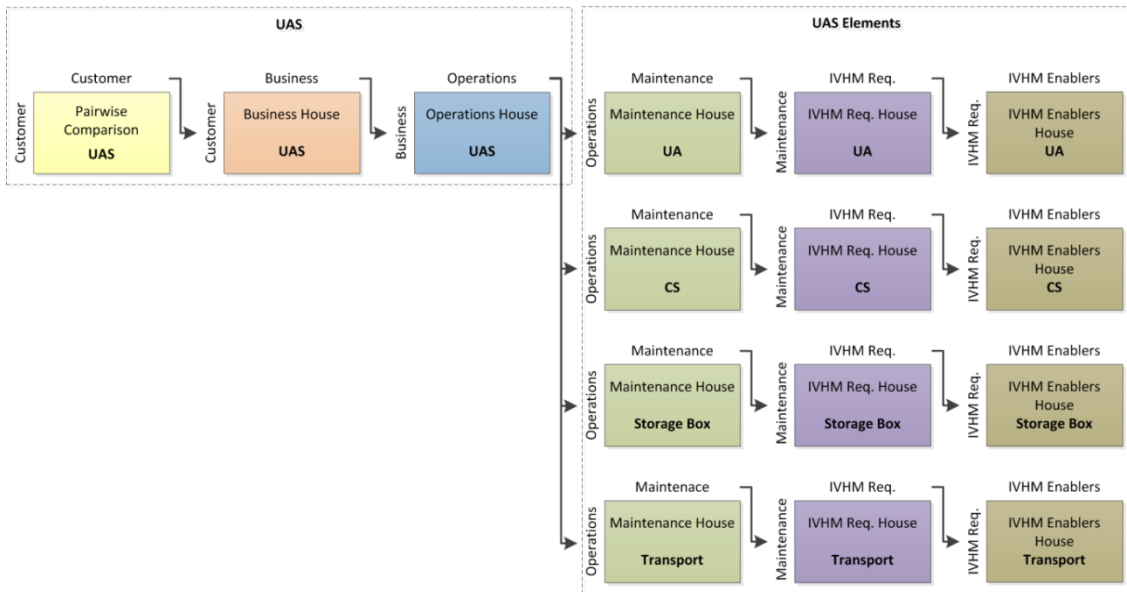


Figure 5-6 IVHM-RD for a Whole Persistent UAS

5.2.2 DEMON UAS Adaptation

5.2.2.1 Requirement Sets for the Demon UAS

The requirements for the Demon UAS come from the fact that it is a research aircraft. Essentially, the Demon UAS only gets used when there is an experiment to be performed. This resulted in there being different groupings to the Persistent UAS. The Demon has been created from the original FLAVIIR project, with its research goals, aims and objectives. As there is no current research programme for Demon to undertake and its current use as a promotional publicity tool for both Cranfield University and BAE Systems, these requirements have been grouped under the Research Programme Criteria. The second grouping is the Experiment Capability which groups together those requirements which deal with successfully using Demon to conduct an experiment. As mentioned before the IVHM requirements and enablers are the same as the persistent UAS.

Table 5-2 Demon UAS Requirement Headings in Stakeholder Groupings

<i>Research Programme Criteria</i>	<i>Experiment Capability</i>	<i>IVHM Requirements</i>	<i>IVHM Enablers</i>
Acquire	Collect Operational Data	Performance Indicators	Degradation Traceability
Operate	Collect Operating Conditions	Sensitivity	Detectability of Impending Failure
Low Maintenance Technologies	Monitor Performance	Conditioning of Data	Performance Monitoring
Non-conventional Flight Control	Capture Experimental/Test Data	Store Data	Standard Data Format
Technology Integration	UAS Ease of Operation	Transfer Data within the Vehicle	Availability of Communications
Originality	Time Between Reconfigure/Mod.	Transfer Data from the Vehicle	Accuracy and Precision of Captured Data
Academic Quality	Per-Flight/Experiment Checks	Diagnostics Analysis	Availability and Accuracy of Historical Maintenance Data
Business Quality	Unscheduled Maintenance	Prognostics Analysis	Availability and Accuracy of Operational Data
Educational Tool	Repair Time	Fleet Analysis	Availability and Accuracy of Failure Data
Publicity Tool	Availability of Spares/Parts	Response to the IVHM	Failure Mode Knowledge
	Staff Availability	Management of Spare Parts	Maintenance Staff Availability
	Tool/Equipment Availability	Reconfigure IVHM in Service	Flexibility of Schedules
	Lab/Workshop Availability		
	CAA		
	Documentation/Airworthiness		
	Design/Modification		
	Research/Publication		

Comparing Tables 5.1 and 5.2 shows how very different customer requirements could be accommodated in the IVHM-RD process and tool.

5.2.2.2 Demon UAS IVHM-RD Structure & Flow

The Demon UAS is not a commercial UAS, and has different stakeholder groupings, thus the structure and the flow of the IVHM-RD is different. The structure and flow for the Demon UAS adaptation of the IVHM-RD can be seen in Figure 5-7. It starts with a PWC for the Research Programme Criteria to establish which are most important. This then flows into the Experiment Capability House to establish how the Research Programme Criteria and the Experiment Capabilities relate to each other. The Experiment Capability House then flows into the IVHM Requirements House to establish how the IVHM relates to the Experiment Capability. Then, as before, the IVHM Requirements House flows into the IVHM Enablers House.

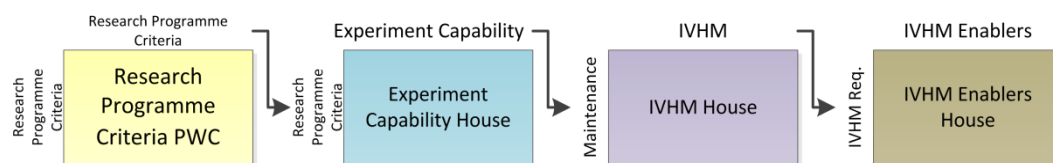


Figure 5-7 IVHM-RD for the Demon UAS

5.2.3 Other Structures & Flows

Other uses for UAS such as military, state (not the civilian commercial one presented above) will need a different structure and flow. The context of the UAS (the organisation and its structure, mission, etc.) will affect the structure and flow of the IVHM-RD for that UAS, but this will also be different from case to case (such as with the two design cases above).

6 Population of the IVHM-RD

This chapter reports on the population of the IVHM-RDs developed for the design cases and analysis of the results . As with the development of the tool, the population has two aspects: first, the generic concept of having a distributed data collation of the IVHM-RD; and second, the specific application of the concept to the design case. This chapter is split into three sections. The first section looks at the distributed population method. The second section looks at the data reliability of the design cases. The third section analysis the results of the IVHM requirements for the design cases.

The traditional method of filling in the forms of a QFD is to have a meeting where all the relevant people (the QFD team and relevant SMEs) are gathered together in a single place and time[88]. In this meeting each interaction between the relationships is discussed between those in the room until they collectively agree how each relationship should be expressed.

This meeting (or series of meetings) is held at fixed place and time can often face scheduling conflicts. Since the inception of the QFD process the nature of aerospace product development has changed. There is much more collaboration between different organisations (some of which are multi-national companies), such as the case with the international Joint Strike Fighter (F-35 Lighting II) programme and the UK's Watchkeeper (WK450) programme that is based on the Israeli Hermes 450. Gathering individuals together from various organisations from across many time zones is a serious challenge. As the IVHM-RD has be built upon QFD, it brings these problems with it. The pros and cons of the traditional method of have been summarised in Table 6-1.

Table 6-1 Pros and Cons for the Traditional QFD Population Method

<i>Pros</i>	<i>Cons</i>
Team building	Meetings are hard to organise
There is discussion on the relationships	Many meetings are needed
	Individual may not feel free to voice opposite opinions (e.g. oppose their boss)
	Meeting can be long (because of large forms or long discussions)

6.1 Distributed Population

In order to overcome the problems with traditional population method and to better suit the current situation in aerospace design a distributed population method was developed. The key difference between the two is that in the distributed population method individual SMEs fill out the relevant IVHM-RD forms individually, and they are then combined into a single master IVHM-RD, where all the linking of forms, calculation of the group opinion, and ranking of the requirements is done.

The advantages of this method of population are:

- **Participants give their opinions independently** – each participant fills in the survey on their own and as such it is an honest personal opinion. There are no inter-organisational politics which could be in the traditional population method e.g. a participant agreeing with their boss even though they hold a different opinion.
- **Participants can fill in the survey in at a time and location which is convenient to them** – as there is no need to gather every one at a place at the same time and discuss each relationship between requirements.
- **Participants' responses can be collected anonymously** – allowing an individual to know their opinion cannot be traced back to them, which

reinforces that they can give their individual opinion freely. However, the choice of whether or not to collect responses anonymously has consequences e.g. you will not know whether or not the same person has completed the IVHM-RD more than once, managers cannot chase individual people to complete the IVHM-RD.

- **A larger amount of participants is possible** – with the traditional population method the more people involved in the population meeting the harder and more time consuming it is to achieve consensus, and there are many relationships.
- **Forms can easily be extended or re-issued** – if there are insufficient responses action can be taken: the response period for the forms can be extended to more participants in a group; or the forms can be re-issued to the same or a new group of participants.

However there are some downsides to this method of population:

- **Relationships may be left blank or have few responses** –allowing the participants to leave relationships blank could lead to a relationship being poorly defined (few responses) or not be defined (no responses) within the HoQ. This could be because the targeted participants have no experience in the specific area. Re-issuing the forms to people with experience can mitigate this, or it could indicate that there is no understanding of that relationship and that further research into its nature is needed.
- **Surveys may be forgotten about or ignored** – as there is no fixed time and date for a meeting, rather there is a response period for the survey, participants (due to workload, etc.) may not complete the survey as soon as they receive it but opt to complete it later, but subsequently forget about it. If an anonymous collection method is used it is not possible to target individuals, but it is possible to remind the group to complete the survey within the specified time period.

- **Post survey combination of the results is needed** – time is needed after the survey to combine the results before they can be used in the forms and equations.
- **Reliability of the results could be questioned** – as the results are collected from individuals and not from a group discussing the relationships then it is possible for there to be disagreement between SMEs, which will bring into question relationship defined within the IVHM-RD.

6.1.1 IVHM-RD Calculations

The PWC uses a simple binary scale where the SME was asked if the requirement under consideration was more (1) or less (-1) important. For the HoQ, the scale to describe the relationship between two requirements from different sets was: no relationship (0), a weak relationship (1), a moderate relationship (3), or a strong relationship (9). Additionally, if the SME participating had no opinion on a relationship they could leave a blank space in both the PWC and HoQ.

Metrics are used to assess the consensus of SMEs and the reliability of the population. As there is no face-to-face discussion between the SMEs, a different way was developed to assess how well the group agrees on the values captured within the combined results⁴. Additionally it is important to know how many of the SMEs have contributed to the combined results in each cell. A single metric on agreement could indicate that there is total agreement in the group, but this does not represent the whole picture concerning the reliability of the result. If that is based on the opinion of one person (i.e. only one SME chose to comment on that relationship), then it is not truly representative of the group. Metrics on the number of participants is needed. Due to the different forms used, and different scales used within them, both PWC and HoQs need

⁴ It is worth noting that even though these discussions may take place within a QFD meeting that they are not recorded formally in the QFD forms, though may be noted if there was a strong disagreement[88].

slightly different metrics to accurately represent the relationship and its reliability.

An IVHM designer can use the metrics to decide if they trust the results or not, and take action. They may wish to: seek more responses, when the responses are low; have discussions with the relevant SMEs (or stakeholders) when opinion is split; conduct more investigations (e.g. literature searches, experiments, simulations) into relationships when opinion is split. It will depend on the individual design case and resources available.

6.1.1.1 Pair-Wise Comparison Metrics

Table 6-2 provides a summary of the different metrics for each cell of the PWC.

Table 6-2 Pair-Wise Comparison Cell Numbers

<i>PWC Cell Numbers</i>	<i>Name</i>	<i>Meaning</i>	<i>Range</i>
1.00	Comparison Value	Scaled average of the individual contributions of SME on whether the column requirement is less or more important than the row requirement.	-1.00 to 1.00
(0)	Dissenters	The number of SMEs which disagreed with the majority.	0+ or =
[5]	Cell Participants	The number of SMEs who participated in the population of the cell	0+
{100%}	Participant Percentage	The percentage of SMEs who participated in the cell relative to the maximum possible per the PWC	0% to 100%

The comparison value describes the combined opinion of the group of the SMEs, based on their individual answers to the PWC – whether a particular requirement was more (1) or less (-1) important to another. The individual responses are combined in an arithmetic mean and then are scaled to be between minus one and one.

The dissenters is what is used to judge the disagreement in the group of SMEs. It counts the number of people who disagree with majority of the group. In the case of an even number for SMEs populating a cell, equally split on whether

one requirement is more or less important than another then an equals sign (=) can be used to represent the split down the middle.

Both the cell participants and the participant percentage are used to assess how representative the combined responses are. The cell participants number counts the number of people who have participated in the population of that cell. The participant percentage is the percentage of the people who participated in the population of that cell compared to the maximum possible for that HoQ (i.e. the total number of SME who participated in that HoQ) as a percentage.

6.1.1.2 House of Quality Metrics

Table 6-3 provides a summary of the different metrics for each cell for a HoQ.

Table 6-3 House of Quality of Cell Numbers

<i>HoQ Cell Numbers</i>	<i>Name</i>	<i>Meaning</i>	<i>Range</i>
9.00	Relationship Value	The average of the individual contributions of SMEs on the relationship between the two requirements.	0.00 to 9.00
(0.00)	Standard Deviation	Standard deviation for a sample of a population, a measure of agreement between the SMEs. With a standard deviation of zero meaning: total agreement, and the higher standard deviation the more disagreement between the SMEs.	0.00+
[5]	Cell Participants	The number of SMEs who participated in the population of the cell.	0+
{100%}	Participant Percentage	The percentage of SMEs who participated in the cell relative to the maximum possible per the HoQ.	0% to 100%

The relationship value describes the combined opinion of the group of SMEs, based on their individual answers to the HoQs – whether there was no relationship (0), a weak relationship (1), a moderate relationship (3), or a strong relationship (9) between two requirements from different sets. The individual responses are combined in an arithmetic mean to form the group opinion.

The standard deviation of the relationship value is used to judge the amount of agreement within the group of SMEs. When the standard deviation is zero it

shows that there was total agreement between all the SMEs who participated in the population of that cell. If the standard deviation is above zero then this denotes that there is disagreement between the SMEs and the higher the standard deviation is then the more disagreement there is within the group. It is important to only use standard deviation as an indicator of agreement, and not to measure the exact disagreement (as is done with the dissenters in the PWC) and assign error bars to the values. It can only show with certainty when there is total agreement, and indicate the amount of disagreement.

Therefore, the threshold for when the standard deviation is too high will be considered case by case, HoQ by HoQ assessment, dependent on how much uncertainty the organisation is willing to accept, how many SMEs participated in defining that relationship, how many participants there are for that HoQ and the IVHM-RD as whole, and the standard deviation in relation to all the other standard deviations in that HoQ (or even the whole IVHM-RD). The decision of what is an unreliable result is subjective and best left to the person (team, organisation, etc.) analysing the IVHM-RD results.

The cell participants and the participant percentage fulfil the same function in the HoQ as they do in the PWC.

6.2 Population of the Design Case IVHM-RDs

6.2.1 Persistent UAS IVHM-RD Population

As the Persistent UAS was used for the IVHM-RD as an exemplar design case, there was no inherent pool of participants for the IVHM-RD (i.e. no design team within an organisation) and voluntary responses from SMEs were sought.

A web-based survey was created using the Qualtrics Research Suite to capture the information from the SMEs representing the stakeholders of the IVHM on the UAS, to populate the IVHM-RD. Ethical approval was sought and gained from the Science and Engineering Research Ethics Committee of Cranfield University before the survey was released.

Survey links were sent out to representatives within seven organisations with experience in UAS and IVHM (who will remain anonymous). The representatives were asked to then distribute to relevant SMEs within their organisations. The survey took the following format:

- **A welcome page** – informing the participant on the task, some background on the UAS, that their responses are anonymous and stored securely, and that they can withdraw from the survey at any time.
- **A screening question** – to direct the participant to the relevant questions representing the PWC and HoQs depending on the areas of experience they have chosen, the areas of expertise are:
 - Costs – directing the participant Business House and the PWC;
 - Business – directing the participant to the Business House and Operations House;
 - Operations – directing the participant to the Operations House and Maintenance House;
 - Maintenance – directing the participant to the Maintenance House and the IVHM Requirements House;
 - IVHM – directing the participant to the IVHM Requirements House and the IVHM Enablers House.

Choosing each area of expertise directed the participant to two parts of the survey e.g. choosing 'maintenance' directed the participant to the Maintenance House and the IVHM Requirements House as the maintenance requirements set is used in both HoQs, but if choosing 'maintenance' and 'IVHM' they were only directed to the IVHM Requirements House once. Figure 6-1 shows the complete flow of the survey if all options in the screening question are chosen.

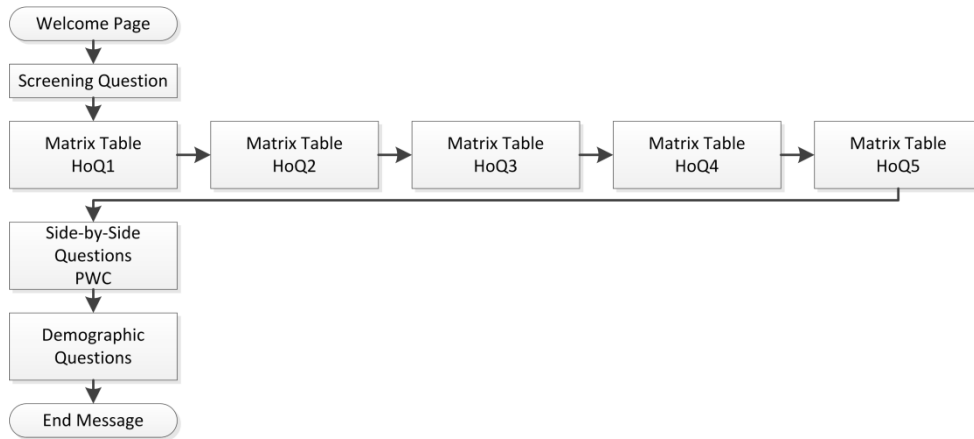


Figure 6-1 Overview of Complete Survey Flow

- Matrix table questions representing the HoQs** – the participants were presented with a two requirements sets in a matrix and asked to fill in each cell with one of the following: Leaving the cell blank = does not wish to comment on the relationship; 0 = No relationship; 1 = A weak relationship; 2 = A moderate relationship; 3 = A strong relationship. The definitions of the relevant requirements sets for the HoQ were also presented below the matrix.

You are presented with a table comparing two sets of requirements. Answer according to the strength of the relationship between each pair of requirements (the nature of the relationship could be one way, two way, positive or negative). You can leave some boxes blank if you wish. The numbers are:

0 - No Relationship
 1 - A Weak Relationship
 2 - A Moderate Relationship
 3 - A Strong Relationship

You can find the definitions of the terms used at the bottom of the page.

	System Downtime	Platform Reliability	Mission Success Rate	Demand of Personnel	Deployability	Operational Readiness
Availability	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Depth of Maintenance Documentation	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
System Ease of Operation	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Total Cost of Operation	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Safety	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Marketing	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Sustain Innovation Leadership	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Compliance with Legislation	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
	System Downtime	Platform Reliability	Mission Success Rate	Demand of Personnel	Deployability	Operational Readiness

Definitions
Business
 Aircraft Availability: Ratio of up time to total time (up time plus down time)
 Quality of Design Documentation: Quality of the documentation produced during the design process

Figure 6-2 Example House of Quality Matrix Table Question

- **Side-by-side table questions representing the PWC** – The participants were asked to choose where a cost to that in a list and choose whether they consider it to be higher or lower.

	Is the cost of Repositioning the Aircraft (D) higher or lower than the following:	
	Lower	Higher
Use of Facilities at Destination (D)	<input type="radio"/>	<input type="radio"/>
Deployment of Personnel (D)	<input type="radio"/>	<input type="radio"/>
Aircrew (O)	<input type="radio"/>	<input type="radio"/>
Mission Planning (O)	<input type="radio"/>	<input type="radio"/>
Fuel (O)	<input type="radio"/>	<input type="radio"/>
Consumables (excl. Fuel) (O)	<input type="radio"/>	<input type="radio"/>
Depreciation of the asset (O)	<input type="radio"/>	<input type="radio"/>
Insurance (O)	<input type="radio"/>	<input type="radio"/>
Communications (O)	<input type="radio"/>	<input type="radio"/>
Ground Equipment (O)	<input type="radio"/>	<input type="radio"/>
Main Base Maintenance Facilities (M)	<input type="radio"/>	<input type="radio"/>
Acquisition of Parts (M)	<input type="radio"/>	<input type="radio"/>
Delivery and Storage of Parts (M)	<input type="radio"/>	<input type="radio"/>
Maintenance Labour (M)	<input type="radio"/>	<input type="radio"/>

Figure 6-3 Example Pair-Wise Comparison Side-by-Side Table Question

- **Several demographic questions** – optional questions to collect information which can be used to judge the validity of the results.
- **A message telling the participant that they have reached the end of the survey and their responses have been recorded.**

6.2.2 Demon UAS IVHM-RD Population

The Demon UAS was build, and is still, at Cranfield University, which provides a pool of SMEs with interest and knowledge that would be suited to populating the IVHM-RD. Instead of using a web-based survey as with the Persistent UAS, spreadsheet forms were sent out to SMEs within the university with knowledge of both the Demon UAS and IVHM.

6.3 Analysis of Populated IVHM-RDs

The populated forms can be analysed in several ways, depending on what the person (or organisation) looking at the data contained within the IVHM-RD is trying to find out – transforming the data into information useful to them. The Data-Information-Knowledge-Wisdom (DIKW) hierarchy (Figure 6-4) is often used to contextualise data, information, knowledge, and wisdom with respect to one another[89].

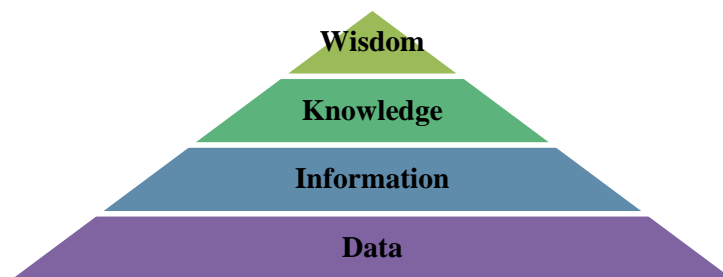


Figure 6-4 The DIKW Hierarchy.

The data contained within the populated IVHM-RD is analysed at in three ways. First, the ranked sets of requirements and enablers are assessed for both design cases individually. Second, the ranked sets of IVHM requirements and enablers are compared to assess the similarities and differences between the design cases. Third, the relationships between IVHM requirement and enablers are assessed to establish the current understanding of them.

6.3.1 Raw Forms

The raw forms hold a considerable amount of data within them, which is hard to take in without being sorted and presented in way which is helpful to those who wish to use it (specifically for this thesis in the ways described above). Below is the raw populated PWC (Figure 6-5) and the IVHM Enablers House (Figure 6-6) for the Persistent UAS, using the metrics from Section 6.1.1. The rest of the forms for both design cases will be contained within Appendix C.

	Costs														
	Deployment Costs			Operation Costs								Maintenance Costs			
	Transportation of the Aircraft	Use of Facilities at Destination	Deployment of Personnel	Aircrew	Mission Planning	Fuel	Consumables (excl. Fuel)	Depreciation of the asset	Insurance	Communications	Ground Equipment	Maintenance Facilities	Acquisition of Parts	Delivery and Storage of Parts	Maintenance Labour
Transportation of the Aircraft		0.20	0.60	0.60	-0.20	1.00	-0.20	0.60	0.60	-0.20	0.60	0.60	0.60	0.60	0.60
Use of Facilities at Destination	-0.20 (2) [5] [100%]		0.20	1.00	-0.20	1.00	0.60	1.00	0.60	-0.20	0.60	1.00	0.60	0.50	1.00
Deployment of Personnel	-0.60 (1) [5] [100%]	-0.20 (2) [5] [100%]		1.00	-0.60	1.00	0.60	1.00	0.50	-0.20	0.50	0.60	0.60	0.60	0.50
Aircrew	-0.60 (1) [5] [100%]	-1.00 (0) [5] [100%]	-1.00 (0) [4] [80%]		-1.00	1.00	0.20	0.60	0.20	-0.60	-1.00	0.60	-0.20	-0.60	-0.60
Mission Planning	0.20 (2) [5] [100%]	0.20 (2) [5] [100%]	0.60 (1) [5] [100%]	1.00 (0) [5] [100%]		1.00	1.00	0.60	0.60	0.20	1.00	0.60	0.20	0.60	0.60
Fuel	-1.00 (0) [5] [100%]	-1.00 (0) [5] [100%]	-1.00 (0) [5] [100%]	-1.00 (0) [5] [100%]	-1.00 (0) [5] [100%]			-1.00	-1.00	-1.00	-1.00	-0.60	-1.00	-1.00	-0.60
Consumables (excl. Fuel)	0.20 (2) [5] [100%]	-0.60 (1) [5] [100%]	-0.60 (1) [5] [100%]	-0.20 (2) [5] [100%]	-1.00 (0) [5] [100%]	1.00 (0) [5] [100%]			0.60	0.20	-0.60	0.60	0.60	0.60	0.60
Depreciation of the asset	-0.60 (1) [5] [100%]	-1.00 (0) [5] [100%]	-1.00 (0) [5] [100%]	-0.60 (1) [5] [100%]	-0.60 (1) [5] [100%]	1.00 (0) [5] [100%]	-0.60 (1) [5] [100%]		0.00	-0.50	-0.50	0.60	-0.20	-0.60	-1.00
Insurance	-0.60 (1) [5] [100%]	-0.60 (1) [5] [100%]	-0.50 (1) [4] [80%]	-0.20 (1) [5] [100%]	-0.60 (1) [5] [100%]	1.00 (0) [5] [100%]	-0.20 (2) [5] [100%]	0.00 (-) [4] [80%]		1.00	0.50	1.00	-0.50	-0.20	0.60
Communications	0.20 (2) [5] [100%]	0.20 (2) [5] [100%]	0.20 (2) [5] [100%]	0.60 (1) [5] [100%]	-0.20 (2) [5] [100%]	1.00 (0) [5] [100%]	0.60 (1) [5] [100%]	0.50 (1) [4] [80%]	-1.00 (0) [5] [100%]		0.60	0.60	0.60	1.00	0.60
Ground Equipment	-0.60 (1) [5] [100%]	-0.60 (1) [5] [100%]	-0.50 (1) [4] [80%]	1.00 (0) [5] [100%]	-1.00 (0) [5] [100%]	1.00 (0) [5] [100%]	-0.60 (1) [5] [100%]	0.50 (1) [4] [80%]	-0.60 (1) [5] [100%]			1.00	-0.50	-0.20	0.20
Maintenance Facilities	-1.00 (0) [4] [80%]	-1.00 (0) [4] [80%]	-0.60 (1) [5] [100%]	-0.60 (1) [5] [100%]	-0.60 (1) [5] [100%]	0.60 (1) [5] [100%]	-0.60 (1) [5] [100%]	-0.60 (1) [5] [100%]	-1.00 (0) [5] [100%]	-0.60 (1) [5] [100%]	-1.00 (0) [5] [100%]		-0.20	-0.60	-0.60
Acquisition of Parts	-0.60 (1) [5] [100%]	-0.60 (1) [5] [100%]	-0.60 (1) [5] [100%]	0.20 (2) [5] [100%]	-0.20 (2) [5] [100%]	1.00 (0) [5] [100%]	-0.60 (1) [5] [100%]	0.20 (2) [5] [100%]	0.50 (1) [4] [80%]	-0.60 (1) [5] [100%]	0.50 (1) [4] [80%]	0.20 (2) [5] [100%]		-0.60	-0.20
Delivery and Storage of Parts	-0.60 (1) [5] [100%]	-0.50 (1) [4] [80%]	-0.60 (1) [5] [100%]	0.60 (1) [5] [100%]	-0.60 (1) [5] [100%]	1.00 (0) [5] [100%]	0.60 (1) [5] [100%]	0.60 (1) [5] [100%]	0.20 (2) [5] [100%]	-1.00 (0) [5] [100%]	0.20 (2) [5] [100%]	0.60 (1) [5] [100%]	0.60 (1) [5] [100%]		0.20
Maintenance Labour	-0.60 (1) [5] [100%]	-1.00 (0) [4] [80%]	-0.50 (1) [4] [80%]	0.60 (1) [5] [100%]	-0.60 (1) [5] [100%]	0.60 (1) [5] [100%]	-0.60 (1) [5] [100%]	1.00 (0) [5] [100%]	-0.60 (1) [5] [100%]	-0.60 (1) [5] [100%]	-0.20 (2) [5] [100%]	0.60 (1) [5] [100%]	0.20 (2) [5] [100%]	-0.20 (2) [5] [100%]	
Raw Score	-6.40	-7.50	-5.30	4.00	-8.40	13.20	-0.80	5.60	-0.70	-5.50	1.40	8.40	1.40	-1.30	1.90
Importance Rank	1	1	1	3	1	5	2	4	2	1	3	4	3	2	3

Figure 6-5 Raw Populated Persistent UAS Pairwise Comparison

	Importance Rank	IVHM Enablers													
		Sense			Acquire	Transfer	Analysis					Act			
		Degradation Traceability	Detectability of Impending Failure	Performance Monitoring	Standard Data Format	Availability of Communications	Accuracy & Precision of Captured Data	Availability & Accuracy of Historical Maintenance Data	Availability & Accuracy of Operational Data	Availability & Accuracy of Failure Data	Failure Mode Knowledge	Maintenance Staff Availability	Flexibility in Schedules		
IVHM Requirements	Sense	Performance Indicators	5	6.00 (3.29) [6] [86%]	8.00 (2.45) [6] [86%]	9.00 (0.00) [7] [100%]	2.20 (1.10) [5] [71%]	3.80 (3.03) [5] [71%]	9.00 (0.00) [5] [71%]	5.60 (4.67) [5] [71%]	5.17 (4.31) [6] [86%]	6.20 (3.90) [5] [71%]	6.60 (3.29) [5] [71%]	3.60 (4.93) [5] [71%]	2.60 (3.78) [5] [71%]
		Sensitivity	3	6.00 (4.24) [5] [71%]	6.00 (4.24) [5] [71%]	5.50 (3.99) [6] [86%]	4.75 (4.92) [4] [57%]	4.40 (4.34) [6] [86%]	6.50 (3.99) [6] [86%]	4.80 (4.02) [5] [71%]	4.80 (4.02) [5] [71%]	4.80 (4.02) [5] [71%]	4.80 (4.02) [5] [71%]	1.25 (1.26) [4] [57%]	1.25 (1.26) [4] [57%]
	Acquire	Conditioning of Data	1	3.25 (4.03) [4] [57%]	3.25 (4.03) [4] [57%]	3.75 (3.77) [4] [57%]	4.20 (4.55) [5] [71%]	4.50 (5.20) [4] [57%]	5.50 (3.99) [6] [86%]	5.25 (4.50) [4] [57%]	5.25 (4.50) [4] [57%]	4.50 (5.20) [4] [57%]	3.00 (4.24) [4] [57%]	0.50 (0.58) [4] [57%]	0.50 (0.58) [4] [57%]
		Store Data	1	3.00 (4.24) [4] [57%]	3.00 (4.24) [4] [57%]	4.80 (4.02) [5] [71%]	5.60 (4.67) [5] [71%]	3.75 (3.77) [4] [57%]	3.00 (3.67) [5] [71%]	3.60 (3.29) [5] [71%]	3.60 (3.29) [5] [71%]	3.00 (3.67) [5] [71%]	1.50 (1.73) [4] [57%]	0.50 (0.58) [4] [57%]	0.50 (0.58) [4] [57%]
	Transfer	Transfer Data within the Vehicle	1	2.60 (3.78) [5] [71%]	3.67 (4.27) [6] [86%]	3.17 (3.13) [6] [86%]	4.50 (3.67) [6] [86%]	6.50 (3.99) [6] [86%]	3.83 (4.12) [6] [86%]	2.60 (3.78) [5] [71%]	3.83 (4.12) [6] [86%]	3.80 (4.76) [5] [71%]	2.67 (3.39) [6] [86%]	0.50 (0.58) [4] [57%]	0.50 (0.58) [4] [57%]
		Transfer Data from the Vehicle	3	3.60 (3.29) [5] [71%]	4.17 (3.92) [6] [86%]	3.50 (2.95) [6] [86%]	4.50 (3.67) [6] [86%]	7.71 (3.40) [7] [100%]	3.83 (4.12) [6] [86%]	3.80 (4.76) [5] [71%]	5.17 (4.31) [6] [86%]	3.80 (4.76) [5] [71%]	2.67 (3.39) [6] [86%]	3.25 (4.03) [4] [57%]	4.75 (4.92) [4] [57%]
	Analysis	Diagnostics Analysis	5	7.80 (2.68) [5] [71%]	9.00 (0.00) [4] [57%]	4.40 (4.34) [5] [71%]	4.40 (4.34) [5] [71%]	6.00 (4.24) [5] [71%]	9.00 (0.00) [5] [71%]	7.00 (4.00) [4] [57%]	6.60 (3.29) [5] [71%]	6.60 (3.29) [5] [71%]	8.00 (2.45) [6] [86%]	3.25 (4.03) [4] [57%]	2.50 (4.36) [4] [57%]
		Prognostics Analysis	4	7.00 (3.10) [6] [86%]	8.00 (2.45) [6] [86%]	3.20 (3.49) [5] [71%]	5.25 (4.50) [4] [57%]	6.00 (4.24) [5] [71%]	8.00 (2.45) [6] [86%]	7.00 (3.10) [6] [86%]	6.00 (3.29) [6] [86%]	7.00 (3.10) [6] [86%]	7.00 (3.10) [6] [86%]	3.20 (3.49) [6] [86%]	3.80 (4.76) [5] [71%]
	Act	Fleet Analysis	5	7.50 (3.00) [4] [57%]	9.00 (0.00) [4] [57%]	5.25 (4.50) [4] [57%]	4.80 (4.02) [5] [71%]	4.00 (4.58) [5] [71%]	8.00 (2.45) [6] [86%]	8.00 (2.45) [6] [86%]	8.00 (2.45) [6] [86%]	7.80 (2.68) [5] [71%]	7.80 (2.68) [5] [71%]	3.80 (3.03) [5] [71%]	3.25 (4.03) [4] [57%]
		Response to the IVHM	4	9.00 (0.00) [4] [57%]	9.00 (0.00) [5] [71%]	3.20 (3.49) [5] [71%]	2.80 (3.63) [5] [71%]	6.00 (4.24) [5] [71%]	7.80 (2.68) [5] [71%]	7.50 (3.00) [4] [57%]	7.00 (4.00) [4] [57%]	7.50 (3.00) [4] [57%]	7.50 (3.00) [4] [57%]	3.60 (3.29) [5] [71%]	1.40 (1.52) [5] [71%]
Management of Spare Parts	3	4.00 (3.46) [4] [57%]	2.67 (0.82) [6] [86%]	3.50 (3.79) [4] [57%]	1.25 (1.26) [4] [57%]	3.25 (4.03) [4] [57%]	6.00 (3.46) [4] [57%]	6.20 (3.90) [5] [71%]	5.50 (4.12) [4] [57%]	5.80 (4.38) [5] [71%]	4.60 (4.10) [5] [71%]	3.40 (3.29) [5] [71%]	3.25 (4.03) [4] [57%]		
Reconfigure IVHM in Service	2	5.50 (4.12) [4] [57%]	6.20 (3.90) [5] [71%]	7.40 (3.58) [5] [71%]	4.40 (4.34) [5] [71%]	5.25 (4.50) [4] [57%]	5.50 (4.12) [4] [57%]	5.00 (4.62) [4] [57%]	4.60 (4.10) [4] [57%]	5.00 (4.62) [4] [57%]	5.00 (3.74) [5] [71%]	4.00 (3.46) [4] [57%]	3.75 (3.77) [4] [57%]		
Raw Score		231.15	258.82	182.87	143.80	188.34	265.53	226.85	219.12	225.50	223.37	113.65	99.30		
Raw Percentage		9.72%	10.88%	7.69%	6.05%	7.92%	11.16%	9.54%	9.21%	9.48%	9.39%	4.78%	4.18%		
Percentage of Maximum		87.05%	97.47%	68.87%	54.16%	70.93%	100.00%	85.43%	82.52%	84.92%	84.12%	42.80%	37.40%		
Importance Rank		4	5	3	2	3	5	4	4	4	4	1	1		

Figure 6-6 Raw Populated Persistent UAS IVHM Enablers House

6.3.2 Persistent UAS Ranked Requirements Sets

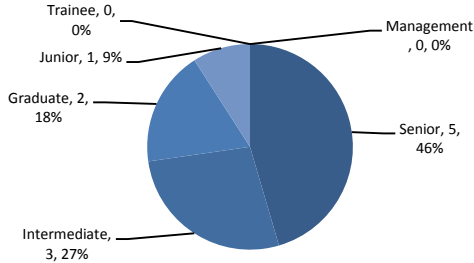
This section covers the analysis of the ranked sets of requirements for the populated IVHM-RD of the Persistent UAS.

6.3.2.1 Demographics

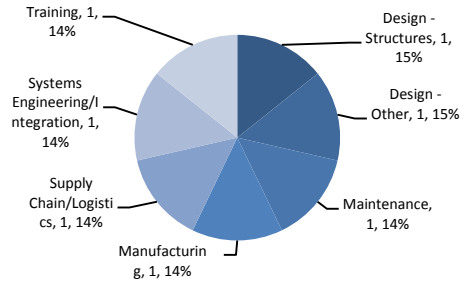
Optional demographic questions were presented to the participants towards the end of the survey; the results of which can be seen in Figure 6-7. As the participants of the survey were anonymous a series of demographic questions was needed to be able to judge whether or not the participants could be considered to be SMEs.

Eleven participants chose to answer the questions (although less chose to answer questions on previous positions). The participants are all highly educated with all having achieved a bachelor's degree or higher. The majority of participants identified they were at a Senior level within their organisation (46%), 27% identified as Intermediate level, 18% as Graduate level, and none as either Junior or Management. The current and previous positions show that there is a wide experience base between all the participants; but it is important to note the areas which areas are not represented: Finance/Accounting, Management/Business, Marketing/Sales, and Operations. 9% of the participants were women, higher than the percentage of the UK Engineering Professionals identifying as female at 5.5% [90].

a. Please indicate your current level within your organisation.

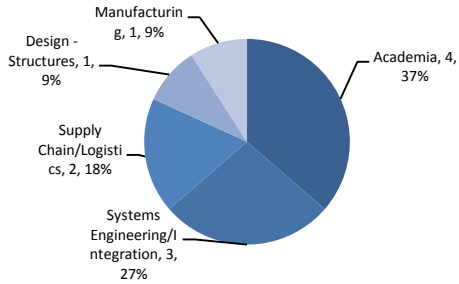


d. Which of the following is the second most recent former area you have worked in?



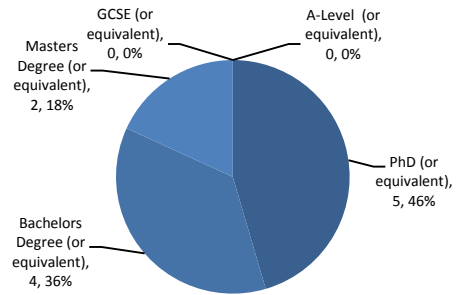
Academia, 0, 0%; Design – Avionics, 0, 0%; Design – Propulsion, 0, 0%; Finance/Accounting, 0, 0%; Management/Business, 0, 0%; Marketing/Sales, 0, 0%; Operations, 0, 0%.

b. Which one of the following areas best describes your current position?

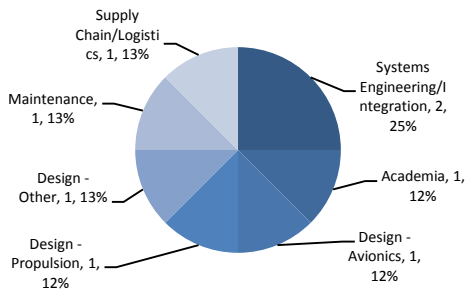


Design – Avionics, 0, 0%; Design – Propulsion, 0, 0%; Design – Other, 0, 0%; Finance/Accounting, 0, 0%; Maintenance, 0, 0%; Management/Business, 0, 0%; Marketing/Sales, 0, 0%; Operations, 0, 0%; Training, 0, 0%.

e. Please indicate your level of education.



c. Which of the following is the most recent former area you have worked in?



Design – Structures, 0, 0%; Finance/Accounting, 0, 0%; Management/Business, 0, 0%; Manufacturing, 0, 0%; Marketing/Sales, 0, 0%; Operations, 0, 0%; Training, 0, 0%.

f. What is your gender?

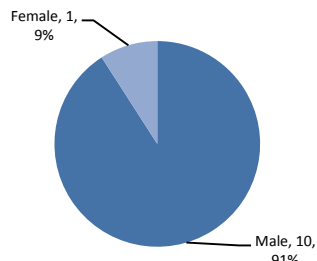


Figure 6-7 Responses to Demographic Questions

6.3.2.2 Cost Pair-Wise Comparison

First the results of the comparison of the costs associated with operating the persistent UAS are analysed, which are compared to one another in the Cost PWC (Table 6-4). The Cost of Fuel has almost unanimously been identified as the only cost with very high importance – echoing research in the costs of operating manned aircraft [91]. Maintenance Facilities has been identified as the second most important cost, although it has slipped down into the High Importance bracket along with the Depreciation of the Asset. Moderately Important costs relating to the IVHM are Maintenance Labour and the Acquisition of Parts both with an equal raw score.

Table 6-4 Summary of Costs Pairwise Comparison Results

	<i>Raw</i>	<i>Rank</i>	<i>Importance</i>
Fuel	13.2	5	Very High
Maintenance Facilities	8.2	4	High
Depreciation of the Asset	5.4	4	
Aircrew	3.8	3	Moderate
Maintenance Labour	1.6	3	
Acquisition of Parts	1.6	3	
Ground Equipment	1.2	3	
Consumables (excl. Fuel)	-0.8	2	Low
Insurance	-0.8	2	
Delivery and Storage of Parts	-1.3	2	
Deployment of Personnel	-5.3	1	Very Low
Communications	-5.5	1	
Transportation of the Aircraft	-6.4	1	
Use of Facilities at Destination	-7.5	1	
Mission Planning	-8.4	1	

6.3.2.3 Business House

Second the results of comparing the cost to the business requirements in the Business House are analysed (Table 6-5). Unsurprisingly with the PWC dealing with costs the Total Cost of Operation has been identified as the only requirement with very high importance and all other requirements with low or

very low importance – indicating that the business requirement have little relationship to the actual costs of operating the UAS as a business assets.

Table 6-5 Summary of Business House Results

	<i>Raw</i>	<i>% Raw</i>	<i>% Max</i>	<i>Rank</i>	<i>Importance</i>
Total Cost of Operation	231.38	39.90%	100.00%	5	Very High
UAS Availability	87.32	15.06%	37.74%	2	Low
System Ease of Operation	63.98	11.03%	27.65%	2	
Legislation	59.17	10.20%	25.57%	2	
Maintenance Documentation	41.55	7.16%	17.96%	1	Very Low
Safety	38.40	6.62%	16.60%	1	
Marketing	37.10	6.40%	16.03%	1	
Innovation Leadership	21.02	3.63%	9.09%	1	

6.3.2.4 Operations House

Third the results of comparing the business requirements to the operations requirements in the Operations House are analysed (Table 6-6). Both the platform reliability and operational readiness have been identified as having very high importance with little difference between them. There are no requirements of high importance and system downtime being the only requirement with moderate importance, which may indicate that system downtime, is only a concern when it starts to affect the operational readiness. It is also interesting to note that mission success has been identified as having low importance.

Table 6-6 Summary of Operations House Results

	<i>Raw</i>	<i>% Raw</i>	<i>% Max</i>	<i>Rank</i>	<i>Importance</i>
Platform Reliability	70.02	20.39%	100.00%	5	Very High
Op. Readiness	69.97	20.37%	99.92%	5	
System Downtime	59.35	17.28%	84.76%	3	Moderate
Demand of Personnel	49.83	14.51%	71.17%	2	Low
Mission Success	49.03	14.28%	70.02%	2	
Deployability	45.22	13.17%	64.58%	1	Very Low

6.3.2.5 Maintenance House

Fourth the results of comparing the operations requirements to the maintenance requirements in the Maintenance House are analysed (Table 6-7). The reliability of repairs has been identified as the only requirement with very high importance which is understandable, as conducting reliable repairs is a key maintenance activity. The next three requirements: mean time to diagnose (high importance), false negatives rate, and fault detection rate (both moderate importance) indicates that the relationships surrounding requirements relating to diagnosing faults are key for maintenance – all of which can be improved with the introduction of IVHM to a UAS and its operations. The maintenance house also ranks the false positive rate as very low importance, but with the use of diagnostic prognostics tools within IVHM in future UAS designs this may rise in importance - due to the consequences of misdiagnosing a fault in an operational system.

Table 6-7 Summary of Maintenance House Results

	<i>Raw</i>	<i>% Raw</i>	<i>% Max</i>	<i>Rank</i>	<i>Importance</i>
Reliability of Repairs	114.81	12.89%	100.00%	5	Very High
Mean Time To Diagnose	102.88	11.55%	89.62%	4	High
False Negatives Rate	92.86	10.42%	80.88%	3	Moderate
Fault Detection Rate	91.03	10.22%	79.29%	3	
Personnel Required	88.54	9.94%	77.12%	3	
Mean Time To Replace	86.90	9.75%	75.69%	2	Low
Average Turnaround Time	84.76	9.51%	73.83%	2	
Auxiliary Equipment Required	79.69	8.94%	69.41%	2	
Availability of Spares	78.67	8.83%	68.53%	2	
False Positives Rate	70.85	7.95%	61.71%	1	Very Low

6.3.2.6 IVHM Requirements House

Fifth the results of comparing the maintenance requirements to the IVHM requirements in the IVHM Requirements House are analysed (Table 6-8). Echoing the Maintenance House the importance of diagnostic related requirements has been shown, with both performance indicators and diagnostics analysis both identified as being of very high importance. Fleet

analysis was also identified of being of very high importance – emphasising the importance of seeing (and implementing) IVHM as fleet wide activity, likewise the response to IVHM has been identified as of high importance reinforcing the need to consider IVHM as a fleet wide activity (not just for in individual UAS) and to react to the information provided by the IVHM accordingly. Looking at the lower half of the ranked IVHM requirements can be interpreted as confidence in using the existing capabilities within a UAS and the ease of incorporating IVHM into the design. The UAS already needs to use sensors and the data they provide in order to fly and conduct its mission and it could be possible to use the existing infrastructure for IVHM needs – this can also explain why there is a difference in ranking between the two requirements about transferring data, transferring data within the UA is less of a concern than transferring from the UA, as the amount of data which can be transferred between the UA and CS is limited and has to be shared with command signals for controlling flight and data collected with the payload.

Table 6-8 Summary of IVHM Requirements House Results

	<i>Raw</i>	<i>% Raw</i>	<i>% Max</i>	<i>Rank</i>	<i>Importance</i>
Performance Indicators	158.57	11.75%	100.00%	5	Very High
Fleet Analysis	153.57	11.38%	96.85%	5	
Diagnostics Analysis	151.03	11.19%	95.24%	5	
Prognostics Analysis	144.86	10.74%	91.35%	4	High
Response to the IVHM	131.96	9.78%	83.22%	4	
Management of Spare Parts	113.76	8.43%	71.74%	3	Moderate
Transfer Data from the Vehicle	112.75	8.36%	71.10%	3	
Sensitivity	107.45	7.96%	67.76%	3	
Reconfigure IVHM in Service	79.25	5.87%	49.98%	2	Low
Transfer Data within the Vehicle	66.84	4.95%	42.15%	1	Very Low
Conditioning of Data	65.67	4.87%	41.41%	1	
Store Data	63.67	4.72%	40.15%	1	

6.3.2.7 IVHM Enablers House

Finally the results of comparing the IVHM requirements to the IVHM enablers (which are not necessary to the IVHM but will help IVHM be implemented on the

UAS) in the IVHM Enablers House are analysed (Table 6-9). The ranking of the IVHM enablers reinforces some of the findings of the ranked requirements of the previous houses. The detectability of the impending failure being ranked as being very high importance, again indicate that diagnostics is important for the IVHM for the UAS. Also with accuracy and precision of captured data ranked as the highest, and one rank higher than: availability & accuracy of historical maintenance data; availability & accuracy of failure data; failure mode knowledge; and availability & accuracy of operational data would indicate that the accuracy of input data is more a concern and that there could be bias towards data-driven techniques over those techniques which are based on the physics of failure. Standard data format has been identified as low importance, again echoing what was found in the IVHM Requirements house – which the various data formats should already be defined as part of the overall UAS design and should be less of a concern for the IVHM designer. Also the availability of communications has been identified as having moderate importance, though there is a need to get information off the UA to inform maintenance and operations of the health of the UA it does not have to be raw data. There is a need for some processing of the health data on-board the UA, as the flight computer will need to make decisions based on the current state of the UA. It is also interesting that maintenance staff availability and flexibility in schedules have been identified as having very low importance where in the previous HoQ response to the IVHM has been identified as having high importance, one reason for this could be that responses to the IVHM system may be automatically carried out by the UA's flight control computer, but this automatic response does not lessen the need for maintenance and operations to take action on information provided by the IVHM.

Table 6-9 Summary of IVHM Enablers House Results

	<i>Raw</i>	<i>% Raw</i>	<i>% Max</i>	<i>Rank</i>	<i>Importance</i>
Accuracy & Precision of Captured Data	265.53	11.16%	100.00%	5	Very High
Detectability of Impending Failure	258.82	10.88%	97.47%	5	
Degradation Traceability	231.15	9.72%	87.05%	4	High
Availability & Accuracy of Historical Maintenance Data	226.85	9.54%	85.43%	4	
Availability & Accuracy of Failure Data	225.50	9.48%	84.92%	4	
Failure Mode Knowledge	223.37	9.39%	84.12%	4	
Availability & Accuracy of Operational Data	219.12	9.21%	82.52%	4	
Availability of Communications	188.34	7.92%	70.93%	3	Moderate
Performance Monitoring	182.87	7.69%	68.87%	3	
Standard Data Format	143.80	6.05%	54.16%	2	Low
Maintenance Staff Availability	113.65	4.78%	42.80%	1	Very Low
Flexibility in Schedules	99.30	4.18%	37.40%	1	

6.3.3 Demon UAS Ranked Requirement Sets

This section will cover the analysis of the ranked sets of requirements for the populated IVHM-RD of the Demon UAS.

6.3.3.1 Demographics

Unlike the Persistent UAS, the participants of the population of the Demon UAS were known, and had knowledge of both the Demon UAS and IVHM, thus no demographics question were needed to judge their suitability. Those who participated in this where: three members of the academic staff and two PhD students.

6.3.3.2 Research Programme Criteria Pair-Wise Comparison

First the results of the comparison of the research programme criteria with operating the Demon UAS are analysed, which are compared to one another in the Cost PWC (Table 6-10). Research Originality and Non-Conventional Flight Controls have been identified as being of very high importance, which supports the original purpose to conduct original research in into non-conventional fight controls. However, another aspect of the FLAVIIR program was to look into low maintenance UAS, which makes the ranking of Low Maintenance Technologies

as of low importance interesting. This could be because of the limitations of investigating maintenance on a one off technology demonstrator. Whereas if investigating technologies to lower maintenance, it would be better to partner with an organisation operating UAS to see what the real maintenance problems are and where possible technologies could help. Technology Integration and the quality of the research have been ranked high importance and requirements concerning the cost and using the Demon UAS as a publicity or educational tool as of very low importance.

Table 6-10 Summary of the Research Programme Criteria Pair-Wise Comparison

	<i>Raw</i>	<i>Rank</i>	<i>Importance</i>
Research Originality	5.3	5	Very High
Non-Conventional Flight Control	3.9	5	
Technology Integration	2.9	4	High
Research Academic Quality	2.6	4	
Research Business Quality	1.7	4	
Low Maintenance Technologies	-1.4	2	Low
Educational Tool	-2.9	1	Very Low
Cost to Acquire	-3.0	1	
Publicity Tool	-4.5	1	
Cost to Operate	-4.6	1	

6.3.3.3 Experiment Capability House

Second the results of comparing the research programme criteria to the experiment capabilities in the Experiment Capability House are analysed (Table 6-11). The need to conduct research and publish has been identified as the only requirement to be of very high importance, coupled with ability to Capture Experimental/Test Data and Monitor Performance being of high importance reinforced the research role of the Demon UAS. The requirements which have been ranked as having moderate importance are mainly concerned with the operation of the Demon UAS, as well as the capturing the design and modifications. Those ranked as low importance are predominantly concerned with the maintenance and airworthiness, with exception of staff availability.

Requirements ranked as very low importance are concerned with the availability of part and the provisions to conduct repairs or modify the aircraft; this indicated that the operation of the UAS is more important than its maintenance.

Table 6-11 Summary of the Experiment Capability House Results

	<i>Raw</i>	<i>% Raw</i>	<i>% Max</i>	<i>Rank</i>	<i>Importance</i>
Research/Publication	208.75	10.80%	100.00%	5	Very High
Capture Experimental/Test Data	185.50	9.60%	88.86%	4	High
Monitor Performance	165.00	8.54%	79.04%	4	
Design/Modification	143.75	7.44%	68.86%	3	Moderate
Collect Operational Data	138.75	7.18%	66.47%	3	
UAS Ease of Operation	135.25	7.00%	64.79%	3	
Collect Operating Conditions	132.00	6.83%	63.23%	3	
Time Between Reconfigure/Mod.	113.25	5.86%	54.25%	2	Low
CAA Documentation/Airworthiness	109.50	5.67%	52.46%	2	
Repair Time	100.00	5.17%	47.90%	2	
Per-Flight/Experiment Checks	98.75	5.11%	47.31%	2	
Unscheduled Maintenance	92.75	4.80%	44.43%	2	
Staff Availability	89.50	4.63%	42.87%	2	
Lab/Workshop Availability	78.00	4.04%	37.37%	1	Very Low
Tool/Equipment Availability	74.75	3.87%	35.81%	1	
Availability of Spares/Parts	67.00	3.47%	32.10%	1	

6.3.3.4 IVHM Requirements House

Third the results of comparing the experiment capabilities to the IVHM requirement in the IVHM Requirements House are analysed (Table 6-12). Once more the rankings of the IVHM Requirements House reinforce those of the previous ones. Those ranked as very high importance go towards supporting the Demon UAS as a research UAS, primarily the ability to store data and transfer it from the vehicle – though these requirements are specifically for the IVHM they are very much akin to the research role, whereas the rest seek to ensure that the flight will be successful (or at least respond to a prompt from the IVHM). The ability to reconfigure the IVHM in service has been identified as

being of high importance, reflecting that the Demon UAS is subject to change as and when needed by an experiment. Longer-term concerns for IVHM (prognostics and spare parts) have only been identified as being of moderate importance. Understandably, fleet analysis is of very low priority for the Demon UAS, being a one off, though the raw score for it is not zero

Table 6-12 Summary of the IVHM Requirements House Results

	<i>Raw</i>	<i>% Raw</i>	<i>% Max</i>	<i>Rank</i>	<i>Importance</i>
Performance Indicators	144.00	10.18%	100.00%	5	Very High
Store Data	143.50	10.14%	99.65%	5	
Diagnostics Analysis	142.00	10.04%	98.61%	5	
Transfer Data from the Vehicle	140.25	9.91%	97.40%	5	
Response to the IVHM	138.25	9.77%	96.01%	5	
Transfer Data within the Vehicle	129.75	9.17%	90.10%	4	High
Reconfigure IVHM in Service	128.75	9.10%	89.41%	4	
Sensitivity	111.25	7.86%	77.26%	4	
Prognostics Analysis	106.25	7.51%	73.78%	3	Moderate
Management of Spare Parts	100.25	7.08%	69.62%	3	
Conditioning of Data	85.25	6.02%	59.20%	3	
Fleet Analysis	45.50	3.22%	31.60%	1	Very Low

6.3.3.5 IVHM Enablers House

Finally the results of comparing the experiment capabilities to the IVHM requirement in the IVHM Requirements House are analysed (Table 6-13). The ability to detect impending failures has been identified as the most important enabler to the IVHM for the Demon UAS. However, the second most important enabler is degradation traceability although in the previous HoQ prognostic abilities are only to be considered as being moderately important. Once more the enablers which are ranked of moderate importance or lower echo the lower priorities of the of those in the Experiment Capabilities House and the IVHM Requirements House – less of a concern for long term concerns for health, the changeable nature of the Demon UAS, and availability of resources to deal with maintenance issues.

Table 6-13 Summary of the IVHM Requirements House Results

	<i>Raw</i>	<i>% Raw</i>	<i>% Max</i>	<i>Rank</i>	<i>Importance</i>
Detectability of Impending Failure	309.75	12.20%	100.00%	5	Very High
Degradation Traceability	306.25	12.06%	98.87%	5	
Performance Monitoring	270.50	10.65%	87.33%	4	High
Accuracy & Precision of Captured Data	244.50	9.63%	78.93%	4	
Availability of Communications	235.25	9.26%	75.95%	4	
Failure Mode Knowledge	234.00	9.21%	75.54%	4	
Availability & Accuracy of Failure Data	221.00	8.70%	71.35%	3	Moderate
Availability & Accuracy of Operational Data	192.50	7.58%	62.15%	3	
Availability & Accuracy of Historical Maintenance Data	191.75	7.55%	61.90%	3	
Standard Data Format	133.50	5.26%	43.10%	2	Low
Flexibility in Schedules	108.00	4.25%	34.87%	1	Very Low
Maintenance Staff Availability	92.75	3.65%	29.94%	1	

6.3.4 Comparison Between Cases

The comparison of the ranked sets of the IVHM-RDs brings out the similarities and differences between the two design cases. Only the IVHM Requirements House and the IVHM Enablers House will be compared. This is because they are the only sets which are the same for both and thus directly comparable. Though there is only two UAS being compared at in this analysis it can still provide some insight as to any commonalties between IVHM for different UAS, further design cases for different UAS will needed to be looked into in order to see if these trends continue.

In addition to both the UAS design cases a third case will be compared, that of a legacy manned military fast jet⁵ – which can be used to seen some differences between manned and unmanned aircraft.

The IVHM-RD for the Fast Jet was populated in the same web-based survey method as the Persistent UAS, and sent to the same organisations at the same

⁵ This case was looked at in conjunction with separate project within the IVHM Centre.

time. There were not enough responses in the HoQs which make up the context for the fast jet. However, the IVHM Requirements House and IVHM Enablers House did get enough responses (similar amount) to compare these results to those for the UASs.

Feedback from some of the participants of the survey indicated that there would be little to no difference between the two IVHM-RDs (Fast Jet and Persistent UAS) and only opted to complete one. In order to compare the results of the Fast Jet to those of the UASs the importance ranks need to be used in the IVHM Requirements House, under the assumption made by the survey participants (that the context for the Persistent UAS and Fast Jet will be the same) the importance ranks from the maintenance requirements were used. Figure 2 shows where the importance rankings from the Persistent UAS IVHM-RD will be imported into the fast jet IVHM-RD.

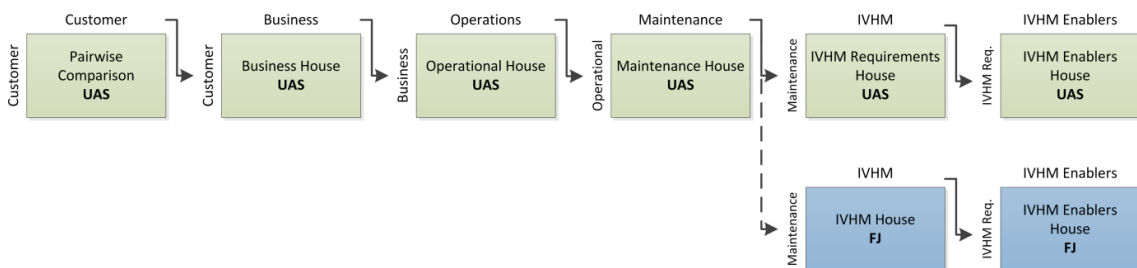


Figure 6-8 Importance Rankings Flow for Fast Jet

The point of reference for the comparison is the Persistent UAS, any changes in rank or order of the requirements and enablers will be compared to those of the Persistent UAS. The comparison diagrams (Figure 6-9 and Figure 6-10, below) show the importance rank of each requirement for the UASs and Fast Jet as well as the numbered order. The diagrams also connect each requirement or enabler between the three lists with the use of lines. The colour coding signifies if there is a change of importance rank (compared to the Persistent UAS): black is used if there is no change in importance rank, blue is used if the importance rank has increased by one or more, and red is used if the importance rank has decreased by one or more.

6.3.4.1 IVHM Requirements Comparison

Figure 6-9 shows the comparison of the IVHM requirements set for the three design cases. Although there is variation between the lists, taking into consideration the context of the design cases there are some interesting points which emerge.

The first thing of note is that performance indicators top the list for both design cases, whereas they are down one importance rank for the Fast Jet and third in order. Diagnostic analysis is ranked as being very high importance and third in order for both UAS, this is still third in order for the Fast Jet, but it has slipped down an importance rank. These two being consistently ranked for both UAS suggest that it will be common for other UAS as well. When considering that the pilot is located off-board, situational awareness of the pilot changes. They are reliant on the reading of sensors to understand what the current state of the UA is, both these requirements support the notion of providing the pilot with information on the UAS – though the exact details of what and how to present the relevant information to the pilot will need further research. Compared to the Fast Jet the UAS have less of a concern for the response to the IVHM, where it is top of the list for the Fast Jet it is fifth in order for both UASs, and one less importance rank for the Persistent UAS. This could be because the pilot is on-board the Fast Jet, and there is a human life at stake.

Importance	Demon UAS	Persistent UAS	Fast Jet
Very High [5]	(1) Performance Indicators	(1) Performance Indicators	(1) Response to the IVHM
	(2) Store Data	(2) Fleet Analysis	
	(3) Diagnostics Analysis	(3) Diagnostics Analysis	
	(4) Transfer Data from the Vehicle		
	(5) Response to the IVHM		
High [4]	(6) Transfer Data within the Vehicle	(4) Prognostics Analysis	(2) Fleet Analysis
	(7) Reconfigure IVHM in Service	(5) Response to the IVHM	(3) Diagnostics Analysis
	(8) Sensitivity		(4) Prognostics Analysis
Moderate [3]	(9) Prognostics Analysis	(6) Management of Spare Parts	(5) Transfer Data from the Vehicle
	(10) Management of Spare Parts	(7) Transfer Data from the Vehicle	(6) Reconfigure IVHM in Service
	(11) Conditioning of Data	(8) Sensitivity	(7) Performance Indicators
			(8) Management of Spare Parts
Low [2]		(9) Reconfigure IVHM in Service	(9) Conditioning of Data
Very Low [1]	(12) Fleet Analysis	(10) Transfer Data within the Vehicle	(10) Sensitivity
		(11) Conditioning of Data	(11) Transfer Data within the Vehicle
		(12) Store Data	(12) Store Data

Figure 6-9 Comparison of the Ranked Sets of IVHM Requirement

Second, the management of spare parts is consistently ranked as being moderate importance for all three aircraft, though there is variation in the order. Third, is that transfer of data within the vehicle and the ability to store data is considered to be of very low importance for both the Persistent UAS and Fast Jet. They are however considered to be of very high and high importance respectively for the Demon UAS. Finally, between the Demon UAS and Persistent UAS the requirements of fleet analysis and store data swap, both in terms of importance ranking and in order, which is understandable due to their differences.

6.3.4.2 IVHM Enablers Comparison

Figure 6-10 shows the comparison of the IVHM enablers for the three design cases. There are fewer similarities in general for the IVHM enablers compared to the IVHM requirements, this indicating that the enablers are more dependent on the context. The detectability of impending failure is of very high importance

for the UAS and of high importance to the Fast Jet, all in the top three in terms of order. Failure mode knowledge is seen as of high importance to all three, and have similar placement within the order. These enablers would support the diagnostic analysis which ranked consistently high in the previous HoQ, and also support the notion of providing situational awareness to the pilot.

Standard data format is ranked as low importance and has the same order for both the UAS, though it rises in one importance rank and one in order for the Fast Jet. This could be because UAS would have a greater level of integration compared to the legacy Fast Jet which would be using federated systems. Finally, both flexibility in schedules and maintenance staff availability have been consistently ranked as being of very low importance to all the design cases. Although the idea of IVHM allowing greater flexibility in maintenance tasks is something which is often stated. These results seem to indicate that they are of little concern at the current time, and that diagnostics is the key attribute of IVHM.

Importance	Demon UAS	Persistent UAS	Fast Jet
Very High [5]	(1) Detectability of Impending Failure	(1) Accuracy & Precision of Captured Data	(1) Availability & Accuracy of Failure Data
	(2) Degradation Traceability	(2) Detectability of Impending Failure	
High [4]	(3) Performance Monitoring	(3) Degradation Traceability	(2) Performance Monitoring
	(4) Accuracy & Precision of Captured Data	(4) Availability & Accuracy of Historical Maintenance Data	(3) Detectability of Impending Failure
	(5) Availability of Communications	(5) Availability & Accuracy of Failure Data	(4) Accuracy & Precision of Captured Data
	(6) Failure Mode Knowledge	(6) Failure Mode Knowledge	(5) Failure Mode Knowledge
		(7) Availability & Accuracy of Operational Data	(6) Availability & Accuracy of Historical Maintenance Data
			(7) Availability & Accuracy of Operational Data
Moderate [3]	(7) Availability & Accuracy of Failure Data	(8) Availability of Communications	(8) Degradation Traceability
	(8) Availability & Accuracy of Operational Data	(9) Performance Monitoring	(9) Standard Data Format
	(9) Availability & Accuracy of Historical Maintenance Data		
Low [2]	(10) Standard Data Format	(10) Standard Data Format	(10) Availability of Communications
Very Low [1]	(11) Flexibility in Schedules	(11) Maintenance Staff Availability	(11) Maintenance Staff Availability
	(12) Maintenance Staff Availability	(12) Flexibility in Schedules	(12) Flexibility in Schedules

Figure 6-10 Comparison of the Ranked Sets of IVHM Enablers

6.3.5 Group Understanding of the Relationships

There are two reasons for looking into the individual relationships contained within the IVHM-RD HoQ (i.e. the values in the cells of the comparison matrix representing their strength). First, would be assessing which relationships are key to implementing the higher importance requirements for the IVHM designs for both design cases. Second, would be assessing what the group populating each HoQ knows and how typical of the group the results (relationships) are.

However, there are also two viewpoints to take when analysing the relationship. First, would be to help the IVHM design to progress. Second, would be the more academic exercise of assessing the current knowledge of the group and

then posit where more research could be conducted in a targeted way (by highlighting what the group of SMEs populating the HoQ does not know). It is the view of the author that the latter would be the most beneficial, as there is no current intention develop the IVHM of the design cases into a physical product.

Though the populations of design cases were different, in terms of the participant percentage for each form, the process of judging which results are valid is needed.







First, the results are to assess whether they are typical of the group (i.e. those who chose to participate in the population of that HoQ). With the populations being relatively small (compared to surveys) the only way to be one hundred percent confident that the results are representative of the group is if all the participants contributed to that cell of the HoQ. Unfortunately it is not always the case that whole group has contributed for each and every cell in a HoQ. Therefore those who have one less than the maximum population have also been included, even though the confidence over their accuracy becomes questionable due to the size of the group. This provides a fuller picture, but could be less accurate, therefore the difference between those cells where the group populated fully and those there was one less.

Second, is to turn the relationship value into a symbol. This will allow quick identification of which relationships are more important than others, much as is done within QFD. However, unlike the population there will be a slightly different scale, cells with a relationship value of less than three will have no symbol, those with a value between three (inclusive) and six (exclusive) will have a symbol representing a weaker relationship, and those with a value over six (inclusive) with a symbol representing a stronger relationship.

Third, is to add the disagreement within the group. This was chosen to be the top twenty percent of the standard deviations for the cells with the HoQ. For those cells with a standard deviation of zero these results were also identified as they show where the group is in total agreement.

Below is the key used for the figures below, based on the criteria detailed above. There is a deliberate reasons for using the ‘-er’ suffix when describing the relationships after this process. First, it is to differentiate them from the scale used to describe the relationships when populating the IVHM-RD (weak, moderate, strong). Second, is to reflect that it is an aggregated opinion of the group, which entails a certain amount of disagreement (apart from the acceptations where there is total agreement).

Table 6-14 Key for Relationship Figures

<i>Symbol</i>	<i>Name</i>	<i>Meaning</i>	<i>Notes</i>
	Black Triangle	A weaker relationship, without total agreement.	
	Black Circle	A stronger relationship, without total agreement.	
	Green Triangle	A weaker relationship, with total agreement.	Not used in the following figures.
	Green Circle	A stronger relationship, with total agreement.	
	Blue Filled Cell	100% of the possible participants contributed to the cell.	Was not used in the figures relating the Demon UAS.
	Red Question Mark	Highest 20% of the stander deviations for the cells of the HoQ	

6.3.5.1 Persistent UAS Relationships

Figure 6-11 and Figure 6-12 show the relationships relating the IVHM requirements for the IVHM Requirements House and the IVHM Enablers House for the Persistent UAS. With the above key applied it is quiet easy to see the significance of the relationships, however there are a few which stick out for both.

The first thing to note in Figure 6-11 is there are seven relationships where the whole group has contributed to their population (blue cells), this is more than in Figure 6-12 which only has two, though none of them have total agreement. Second, is the two weaker relationships which relate Auxilliary Equipment

Required to both Diagnostics Analysis and Prognostics Analysis. These relationships have eight out of the nine (89%) SMEs providing responses, yet they are two of the highest standard deviations for the HoQ. This indicated that the group is divided on the strength of this relationship. Finally, the strong relationship between False Negative Rates and Reconfiguration of the IVHM in Service is also contested in the same fashion as the two before.

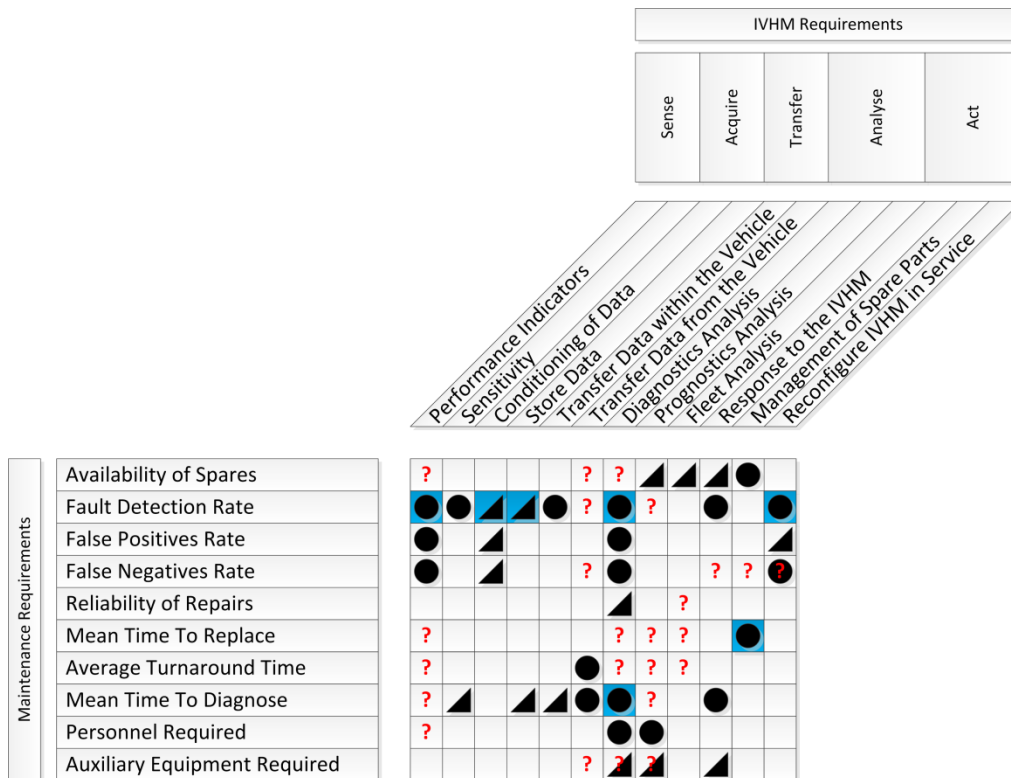


Figure 6-11 Persistent UAS Maintenance & IVHM Requirements Relationships

The first thing to note in Figure 6-12 is that of the two blue cells, there is total agreement between Performance Indicators and Performance Monitoring, the only one in the HoQ. This may be in part due to the wording in the headings. Also to be noted, contested relationships where six out of seven (86%) SMEs provided responses. These are weaker relationship between Transfer Data within the Vehicle and Detectability of Impending Failure and the stronger relationship between Transfer Data from the Vehicle and Availability and Accuracy of Operational Data.

which the group is in total agreement. Two of which are weaker relationships: between collect operational data and response to the IVHM and between design/modification and diagnostic analysis. The stronger relationship agreed upon is between collect operating conditions and transfer data form the vehicle.

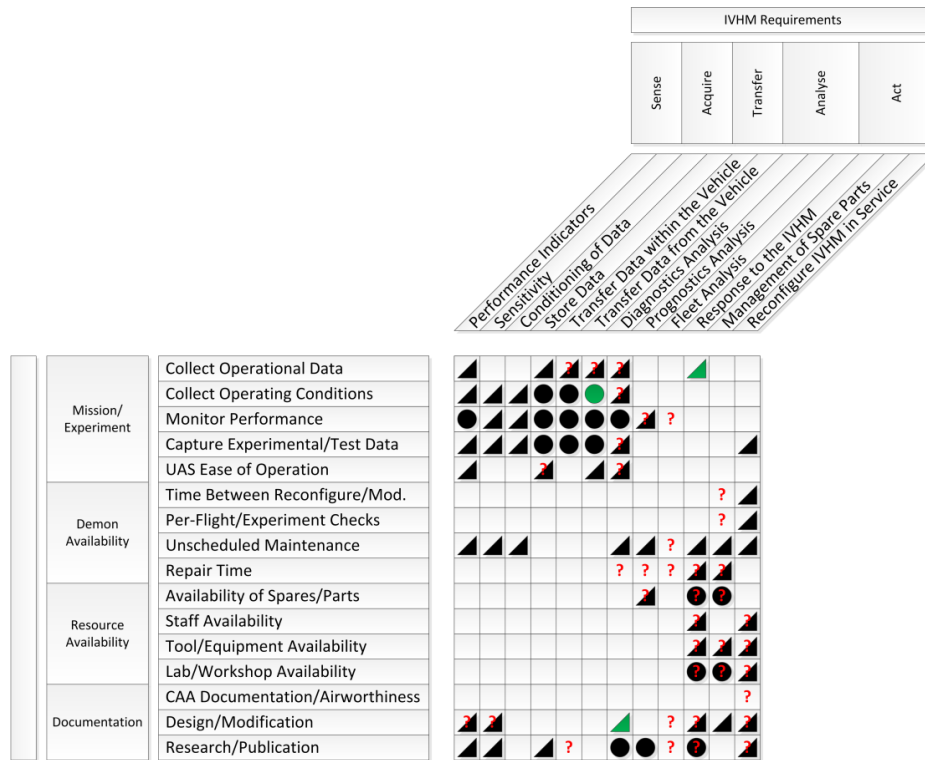


Figure 6-13 Demon UAS Experiment Capability & IVHM Requirement Relationships

The first thing to note about Figure 6-14 is a large number of relationships is filled in, compared to Figure 6-12, this could suggest that the academics are more inclined to give an opinion over those in industry. Second, there is six relationships where there is total agreement within the group. One of which is a weaker relationship, between management of spare parts and performance monitoring. There are three stronger relationships: between performance indicators and degradation traceability, detectability of impending failures, and performance monitoring. Stronger relationships between sensitivity and degradation traceability and between transfer data from the vehicle and availability of communications. Third, there is a large amount of disagreement between prognostics analysis and many of the relationships with the IVHM

enablers, this could mean that it is uncertain as to whether these enablers would be able to help implement prognostic capabilities to the Demon UAS. Fourth, there is also some disagreement about the enablers and fleet analysis, this probably reflects the fact that the Demon UAS is a single UAS.

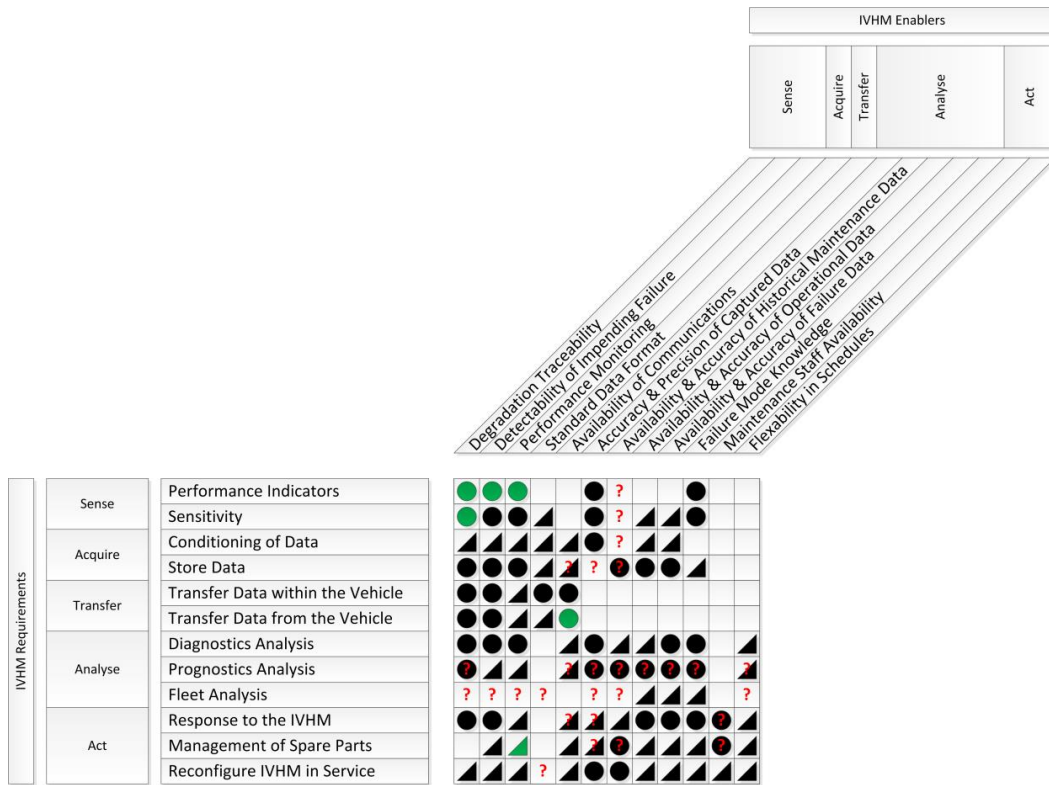


Figure 6-14 Demon UAS IVHM Requirements & Enablers Relationships

6.3.5.3 Relationship Summary

The scales used in this analysis is only one of many possibilities. It will be dependent on the scales (e.g. for population of the HoQs) used with the IVHM-RD and the amount of uncertainty an organisation is willing to accept. The most disputed cells (i.e. those with question marks, the top twenty percent disagreed upon) provide a guide as to where to investigate next for research into IVHM on UAS to improve the scope of understanding. But taking the other view point, using the analysis to progress the design of the IVHM, looking at those providing a relationship value (weaker or stronger) but which are also in the top twenty percent which are disagreed on provide the most interesting results.

These relationships will need to be investigated further, by looking at the literature, conducting test/experiments, or discussing the results. Discussing the results would be much akin to the traditional method of populating a QFD form. But unlike the traditional meeting, an agenda can be set to look specially at certain results, as the other results have passed the assessment criteria and do not need to be discussed. This allows the discussion to be focussed on where it is needed most. Also another notation can be used within the diagram to designate a relationship which has been changed in this way (e.g. different coloured triangle or circle).

7 Analysis of the IVHM-RD

This section will discuss the IVHM Requirement Deployment (IVHM-RD) process. First, the process itself will be discussed, which will be subdivided into sections on the tool, the population, and the process as a whole. Second there will be a discussion of the results from the populations of the IVHM-RDs for the design cases, which will also be split into three sections on the ranked requirement sets for both design cases, a comparison of the ranked IVHM requirements and IVHM enablers for both design cases, and assessing group understanding of the relationships contained within the IVHM Requirements House and IVHM Enablers House for both cases.

7.1 Analysis of the Tools

This section will discuss the tool part of IVHM-RD. First, it will discuss the requirements sets created for both the design cases. It will then discuss the flow and structure of the tool and finally a comparison between the two tools created for the design cases.

7.1.1 Requirements Sets

The stakeholder requirements for both design cases are slimmed down sets. A comprehensive set of requirements for all stakeholders involved would provide a comprehensive and complete picture of the context going into the IVHM design. However, there are likely to be many stakeholder requirements which will not relate to the IVHM (but will be of concern to other parts of the UAS design) and including these in the IVHM-RD will only increase the size of the forms (PWC and HoQ), and the time needed to complete them as the participants will still need time to think about the relationship. This was a factor in reducing the sets to only those stakeholder requirements relevant to IVHM. Considering the SMEs participating had no real gain in completing the IVHM-RD (e.g. it is not part of their job, the UAS in question is not related to their business), they are less likely to fill out a large matrix.

These reduced sets could lead to some relationships between requirements being missed which could be of importance to the IVHM, although every effort was made to ensure that stakeholder requirement set were lean but sufficiently capture the context to solve the problem at hand.

The decision to make the IVHM requirements the same for both implementations of the IVHM-RD was made to allow comparison of the ranked sets between the two design cases. The IVHM requirements are of a high level and they are common aspects of IVHM which could be considered in any IVHM design. It is also not prudent to develop them into more actionable requirements (e.g. perform prognostics on the fuel system with a prognostic window of X) as these would need more information than is available to the project (which would also be unavailable during the early stages of design) such as: reliability information of the systems and their components, architecture of systems, operational time scales, etc. These other aspects are also likely to change during the design of the UAS, and it is not appropriate to incorporate these into the IVHM-RD. The only possible exception which could have been made to the IVHM requirements lists between the two design cases is that 'fleet analysis' could have been removed from the set for the Demon UAS, but it has been kept in to allow a full comparison.

The addition of IVHM enablers to the IVHM-RD should also provide value to the design of the IVHM, with the lack of information available at the start of the design. Again, just as the IVHM requirements they are the same for both design cases (which allows comparison) and just as the IVHM requirements this should not affect the validity of the results. These are a set of generic high-level enablers to IVHM and populating the IVHM-RD shows which of them will be of benefit to the design of the IVHM for both of the design cases. As with the IVHM requirements, they need to be linked with the rest of the UAS design, e.g. Failure Mode Knowledge will be linked to systems and their architecture of the UAS.

The process of reviewing the requirements sets (the stakeholder requirements, IVHM requirements, and IVHM enablers) to ensure that the sets were lean, but

still sufficient to cover the context was done which too considerable care. As stated before, the requirements were taken from the literature and they refined with the help of the IVHM Centre and BAE Systems, through several iterations. This has allowed the expertise of multiple experts to judge which requirements are relevant to the IVHM, as well as refine the wording and definitions of the requirements, and ensuring that no requirements are repeated (within a set or between sets).

7.1.2 Structure & Flow

Taking only the UA of the Persistent UAS into consideration when developing the IVHM-RD Process is an obvious cropping of the full picture (Figure 5-6). Figure 7-1 shows the flow and the forms used in the IVHM-RD process for the UA. It also shows the unused forms for capturing relationships between all combinations of the requirement sets. The used forms capture five hundred and ninety seven out of the 2,221 possible relationships if all forms are used – even more if all the elements of the UAS are represented.

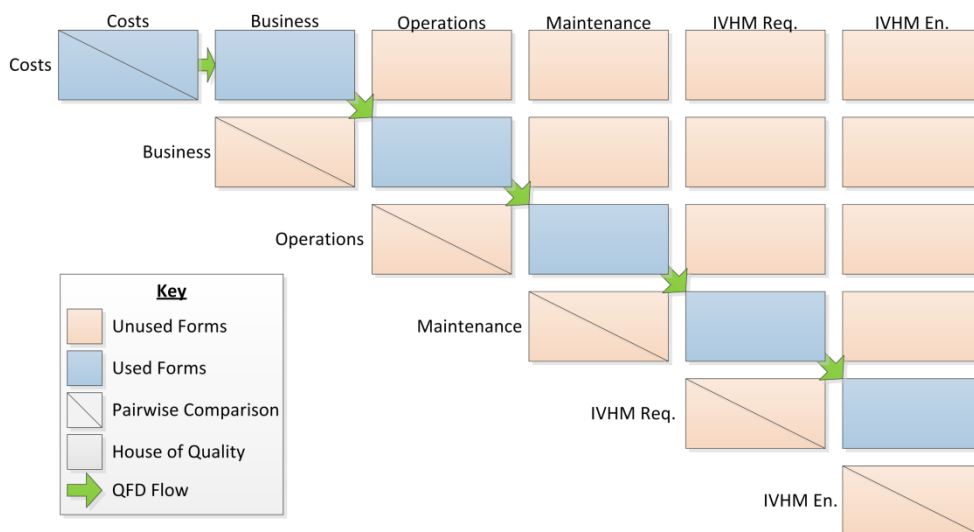


Figure 7-1 Overview Possible Form of the IVHM Requirements QFD Process

Capturing all the interactions between the requirements sets (either by including the additional PWCs and HOQs or by having a single form including all interactions) would allow a greater insight into the relationships between all the stakeholder groups. The key question to be asked is: whether the information

on the relationships gained is worth the cost? There will have to be a trade-off between the amount of information which can be captured and the amount of time it takes to develop the IVHM-RD – creation of the forms, how each form will interact with each other. More importantly, it affect the practicalities and motivation of SME participation.

This reduction to the number of relationship defined within the IVHM-RD also allows better targeting of the HoQs to the stakeholder groups (and the SMEs representing them) compared to one large form for all stakeholders – e.g. an experienced maintenance engineer will not have to comment on the business requirements which are out of their domain expertise.

The current flow of the IVHM-RD for the Persistent UAS provides a logical flow to relate the customer requirements (in this case the costs) to the IVHM (requirements and enablers): the customer interacts with the business, with the intent of hiring the UAS to monitor crop or other vegetation; the business which operates the UASs will inform operations to schedule and conduct the flight of the UAS and collect data from the sensors on-board the UAS; maintenance maintains the UAS, so they can be used by operations, and the IVHM is there to provide information on the health of systems so that they can be better maintained. This flow represents the simplest view of the interactions between the stakeholder groups – each previous stakeholder group have influenced the importance ranking of the next set of requirements, resulting in all the identified stakeholder groups being accounted for in the ranking of the IVHM requirements and enablers. However, this daisy-chaining will dilute the influence the earlier stakeholder groups as they are fed through the IVHM-RD to the IVHM requirements and enablers.

The addition of any new forms will have to be justified in the trade-off between the cost and benefit it hopes to provide. Therefore the adding any new form must have justified reason for being included as it is not as simple as adding a new form – the flow of the IVHM-RD must be reassessed. For example, it is entirely feasible that the IVHM will report directly to the operations (i.e. not just through maintenance) on the availability and the current functionality of the

UASs in the fleet so that they can best utilise each one. Including a HoQ where the operations requirements are set against the IVHM requirements can be justified as it provides a better representation of how the UAS will be operated. Once this form is introduced then the IVHM requirements can be ranked with direct influence from the operations requirements, but still taking into account of the previous stakeholder groups (costs>business>operations>IVHM requirements). However, this ranking of the IVHM requirements will need to be combined with rankings from comparing the maintenance requirements and IVHM requirements, which have already taken into account of the operations requirements (costs>business>operations>maintenance>IVHM requirements). The combination of the two rankings will need to be carefully considered as to not unduly bias the viewpoint of the operations stakeholder group. Adding more forms in this manor will only increase the complexity of the interactions further, and understanding the full impacts of this will require more research.

When considering the Demon UAS structure and flow, the same arguments, mentioned above, over the complexity of the interactions still hold. However, unlike the Persistent UAS the organisation and mission are different, resulting in a different number of HoQ, headings, and relationships needed to be defined. As the Demon UAS has a somewhat simpler operation compared to the Persistent UAS (the Demon UAS is a single UAS which is configured, made airworthy, and used when there is an experiment to be run, and if there is no experiment is stowed away – except when it is used as a display piece). This simpler mode of operation has affected the number of HoQs, in that functions which could be considered separate have been folded into fewer HoQ as they do not need a HoQ of their own. This is the case with the Experiment Capability House, which contains requirements concerning the operation of the Demon UAS and its maintenance – two separate HoQ for the Persistent UAS.

7.1.3 The Design Cases Tool Comparison

Table 7-1 provides an overview of the differences between the differences between two design cases. Both have one PWC, to provide the initial set of importance rankings, though each compares different requirements: for the

Persistent UAS it is the needs of the customer and for the Demon UAS it is the goals of the research. Though different they represent the activity of the UAS which the IVHM must support. For the Persistent UAS this is providing the service of crop monitoring to the customer at an acceptable price. For the Demon UAS this is fulfilling the research goals and contributing to knowledge and industry.

Though there is a difference between the numbers of HoQ making up the context of the UAS's mission and the organisation operating it, the overall number of relationships which are defined within each IVHM-RD only varies by fifty six relationships – this closeness was not intentional. Though there is a lesser number of HoQ, the experiment capability requirements set contains the most requirements of any of the sets (in both design cases). This indicates that the number of requirements needed to accurately depict the context of UAS and relate it to the IVHM for that UAS is between five hundred and six hundred. This is only based for the two design cases, further implementations of the IVHM-RD will be needed to see if it is truly the case.

Table 7-1 Comparison Between the Design Cases

<i>Design Case</i>	<i>Role</i>	<i>No. of PWC</i>	<i>No. of HoQ</i>	<i>No. Relationships in the IVHM-RD</i>
Persistent UAS	Crop Monitoring	1	5	597
Demon UAS	Research	1	3	541

7.2 Analysis of the Populations

This section will discuss the population of both design cases. First, it will discuss the distributed population and then the usefulness of the new population metrics when conducting a distributed population. It will then discuss the population of both design cases.

The shift from the traditional population method to the distributed population method does provide some advantages. Relaxing the constraints of having all the relevant people to populate a HoQ (or PWC) in a meeting at a single time in

order to populate the form allow each person to complete in their own time (although it will have to have deadline set) around other work which they may have. Distributing also allows potentially larger amounts of people to participate in the population than if they were all gathered within a single place at the same time.

7.2.1 New Population Metrics

In the traditional method of populating a QFD the participants are known, and each relationship is discussed till an agreement is reached [88], which can cause problems with completing forms [73]. However with the distributed population there is no discussion and the participants are not necessarily known and there is no discussion – bringing in to question on the validity of answers. Hence the need for the demographic questions in the population of the Persistent UAS (which were not needed for the Demon UAS as the participants were known) and the cell metrics: cell participants, dissenters, participant percentage, and the standard deviation.

These cell metrics can be used in order to assess the reliability of the population of the IVHM-RD. First, looking at the cell participants will tell how many of the SMEs feel competent to answer that question and ideally it should be higher than thirty – to ensure that the answers are statistically significant. However it may not be possible to achieve a sample of SMEs of that size from the personnel allocated to the design of the UAS in question, or in the case of the design cases the number of SMEs who volunteered their opinions. Although there is a smaller group of highly experienced and educated SMEs, it might be worth extending the populations to people with less competence in order to achieve a statistically viable sample, as it may lead to better representation of true relationship between the two requirements [92].

Using the cell participants number in combination with the participant percentage can also give further insight into how confident the group of SMEs participating is in understanding the relationship – the lower the percentage indicated that certain experts do not feel confident in their understanding in order to comment. So even if the cell participant number is over thirty, when the

participant percentage is low it can indicate that there is still a lack of understanding within the group of SMEs. Both the cell participants and participant percentage can be used for PWC and HoQ. The dissenters and standard deviation indicate the amount of agreement for the PWC and HoQ respectively. Where the number of dissenters counts the number of people who disagree with the majority, or in case of an even number of cell participants indicate that opinion is split, the standard deviation indicates the variation in the opinions of the SMEs.

Although using the standard deviation as a quantitative measure of the variance is not particularly useful, especially when the number of cell participants is below thirty, however if it is zero then there is total agreement and any number higher does show that there is some amount of disagreement between the SMEs.

The best way for the reliability of the results to be assessed is to take into account all the cell metrics and the demographics to perform a qualitative assessment. Looking at them individually can be misleading (e.g. a standard deviation of zero is not much indication of valid result if only two SMEs contributed out of a possible ten), although this may take some time if all the interactions are looked at individually. It may be necessary to implement some criteria for judging the reliability of the combined results. Establishing the threshold between what is a good or bad result may be specific to each design case or even between IVHM-RD forms. Once 'invalid' results are identified then further investigations can be made into that relationship, which could take the form of discussion between SMEs (in the same way as the traditional method, but it allows an agenda to be set to look only at the disagreed upon relationships), reviewing the literature, experiments, etc.

7.2.2 Persistent Population

The Persistent UAS IVHM-RD was sent out in survey format to seven organisations (one of which was Cranfield University). SMEs from four of the seven organisations completed the survey and an overall survey completion rate of 52% was achieved – a complete breakdown of started and completed

responses per organisation can be seen in Table 7-2 which also shows the breakdown of the responses per IVHM-RD form.

Table 7-2 Persistent UAS Survey Responses

	<i>Survey Completion</i>				<i>Responses Per IVHM-RD Form</i>				
	<i>Started</i>	<i>Completed</i>	<i>Completion %</i>	<i>PWC</i>	<i>HoQ 1</i>	<i>HoQ 2</i>	<i>HoQ 3</i>	<i>HoQ 4</i>	<i>HoQ 5</i>
Organisation 1	10	6	60%	1	3	3	5	5	3
Organisation 2	3	1	33%	1	1	1	1	1	1
Organisation 3	9	6	67%	2	3	3	3	3	3
Organisation 4	1	0	0%	0	0	0	0	0	0
Organisation 5	3	1	33%	1	1	0	1	0	0
Organisation 6	0	0	N/A	0	0	0	0	0	0
Organisation 7	1	0	0%	0	0	0	0	0	0
Total	27	14	52%	5	8	7	10	9	7

Table 7-3 shows a breakdown of the form completion rates and also the number of relationships which have been defined by the participants. The IVHM Requirement and IVHM Enablers HoQs have the lowest form completion percentages. Though they are the lowest in terms of form completion percentage they have some of the highest number of relationships defined, and the low completion percentage maybe indicative of IVHM being a relatively new concept.

Table 7-3 Persistent UAS Form Completion Percentages

	<i>Relationships per Form</i>	<i>Participants per Form</i>	<i>Max. No. Relationships Defined</i>	<i>No. Relationships Defined</i>	<i>Form Completion %</i>
PWC	105	5	525	512	97.52%
HoQ 1	120	8	960	804	83.75%
HoQ 2	48	7	336	278	82.74%
HoQ 3	60	10	600	522	87.00%
HoQ 4	120	9	1080	859	79.54%
HoQ 5	144	7	1008	704	69.84%
Total	597		4509	3679	81.59%

7.2.3 Demon Population

The Demon UAS IVHM-RD was sent out in spreadsheet format. Table 7-4 shows a breakdown of the form completion rates and also the number of relationships which have been defined by the participants. Unlike the Persistent UAS the PWC is the form with the lowest completion percentage.

Table 7-4 Demon UAS Form Completion Percentages

	<i>Relationships Per Form</i>	<i>Participants per Form</i>	<i>Max. No. Relationships Defined</i>	<i>No. Relationships Defined</i>	<i>Form Completion %</i>
PWC	45	5	225	185	82.22%
HoQ 1	160	4	640	640	100.00%
HoQ 2	192	4	768	768	100.00%
HoQ 3	144	4	576	576	100.00%
Total	541		2209	2169	93.32%

7.2.4 Population Summary

The distributed population method overcomes the need for all the participants to gather for a meeting (or series of meetings) – which can be seen as a double edged sword. On the one hand it saves the logistical challenge of gathering people of the stakeholder groups from across an organisation(s) to meet at the same time, and discussing the hundreds of individual relationships until agreement is reached on all of them, giving the potential for more participants in the populating. It also captures which relationships are disagreed on and how many of the participants contradicted to defining that relationship.

However it does not bring the different stakeholders together to discuss the design of the IVHM, which are a chance for teambuilding around the project and to gain a common understanding between different disciplines and stakeholder groups. For these reasons it might be best to propose a meeting with the stakeholders with the populated IVHM-RD with a more focussed agenda, agree with the already agreed upon relationships and discuss on those relationships where there has been disagreement.

7.3 Analysis of the Process

A generalised process for creating and populating the IVHM-RD would allow the designer of an IVHM for a UAS to create and populate an IVHM-RD customised to the context of that UAS.

The IVHM-RD allows the customers' requirements to be related to the IVHM requirements in a way which allows traceability through different aspects of the operation of the UAS – allowing the benefits to the customer to be seen, which is a key factor for enabling commercial success of IVHM[10]. It also captures the requirements and viewpoints of the various stakeholder groups involved with different aspects of operating a UAS, helping to understand the complex nature of designing IVHM for a UAS.

One advantage is that the process does not rely on precise figures, but the expertise of the relevant stakeholder groups, allowing the IVHM-RD to be completed during the initial stages of design to help guide decisions which in turn should help reduce the life-cycle costs of the UAS[70] – the IVHM-RD can also be revisited later in the design process and updated with new (more accurate) information as the design for the UAS becomes more developed.

The IVHM-RD process presented does have some shortcomings and also room for addition and expansion. One shortcoming is that it is reliant on the expertise of those populating the forms[70]; this could cause a problem for IVHM on UAS as both IVHM and UAS are emerging fields and there is still a lot of uncertainty – assumptions made today which later prove to be wrong could lead to wrongly ranked requirement sets.

There is also scope to expand the rooms contained in each HoQ. One such room which could be added is benchmarking against the company's own products and competitors. The current format of the IVHM-RD process also may not capture all the relationships between requirements, due to its cascading nature (direct relationships between customer requirements and IVHM requirement, relationships between the different streams relating to the UAS elements, etc.). One possible way to capture these relationships could be to use

a Matrix of Matrices approach[69], but doing so would increase the number of forms (and relationships needing to be defined) and the time needed to populate the IVHM-RD – further work is needed to assess if the extra information gained is worth the cost and complexity.

7.4 Application to Other UAS

7.4.1.1 The IVHM-RD for Other UAS

The two design cases in this thesis, though of use in and of themselves to their respective designs, have no particular use for someone wishing to design IVHM for a different UAS (e.g. a quad-copter for film/television work). Therefore a process is designed for building the IVHM-RD tool and populate it for a new design. Although there will be differences between any one implementation of the IVHM-RD to another there will also be similarities – this can be seen with Persistent and Demon UASs. This shows that there can be value in looking over other implementations of the IVHM-RD. Doing this with the intentions of using the IVHM-RD for a different UAS should take all the due diligence needed when trying to construct the complex mix of stakeholders (and their requirements) and end up with an adaptation to the context for a different UAS. Making mistakes at this stage will incur a greater cost to be rectified later in the design and development of the UAS or in the worst case during its operational life. Although it is understood that there will be some in-operation fine tuning of IVHM, there is little understanding of the costs involved and it is certainly not the intention to rectify mistakes made during the design of the UAS – which is known to have life-cycle cost implications.

The IVHM-RD Process is there to guide a designer in order to create the IVHM-RD tool (the forms, the requirements, the flow), then populate it using the distributed method (collecting the information from individual SMEs, combining the results), and finally produce the populated forms. The process is divided into thirteen steps (Figure 7-2): steps one to eight are about ensuring that the context of the UAS is understood and represented sufficiently; step nine is the creation of the forms needed, step ten to twelve are about the population and combination of results; and finally step thirteen is the reporting of the results.

Although presented in a linear fashion the process may need to accommodate some iteration. The IVHM-RD is to be used during the start of the design of the IVHM for the UAS and aspects of the UAS, its intended customers, and uses are subject to changes. Changes could have possible effects on which requirements are important to the stakeholders.

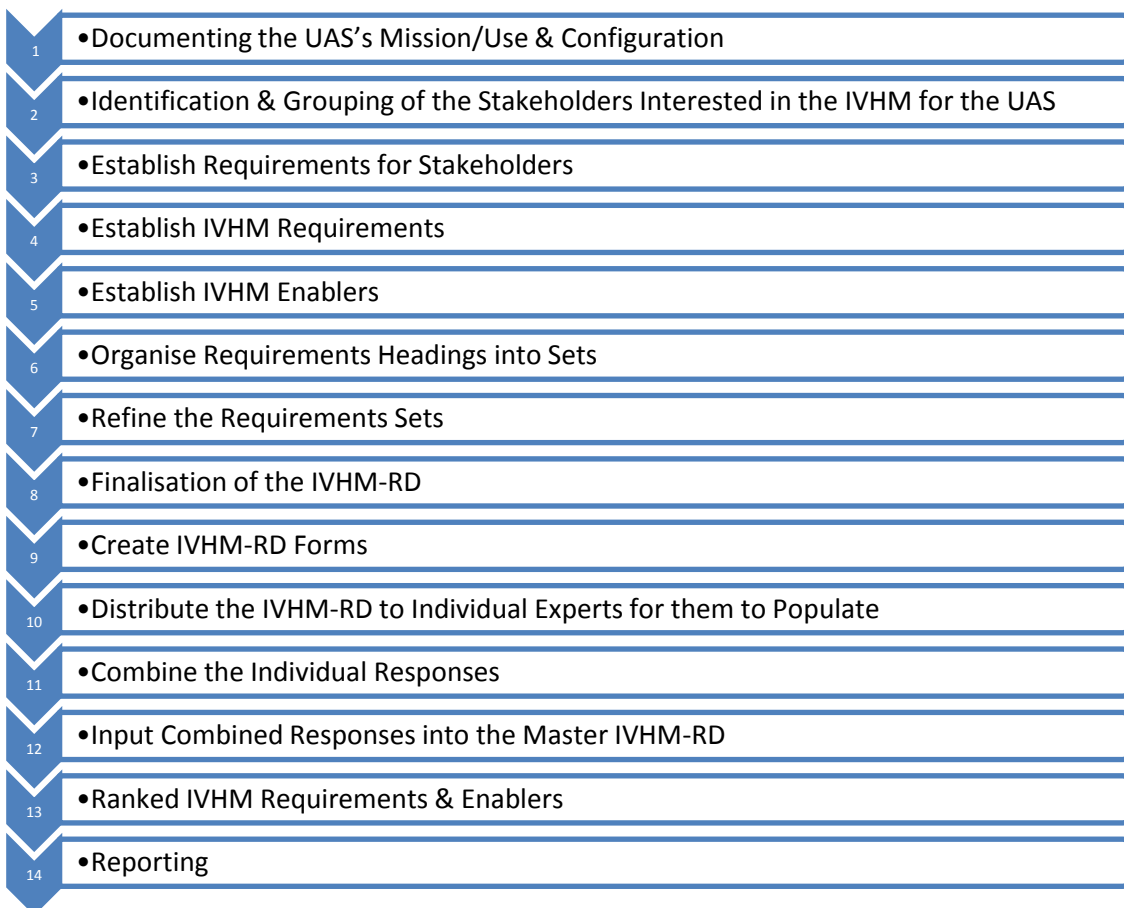


Figure 7-2 Overview of the IVHM-RD Process

Documenting the UAS’s Mission/Use & Configuration

The first step of the process is to gather together and document information on the UAS its context. This information should be about the UAS’s intended use/mission, as well as its type and configuration. Additionally the identification of the customer of the UAS (or services the UAS provides).

Identification & Grouping of the Stakeholders Interested in the IVHM for the UAS

Once the documentation of the context is completed the next step is to identify the stakeholders who are interested in the IVHM for the UAS. Once identified the stakeholders should be grouped together.

Establish Requirements for Stakeholders

Each grouping of stakeholders will have their own requirement for the UAS.

Establish IVHM Requirements

These requirements will be high-level ones relating to the IVHM.

Establish IVHM Enablers

Once the requirements of the IVHM for the UAS have been gathered enablers to those requirements can be established.

Organise Requirements Headings into Sets

Once there are lists of requirements for the stakeholders and the IVHM (and the IVHM enablers) they can be organised into sets.

Refine the Requirements Sets

There are two tasks for refining the requirements sets. First, to make sure that there are no duplicated requirements across sets – this can be in requirement heading, the definitions, terms which could be considered to be too similar and cause confusion (e.g. differentiating between the different types of availability).

Second, to ensure that the IVHM-RD represents the context sufficiently without it becoming too cumbersome. This will save time in the population (for the individuals) and the combination (less relationships to combine). It also prevents irrelevant information from being collected.

Finalisation of the IVHM-RD

This is the stage where the where the requirements sets and flow become fixed, prior to population. Also, during this stage the method of population should be chosen, the most appropriate method of population will depend on the organisation developing the IVHM-RD, and who is contributing to the population.

Create IVHM-RD Forms

Several versions of the forms will be created in this stage, each with a different purpose:

Population Forms – these are the forms which are sent out to be populated by the SMEs. The exact format of the forms will be different depending on the method of population. If choosing to use spreadsheet/paper forms these will have a different construction to those of a web-survey, or dedicated software. The key is to accurately produce the PWC and HoQs in whatever medium, and include the definitions for sets. The advantages using some rather than others e.g. using spreadsheets over paper forms has an obvious advantage during the combination of results.

Master IVHM-RD – this form is the one used to calculate the importance rankings. Once the Population Forms have been completed and combined, the results are put into the Master IVHM-RD. Again this can be produced on paper, but electric formats have the advantage of containing all the equations needed to calculate the importance ranks in each HoQ (and PWC), and the provision to flow the importance rank from the previous HoQ to the next (and the same for the PWC). In addition to establishing the importance ranks for the various requirements sets, the metrics need to be defined for judging the reliability of the results.

Distribute the IVHM-RD to Individual Experts for them to Populate

Depending on the chosen method of population this can be conducted in several ways: distributing spreadsheet/paper forms to the SMEs, sending hyperlinks to surveys, etc.

Combine the Individual Responses

Once the population period is over, the individual responses from the SMEs will be combined together.

Input Combined Responses into the Master IVHM-RD

To calculate the importance ranks for the requirements sets the combined results should be inputted in the Master IVHM-RD. It is in this Master IVHM-RD that all the calculations for the IVHM-RD are conducted.

It is worth noting that developing software which could combine steps nine to twelve could reduce the time needed to create the forms, analyses the results of the population, and aid in the production of documentation.

Data Analysis

The data contained within the IVHM-RD will be analysed and formatted so that it can be useful to the design process. It is also at this stage that the decision whether to gather more information is made, based on the analysis (e.g. a HoQ could have significantly fewer responses than others and the decision to re-issue the forms to more SMEs could be taken).

Reporting

This is the final stage of the process where the relevant documentation and reports are produced.

7.4.1.2 IVHM-RD in the Wider Design

The IVHM-RD is only dealing with a small section of the design of IVHM, which itself is only a part of the design for the UAS. Once IVHM has proved its worth on an aircraft, these high-level requirements of the IVHM-RD will need to be

flowed down to actionable ones[77]. Further analysis of the aircraft and its systems is needed, such as reliability analysis, fault tree analysis, failure modes effects analysis, level of repair analysis, etc. These analyses will provide information to some of the enablers (Failure Mode Knowledge and Availability & Accuracy of Failure Data) and also focus which systems and sub-systems are most problematic to operating and maintaining the aircraft.

The ranked high-level requirements of the IVHM-RD will give focus to which aspects of IVHM are more important to implement on any system (sub-system, comments, etc.) and provide maximum benefit to the stakeholders, thus allowing them to set which requirements are essential and which are desired, and plan resources accordingly during the design. Additional information from the organisation operating the aircraft will be needed (e.g. logistical, concept of operations for the aircraft and fleet) to set requirements around timing (e.g. the time which a prognostic tool can accurately predict the failure of a component so that the logistics and maintenance can react to position the right parts, personnel and tools where they are needed). Also, conducting the IVHM-RD at the start of a programme will get people thinking about the IVHM (and the supportability of the aircraft) from the get go and how it relates to the stakeholders and ultimately the customer.

7.4.2 Other IVHM Designs

The IVHM-RD process can also be adapted other assets (e.g. airliners, power plants). When considering using the IVHM-RD process for other assets the majority of cases will conform to the format of a PWC followed by five linked HoQs (Figure 7-3).

There may be exceptions to the standard PWC and five HoQs format presented in here (just as with the Demon UAS), because an asset could have a different mix of stakeholders and no need for a requirements set (and thus no need for a HoQ) e.g., for a commercial satellite IVHM can be beneficial, but having no routine maintenance and cost and difficulty of sending a manned spaceflight for repairs there is little need for a dedicated maintenance requirements set or maintenance HoQ – similar to the removal of HoQs in the Demon design case.

The operations requirement set could include some maintenance requirements (e.g. reconfiguration of signal paths, software updates) and may feed directly into the IVHM House.

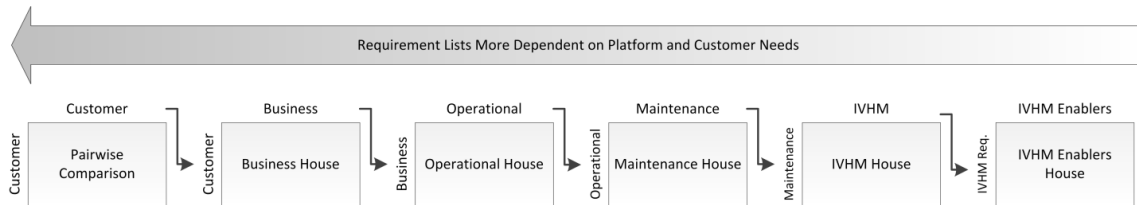


Figure 7-3 General Format of the IVHM-RD Process

Other Complex Stakeholder Problems

It should also be possible to adapt the IVHM-RD to different complex stakeholder problems – i.e. those similar to problem encountered IVHM but in a different domain. It was not the intention of this project to approach the wider problem of analysing the through-life requirements of multiple stakeholders for complex product-service system, and at this stage it is just a postulation. But, due to the modularity and flexibility in the IVHM-RD process it seems likely what it could be applied to other, non-IVHM, problems – though further research will needed to be conducted to see whether or not this is the case.

8 Validation

Validation is necessary for any design research to be accepted by those who it is intended for – this task is simpler said than done. Whereas a model can be referenced against reality to judge whether it is valid (e.g. a model of an aircraft’s aerodynamic performance can be checked against wind tunnel testing, and if further validation is needed against test flights), for design research there needs to be a gradual building up of confidence that the tool (or method, process, etc.) will perform as intended and be of value to the designer. One such way of building confidence has been suggested that a series of trials (similar to medical treatments[93]), however this is impractical due to the time allocated to the project. Another way in which the validation of design research can be conducted is using the Validation Square[81].

8.1 Validation Square

The validation square sets out to validate research using six steps organised into four boxes (Figure 8-1). These six steps can also be organised into two headings: structure validation and performance validation.

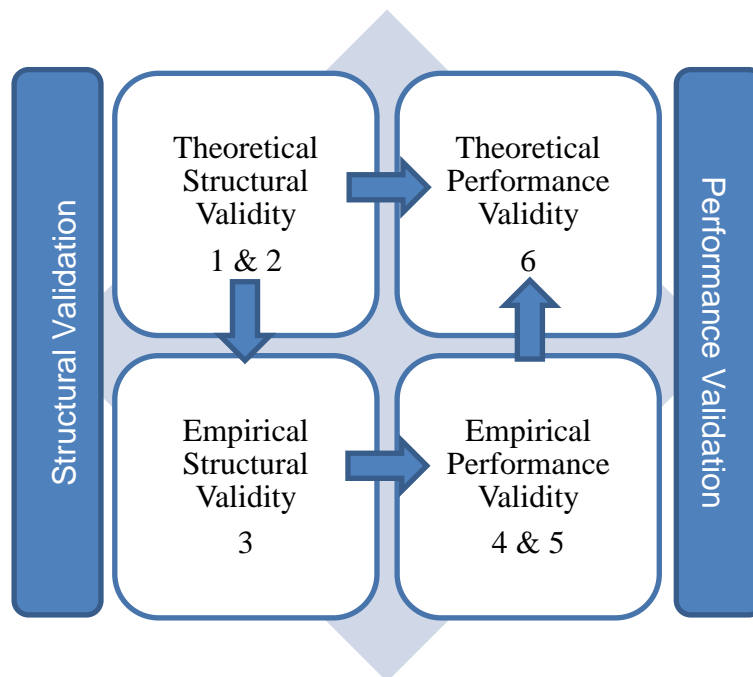


Figure 8-1 The Validation Square

Structural Validation – A Qualitative Process

1. Accepting the construct's validity.
2. Accepting method consistency.
3. Accepting the example problems.

Performance Validation – A Quantitative Process

4. Accepting the usefulness of the method is useful with respect to the example problems.
5. Accepting that usefulness is linked to applying the method.
6. Accepting usefulness of method beyond example problems.

8.1.1 Theoretical Structural Validity

8.1.1.1 Constructs Validity

In order to accept that the construct is valid for the IVHM-RD, then it must be built on established knowledge. This has been done in the literature review.

The IVHM-RD is not simply an adapted use of QFD, there are changes to purpose and population method. There have also been changes made which overcome some of the problems associated with QFD and the population of its forms.

8.1.1.2 Method Consistency

To establish the consistency of the IVHM-RD the design cases and the analysis of them post population are assessed. The analysis of the IVHM-RDs for the design cases shows that there is an internal logical consistency to both. This consistence has allowed the IVHM-RD process to be generalised so that other may use it for other IVHM designs for UAS.

8.1.2 Empirical Structure Validity

To establish the empirical structural validity the two UAS design cases used for when developing the IVHM-RD are assessed to see if they represent typical/real problems. First, the two design cases are well documented, this removes some of the uncertainty as to what the IVHM-RD and its populated forms represent.

Second, the design cases have been created to represent typical problems for UAS designers. The Persistent UAS represents the next generation of UASs, which is being designed and is of similar scale to some current military UAS. The Demon UAS represents the current generation of UASs, which have been produced (constraining the available weight and space for any IVHM on the UA). These cases have been developed from looking at the literature and consultation with members of staff at Cranfield University and BAE Systems to establish their suitability.

8.1.3 Empirical Performance Validity

8.1.3.1 Usefulness

To establish the usefulness of the IVHM-RD to look at the population and the analysis of the results are assessed. First, the IVHM-RD has been applied to the design cases, which are typical problems. This helps to build confidence in the IVHM-RD's ability to solve real problems faced by designers of IVHM for UAS.

Second, the number of SMEs who took part in the population of the IVHM-RD has to be sufficient to represent their opinions. If we look at the numbers in a statistical manner then there are too few (less than thirty) to establish a normal distribution, which would bring into question the reliability of the results. However, this is not the best threshold to judge if the population size is sufficient. Comparing the numbers of SMEs populating the IVHM-RD, this is comparable to numbers when population a QFD[88; 94]. However, with the smaller numbers of SMEs participating in the populations of the IVHM-RDs being able to judge their expertise becomes more important. This has been achieved for the Demon UAS by selecting the SMEs who participated to people who have knowing about both Demon and IVHM. For the Persistent UAS, this was achieved though the demographic questions.

Finally, the analysis of the results from the population can be assessed. The results in this thesis have been analysed at in three ways to provide information of interest to different people. First, the ranked sets of requirements and

enablers have be assessed for both design cases individually – of interest to the designer in those cases. Second, the ranked sets of IVHM requirements and enablers have be compared to assess the similarities and differences between the design cases. Third, the relationships between IVHM requirement and enablers have be assessed to establish the current understanding of them.

8.1.3.2 Usefulness Linked to the IVHM-RD

To establish whether the usefulness is linked to the IVHM-RD the analysis of the results is used again. Though it is possible to just give a person the list of requirements (and enablers) and ask them to rank them in order of importance, this method does not provide the same amount of information as the IVHM-RD does. In addition to the rankings, we also get the raw score, relative percentage, and the percentage of the maximum to help the designer when trading-off the IVHM requirements.

Also, the population method used also allows the analysis into the relationships defined by the group of SMEs. This is something which is not normally possible, as the discussion is not normally recoded in a QFD.

8.1.3.3 Validation Exercise with BAE Systems

A validation exercise was conducted with three members of BAE Systems staff. These members of staff have experience with IVHM and UAS, and have been involved with the project at various times. They are known to have taken part in the population of the Persistent UAS - but their particular responses cannot be traced back to them due to the anonymity within the web survey.

The main purpose of the validation exercise was to help in the establishment of the usefulness of the IVHM-RD and that the usefulness is linked to the use of the IVHM-RD. The meeting also provided an opportunity to ask the question whether or not the tool could be used for other design cases and to gather some feedback of the tool as it is. The participants were presented with the raw populated forms (Figure 6-5, page 124; Figure 6-6, page 124; and the figures of Appendix C), the figures comparing the IVHM requirements and enablers for both UAS and the fast jet (Figure 6-9, page139 and Figure 6-10, page141), and

forms showing the most agreed and most contested (lowest twenty percent and highest twenty percent of the standard deviations for that HoQ) of the IVHM Enablers House for both UAS (Appendix D).

The following are the key points from that meeting:

- Analysis of the information is needed. The raw forms present too much information to the person looking at them. Additionally, presenting part of the information (such as in Appendix D) is useful but does not provide the full picture. It was suggested that the raw forms be analysed to provide the information needed by the design team.
- The ranked sets were useful in prioritising the IVHM requirements and enablers, but it was also commented that any method of ranking requirements would be of use.
- The comparison between the different UAS and fast jet is useful in identifying the differences between the design cases.
- The information about the agreement/disagreement and the number and percentage SMEs participating is useful, and that this information would be useful in identifying the most important relationships between the higher ranked requirements – which you would not get from simply ranking the requirement (and enablers) sets.
- Each participant in the population of the IVHM-RD puts their own independent opinion to the extent that there was “no one looking over their shoulder” influencing their opinions, but their opinion is based on their knowledge and experience from previous work and conversations with other people.
- The length of the IVHM-RD was questioned. The requirements were considered to be self-pruning, those which have been ranked lower could be left out in future IVHM-RDs. The number of HoQ was considered to be a large. For the designers of the IVHM the last two houses are relevant to them, and they would assume that the first HoQs concerning the business and customer would have been already decided if the company has started a project.

Though these HoQ were necessary in developing the IVHM-RD providing the context of the design cases, the author agrees that they are of little relevance to the designers, and it is noted that the SMEs who participated in the population the Persistent UAS's IVHM-RD are primarily associated with the technology, were those who the earlier HoQs are targeted more at those SMEs who are associated with the business. The assumption that the business would have prioritised their requirement before the IVHM will need to be investigated and if true how it can be fed into the IVHM-RD without the need for the earlier HoQ.

- A web-survey may not be the best method of population. It was suggested that a web-form with dropdown boxes to select the relationship may be more suited to the task. It was also suggested that although more useful to the person analysing the IVHM-RD the scale used (blank for no opinion, 0 for a no relationship, 1 for a weak relationship, 2 for a moderate relationship, 3 for a strong relationship) is not best for those filling out the forms. It was suggested that the binary choice of if there is a relationship or not would be best for the participants – but that there may also be a middle ground between the two.
- The IVHM-RD was judged to be suitable for use with other UAS design cases and also for other assets.

8.1.4 Theoretical Performance Validity

To establish that the IVHM-RD is useful beyond the cases which it has been applied to, the previous five steps of the validation square are looked at. Since the IVHM-RD's constructs and method consistency have been validated, along with the design cases, and the application and usefulness of the results, then it can be assumed that the IVHM-RD will be of use for other design cases. In addition to this the validation exercise stated that the IVHM-RD is suited for other design cases.

As mentioned before, validation of research of this nature is a gradual building of confidence. The application of the IVHM-RD will provide more cases and thus more evidence of the validity for being applied new cases.

9 Discussion & Conclusions

9.1 Thesis Summary

This thesis sets out the investigation conducted in how the design of IVHM for UAS can be improved. It presents the specific problem being addressed – that of a complex requirements problem with several stakeholders, who's requirements need to be satisfied by the IVHM, while taking into account the context of the UAS, and limited available information at the start of a design.

It presents a review of the relevant literature relating to the problem, providing the foundation for the research. It then presents how the design cases (the Demon and Persistent UAS), which were used to provide the context for the IVHM-RD process.

The thesis then goes into detail in how the IVHM-RD process was developed, and applied to the design cases. Followed by how the IVHM-RDs for the said design cases were populated with a distributed population method, taking individual populations from SMEs and combining them in a way which captures the amount of agreement between the SMEs and can establish the reliability of the population. The IVHM-RD process is then discussed along with its results which were analysed in the multiple ways to get different information from the data contained within the populated IVHM-RDs. Finally, the IVHM-RD underwent a structured validation exercise.

9.1.1 The IVHM-RD Process Summary

The IVHM-RD process developed, tried, and validated during this PhD project achieves the aims and objectives set – and thus contributed to both the understanding of how IVHM can help a UAS in its intended operation and provide the designer of IVHM for the UAS with useful information. Figure 9-1 is a summarised view of the IVHM-RD process.

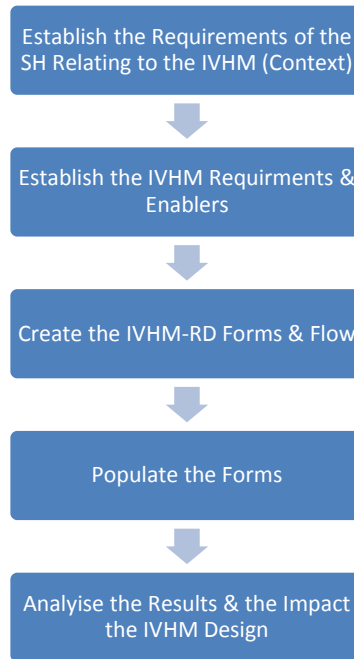


Figure 9-1 Summarised IVHM-RD Process

9.2 Review of Aims & Objectives

The aims of the project were as follows:

- Develop a method which can prioritise the requirements and enablers of IVHM to aid the designer of the IVHM for a UAS.
- To develop the relationship between the customer and mission requirements for a UAS and the requirements of the IVHM for that UAS.

In order to establish whether or not these aims have been achieved we need to look at the objectives. Table 9-1 provides a recap of the objects and whether or not they have been achieved – which they all have. The table also proves some notes as which part of the work goes towards meeting those objectives.

Table 9-1 Achieved Objectives

<i>Objective</i>	<i>Achieved?</i>	<i>Notes</i>
Establish the context which will influence the design of IVHM for UAS.	Yes	Development of the design cases.
Develop a method to relate the stakeholder and mission requirements of a UAS to requirements of the IVHM for that UAS.	Yes	The IVHM-RD Process.
Develop a process to prioritise the requirements and enablers of the IVHM, which can:	Yes	The IVHM-RD Process. Two sub-objectives, which have both been achieved.
a) Efficiently solicit the opinions of stakeholders.	(Yes)	Via the distributed population.
b) Establish the reliability of the opinions of the stakeholders.	(Yes)	Using the reliability metrics.
Apply techniques to UAS design cases.	Yes	Two design cases: Demon UAS & Persistent UAS. Also a manned Fast Jet, primarily for comparison with the other cases
Develop a generalised process which can be used in other design cases.	Yes	A validation exercise of the process has also been conducted.

9.3 Impacts of the Research

This section will discuss the general wider impacts of the results of the IVHM-RD on the different stakeholder groups to IVHM. First, how the results relate the operators, both civil and military will be looked at; second, the implications for the OEMs; third, on the maintainers and the logistics; and finally the implications for IVHM technology providers and designers.

9.3.1 Operators

Operators are ultimately the ones who will have to benefit from any IVHM implemented on an aircraft. Although the focus on the high-level goals of IVHM will be different between operators, there is however an operator or maintainer wants is “no surprises” [95].

Commercial operators will look to see how IVHM relates to the bottom line, as is the case in Table 6-5. It is they who will need to see the increase in availability (allowing them to utilise the aircraft for making profit) and the reduction in maintenance costs. Though not a priority to the business, the increase in safety offered by IVHM will surely be welcomed, and its low importance rank (Table 6-5) could be because an operator would assume the required level of safety has been met through the certification process.

For military operators the increased availability and safety will be more of a concern, over the reduction in the maintenance costs, because as military assets are not run for profit but rather to achieve a strategic goal. This being said there are differences in which UA are treated. There is a view that since there is no pilot on-board a UAs does not need to be as safe as a manned aircraft. Additionally, as there is no life to save a UA may be crashed internally to stop it from falling into enemy hands – where as a commercial operator would not want to lose their asset if it could be helped.

Civil non-profit operators (e.g. police, fire), as the military, do not have a profit motive, although they may be concerned with maintenance costs, as they may be under budgetary constraints. Maximising the availability of the UAS to conduct as many mission/jobs as possible, may be less of a concern, but they could be more concerned with the operational readiness (Table 6-5) of the UAS (e.g. the police sending out the UAS in response to an incident). Safety, however, maybe more of a concern, with operations more likely to take place over populated areas (e.g. traffic policing).

9.3.2 Original Equipment Manufacturers

With IVHM, the OEM can take on greater responsibility for the maintenance, often coupled with availability based contracts. How much responsibility will depend on the service the OEM is offering to the operator. Information flowing from many operators back to the in OEM will allow them to start building up data and knowledge of theirs product. With many of the enablers identified as high and very high importance relating to data and knowledge this can be fed back into the IVHM they provide to optimise and improve it during the life of the

aircraft [62; 76], though the ability to reconfigure the IVHM in service is only seen as moderate to low importance. It also provides them with information to be used in the next generation of aircraft they produce [76]. There is the idea of having an open platform for IVHM (where different suppliers/sub-contractors can work to open standards lessening the need for integrating into the larger IVHM solution) [49], though it is not necessary to implement IVHM and has been refuted in the results as the enabler Standard Data Format as being moderate to low importance. This could be because the participants were only asked to consider the particular aircraft in the IVHM-RD, and not any wider benefits to the organisation designing it – such as the reduced costs [50].

9.3.3 Maintainers and Logistics

The maintainer (whether it is the operator, OEM, or a third party) will have to use information provided by the IVHM, and could be considered the primary response to the IVHM, which has been identified as being of high to very high importance. What information is provided will be dependent on the type of maintenance needed. For Line Replaceable Units (LRU) the maintainer only needed to know which LRU to change. However when the LRU is sent to be repaired, IVHM could aid the process. As well as the benefits mentioned earlier to maintenance which IVHM can provide, IVHM could also help in a No Fault Found (NFF) situation. IVHM can provide those investigating a fault a greater range of detail of the system at the time – operational conditions, health status of other systems, etc.

The ability of IVHM to analyse the health of a fleet can be of great use to both the operator and maintainer of that fleet – reflected in its high ranking in the IVHM-RD. Knowing the health of all aircraft can enable better utilisation of each aircraft, matching capabilities to missions. Also, degradation and failure mode knowledge can be built from the experiences with individual aircraft and then applied to the fleet.

IVHM has an integral relationship with the logistics needed for maintenance – IVHM supplies information needed to have the right parts and tools, in the right place, at the right time. This can allow for opportunistic maintenance to take

place. IVHM can be seen as an enabler to Autonomic Logistics [95], however the results show that the management of spare parts was only of moderate importance, and that the enablers Maintenance Staff Availability and Flexibility in Schedules were ranked as the lowest two – indicating that opportunistic maintenance and improving the logistics is not a high priority for IVHM.

9.3.4 IVHM Technology Providers and Designers

IVHM technology providers (OEM, sub-contractor, etc.) are the ones who will have to provide the systems and sub-systems to meet these requirements. The IVHM-RD provides them with a ranked set high-level IVHM requirements (and enablers) for two cases. When comparing these two cases with the ideal IVHM system [11] we can see that the high importance rankings for Prognostic Analysis, Diagnostic Analysis, and Fleet Analysis. Implementing these aspects of IVHM will be highly beneficial in all the benefits classes (mission availability, mission effectiveness, mission capability, design paradigm) presented in the ideal IVHM system. This gives clear direction for technology suppliers to take when developing technology. The differences between the two cases do confirm that IVHM will be different from vehicle to vehicle [49], but also that the operational and business context has an impact.

Although there will be differences between the overall IVHM solution for a vehicle, systems and sub-systems will be common across aircraft and the methods for monitoring them will be common between them (e.g. engines [5], structures [6]). This could allow system/sub-system providers to create built-in health monitoring for the system/sub-system they have designed, which then can be integrated into the IVHM for the aircraft. Of course any health monitoring for that system/sub-system must meet the requirements, but the ranked high-level requirements provided by the IVHM-RD can be a starting point for any such capability – again, the use of standards would aid this.

This analysis has looked at the high-level requirements of IVHM for both a UAS and a Fast Jet, and how they were ranked according the IVHM-RD. These ranked sets have identified which high-level IVHM requirements (and enablers) are important in each case. As with all projects the designers of IVHM are

working to budget and time constraints, and for new aircraft they are within a larger design process. IVHM (along with other supportability) is often seen as a lower priority than other aspects of the design, often only being considered in the later stages (bringing with it impacts on life-cycle costs). Designing IVHM for legacy aircraft is slightly different; the problems have been identified while it is in use. But with both cases it can come down to a cost benefit analysis, for new designs whether the spending on IVHM will bring greater benefit compared other areas of design (e.g. improving the reliability of components, improving the performance) and for legacy whether introducing IVHM will improve the operating of that aircraft (and the fleet) compared to the status quo. The rankings in this paper can be used as a starting point for any cost-benefit analysis – allowing an analysis or simulation to be tailored (weighted) to include which aspects of IVHM are most important to the aircraft and stakeholders for that particular case.

Once IVHM has proved its worth on an aircraft, these high-level requirements of the IVHM-RD will need to be flowed down to actionable ones [77]. Further analysis of the aircraft and its systems is needed, such as reliability analysis, fault tree analysis, failure modes effects analysis, level of repair analysis, etc. These analyses will provide information to some of the enablers (Failure Mode Knowledge and Availability & Accuracy of Failure Data) and also focus of which systems and sub-systems will most problematic to operating and maintaining the aircraft. The ranked high-level requirements of the IVHM-RD will give focus to which aspects of IVHM are more important to implement on any system (sub-system, comments, etc.) to provide maximum benefit to the stakeholders, thus allowing them to set which requirements are essential and which are desired, and plan resources accordingly during the design. Additional information from the organisation operating the aircraft will be needed (e.g. logistical, concept of operations for the aircraft and fleet) to set requirements around timing (e.g. the time which a prognostic tool can accurately predict the failure of a component so that the logistics and maintenance can react to get right parts, personnel and tools are where they are needed). Also, conducting the IVHM-RD at the start of a programme will get people thinking about the IVHM (and the supportability of

the aircraft) from the get go and how it relates to the stakeholders and ultimately the customer.

9.4 Future Work

Future work relating to this project can be split into several categories, each with subcategories, these categories are: use of the IVHM-RD on other design cases, further development of the IVHM-RD, and adaptation for other complex stakeholder problems.

9.4.1 Use of the IVHM-RD on other Design Cases

The IVHM-RD can be applied to other UAS which IVHM is being designed for. However, instead of creating the design cases, as was the case for this project, it would be better to involve a 'real' UAS. This could be one which is in development, allowing to see how the IVHM interacts with the rest of the design process, or a UAS currently being operated – which will have established maintenance problems, costs, etc. Either way, using real UAS will provide further validation of the IVHM-RD and allow researchers to see how effective it is in solving a real world problem. There would also be benefit in looking at different UAS and modes of operation (e.g. a quad-copter UAS for a television/film production company) to see if the trends which have been indicated in the comparison of the ranked IVHM requirements and enablers hold for different UAS.

In addition to being applied to different UAS, the IVHM-RD could also be applied to different assets (e.g. passenger airlines, ships, trains, power plants). As the process builds the context of an asset into the IVHM-RD it should be able to be used with different assets which could benefit from IVHM.

9.4.2 Further Development of the IVHM-RD

As mentioned in the Discussion chapter, there are some improvements to the IVHM-RD which could be made, given time to investigate them. There are several rooms which could be added to the HoQs which could enhance the

information provided by the IVHM-RD, and also other possible forms which could be used.

9.4.2.1 Integration with Design Processes

The IVHM-RD process in this thesis currently stands alone and it will need to be tied into the general IVHM design process. Additionally, the general IVHM design process needs to be tied into the overall design process for UAS (and also for other assets).

9.4.2.2 The IVHM-RD as a Product

The IVHM-RD could be developed as a product which could then be used by designers of IVHM for UAS (or other assets). The product would essentially guide the designer through creation of the IVHM-RD and its population, and also combine the results and produce figures/reports automatically.

9.4.3 Adaptation for Other Complex Stakeholder Problems

It could also be possible for the IVHM-RD to be applied to other complex stakeholder problems. Although, these problems will need identifying and the IVHM-RD adapting to the specifics and natures of them (least of all a change in name).

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A. UAS Design Cases

UAS Architecture

Although the focus of the project is on the IVHM systems the UAs (i.e. the aircraft itself), and not the rest of the UAS, it is important to note the entire system, as the respective IVHM systems will have impacts on the entire UAS, not just the UA (e.g. mission monitoring and control conducted from the ground control station).

The architecture for the Persistent UAS is going to be assumed to follow the generic UAS architecture established by the ASTRAEA project[17], Figure 2-1, page 31.

The DEMON UAS will also be assumed to conform the “GCS” (ground control station) and “Aerodrome Infrastructure” parts of Figure 2-2, but not the “UA” part.

Description of the UASs

This section of the thesis displays various aspects of the two UASs side by side in table format, for ease of comparison. The information for the DEMON UAS is presented on the left and the Persistent UAS on the right.

Mission

Table 9-2 Mission Comparison

DEMON UAS	Persistent UAS
Technology Demonstrator Demonstrate various technologies resulting from the FLAVIIR Project. Operates in segregated airspace.	Crop Monitoring Monitoring a given area of vegetation for a 48 hour period. Capable of operating in all classes of airspace (A, B ⁶ , C, D, E, F, G).

Airframe

Table 9-3 Airframe Comparison

DEMON UAS	Persistent UAS
Blended wing body. Diamond shaped wings, single tail with rudder.	Conventional configuration. High aspect monoplane wings.

Mission Payloads

Table 9-4 Mission Payloads Comparison

DEMON UAS	Persistent UAS
Test equipment.	EO/IR turret. Ground looking Radar/LiDAR.

⁶ There is no class B airspace within the UK, but the Persistent UAV should be about to operate in it.

Guidance and Control

Table 9-5 Guidance and Control Comparison

DEMON UAS	Persistent UAS
Partial autonomous capability. Novel fluidic flight controls.	Full autonomous capability. Conventional control surfaces.

Launch

Table 9-6 UAS Launch Type Comparison

DEMON UAS	Persistent UAS
Conventional wheeled take off.	Conventional wheeled take off.

Recovery

Table 9-7 UAS Recovery Comparison

DEMON UAS	Persistent UAS
Conventional wheeled landing.	Conventional wheeled take off.

Specification

Table 9-8 UAS Specification Comparison

DEMON UAS	Persistent UAS
Power Plant	
One turbojet.	Two turboprops.
Dimensions	
<i>Wing Span</i>	
2.53 m[96]	15 m
<i>Wing Area</i>	

3.13 m ² [96]	7.5 m ²
<i>Aspect Ratio</i>	
2.047[97]	30
Weights	
<i>Maximum Take-off Weigh</i>	
70 kg[96]	1175 kg
<i>Payload Weight</i>	
8.5 kg[96]	Maximum 400 kg ⁷
Performance	
<i>Speeds</i>	
70 – 150 knt[98]	40 – 210 knt
<i>Ceiling Height</i>	
Within line of sight. ⁸	20,000 ft
<i>Operational Range</i>	
Within line of sight. ⁸	Maximum 300 km ⁷
<i>Endurance</i>	
~20 minutes	48 hours

⁷ As to comply with the MTCR (Missile Technology Control Regime)

⁸ The DEMON UAV has to be operated within line of sight for a human operator to perform “see and avoid” activities for the aircraft.

Life Cycle Stage

The DEMON and Persistent UAS are at different stages in their respective life cycles (Figure 9-2). Due to the two UASs being at different life cycle stages there will have to be slightly different approaches to the design of their IVHM systems.

The DEMON UAS has been designed and built, and is now currently in the “operation and support” stage of its life cycle. With the DEMON UAS being part way through its life cycle, and the IVHM system being retrofitted on, this will impact on areas such as: the design of the IVHM system (constraining the design space), the cost benefit analysis over the (remaining stages of) life cycle, and the established operation pedicures associated with the DEMON UAS.

The Persistent UAS is in the “design” stage of its life cycle. With the Persistent UAS in the design stage this allows IVHM system to be truly integrated from the start of the design process, instead of partway through. With the preliminary sizing of the Persistent UAS now complete past Cranfield University aerospace design projects (ones designing UASs) can be reviewed to assess if they are suitable to be used and adapted to suit the needs of the Persistent UAS within the context of the project.

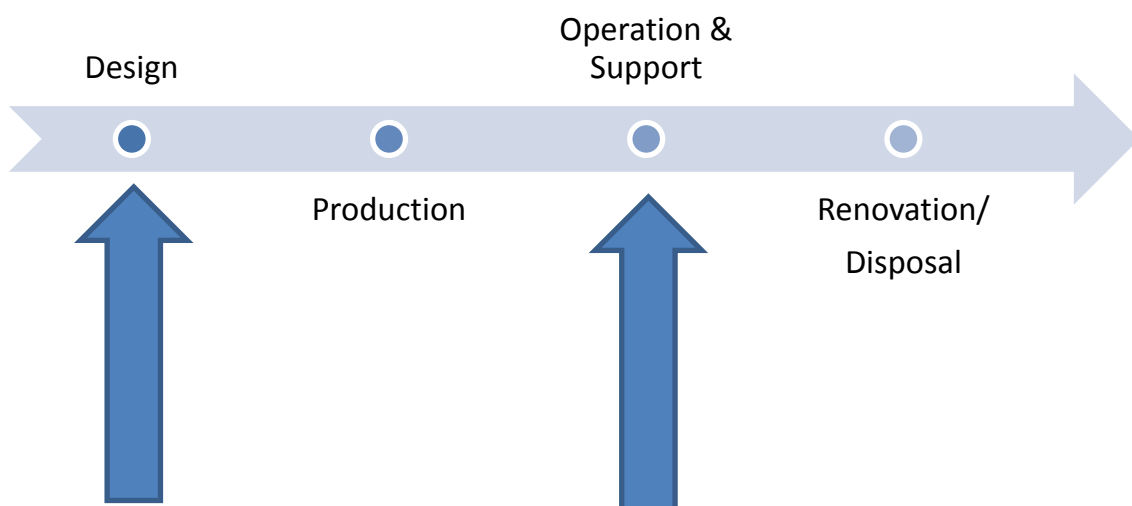


Figure 9-2 The Current Life Cycle Stages of the Two UASs.

Regulations

This section compares the regulations that are applied to the UASs (Table 9-9).

In the DEMON UAS's case it is the regulations that it has already been designed too: CAP 722 and VLA (Very Light Aeroplanes)[96].

The regulatory body that would be in charge of certifying the Persistent UAS depends on its use, as it is over 150 kg[33]. If they Persistent UAS is being used in a commercial roll (e.g. monitoring farm crop growth and condition) then it fall under EASA regulation. Additional if it is being used in a scientific research roll (e.g. monitoring forest growth and condition) it would fall under the CAA regulation.

In order to ascertain what airworthiness certification specifications should be applied, to the Persistent UAS, the CAA's method of assessing the kinetic energy of a two crash scenarios and then relating that kinetic energy the equivalent manned aircraft certification specifications was used. This method indicated that a combination of CS 23 should be use, with possible referrals to CS 29. Additionally to the airworthiness certification specifications the Persistent UAS must be compliant with the Missile Technology Control Regime (MTCR)[99]. The main constraints which apply to the Persistent UAS is the limiting of the payload to less than 500 kg and limiting of the range to less than 300 km (~186 mi).

Table 9-9 Regulation Summary

DEMON UAS	Persistent UAS
<i>Regulating Body</i>	
UK CAA.	UK CAA. EASA.
<i>Certification Specifications</i>	
CAP 722. VLA.	CAP 722. CS 23. MTCR.

Mission Profiles

This section shows the basic mission profiles for both the DEMON UAS and the Persistent UAS. These basic mission profiles can be used as base of reference for alternate mission profiles/scenario. The mission profiles shown are not to scale.

DEMON UAS Mission Profile

The DEMON UAS only has on real mission: to conduct test flights.

1. Engine start and warm up.
2. Taxi.
3. Take-off.
4. Climb.
5. Cruise.
6. Decent.
7. Landing, taxi and shutdown.

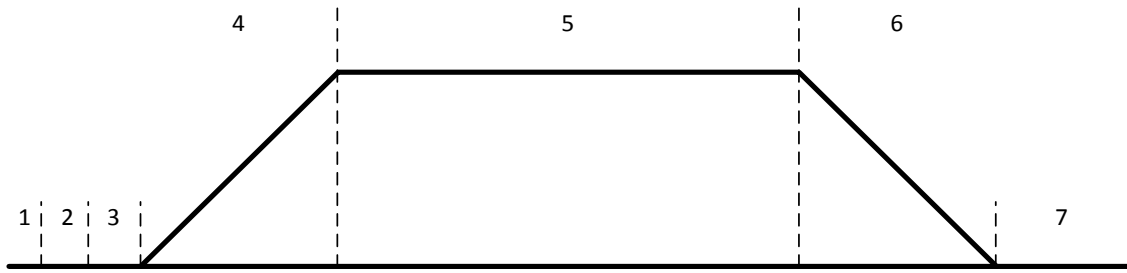


Figure 9-3 DEMON UAS Mission Profile

Persistent UAS Mission Profiles

For the Persistent UAS there have been two basic mission scenarios created: crop monitoring, and flying to a destination. Both of these have had a contingency of a 50 mile flight to an alternate landing site (coloured red on the mission profiles).

Crop Monitoring

Monitoring of given area of vegetation (e.g. field) for a 48 hour period.

1. Engine start and warm up.
2. Taxi.
3. Take-off.
4. Climb.
5. Cruise to field.
6. Loiter – Crop monitoring 48 hours.
7. Cruise from field.
8. Decent.
9. Landing, taxi and shutdown.
10. Climb.
11. Cruise to alternative landing site within 50 mile range.
12. Decent.

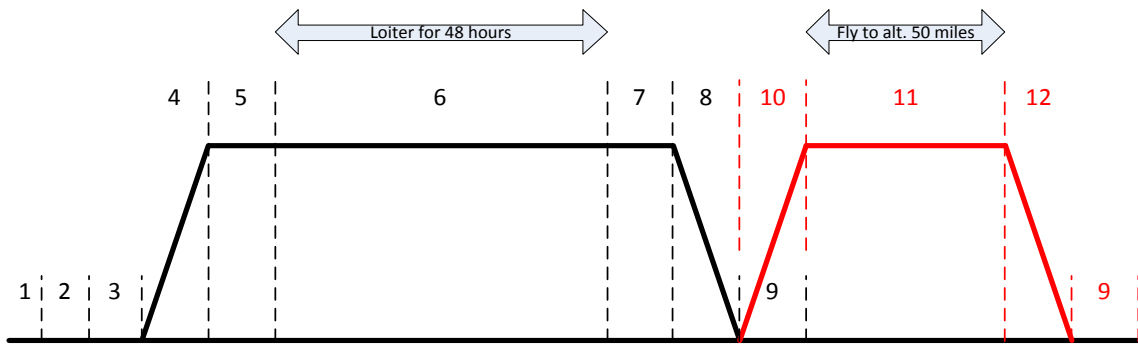


Figure 9-4 Persistent UAS Crop Monitoring Mission Profile

Fly to Destination

Flying from one point to another (e.g. airfield).

1. Engine start and warm up.
2. Taxi.
3. Take-off.
4. Climb.
5. Cruise.
6. Decent.
7. Landing, taxi and shutdown.
8. Climb.
9. Cruise to alternative landing site.
10. Decent.

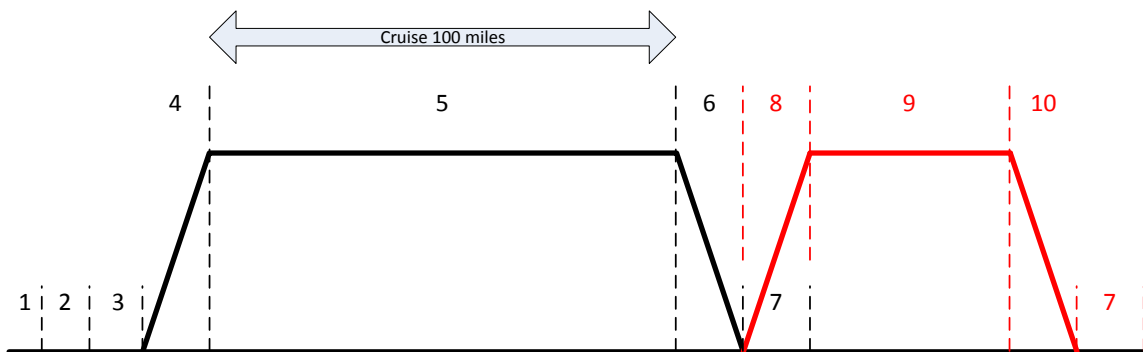


Figure 9-5 Persistent UAS Fly to Destination Mission Profiles

B. Requirements Glossary

The DEMON UAS

DEMON Research Programme Criteria

- **Low Cost UAS**
 - **Acquire**
 - The cost incurred to acquire the DEMON UAS.
 - **Operate**
 - The cost incurred during operation of the DEMON UAS.
- **Low Maintenance Technologies**
 - Research into low maintenance technologies.
- **Non-conventional Flight Control**
 - Research into non-conventional flight technologies.
- **Technology Integration**
 - Research into the integration of technologies into one DEMON UAS (could be low maintenance technologies, non-conventional flight controls, or other technologies).
- **Research Impact**
 - **Originality**
 - The originality of the research being carried out on the DEMON UAS.
 - **Academic Quality**
 - The quality of the research to academia.
 - **Business Quality**
 - The quality of the research to business.
- **Educational Tool**
 - The use of the DEMON UAS as an aide to educating students.
- **Publicity Tool**
 - The use of the DEMON UAS as a publicity tool (for Cranfield University and BAE Systems).

Experiment Capability

- **Mission/Experiment**
 - **Collect Operational Data**
 - The ability to collect and store data on the operation of the DEMON UAS.
 - **Collect Operating Conditions**
 - The conditions the DEMON UAS is being operated in.
 - **Monitor Performance**
 - The ability to monitor the performance of the DEMON UAS (e.g. fuel consumption, flight speeds).

- **Capture Experimental/Test Data**
 - The ability to collect and store data on the experiments being conducted on the DEMON UAS.
- **UAS Ease of Operation**
 - How easy the unmanned aerial system is to operate.
- **Demon Availability**
 - **Time Between Reconfigure/Mod.**
 - The time it takes to change the DEMON UAS from one configuration to another, or to modify/make alterations to the configuration,
 - **Per-Flight/Experiment Checks**
 - The checks and inspections needed to ensure that the DEMON UAS is ready and safe to fly and conduct the experiments.
 - **Unscheduled Maintenance**
 - Any maintenance actions which are not planned.
 - **Repair Time**
 - The time it takes to repair the DEMON UAS.
- **Resource Availability**
 - **Availability of Spares/Parts**
 - The availability of any spare parts, or alternate parts needed for maintenance of reconfiguration of the DEMON UAS.
 - **Staff Availability**
 - The availability of Cranfield University's staff and students.
 - **Tool/Equipment Availability**
 - The availability of any tools, jigs, equipment needed to maintain or modify the DEMON UAS.
 - **Lab/Workshop Availability**
 - The availability of a suitable workspace to maintain or modify the DEMON UAS. The suitability of the workspace is dependent on the complexity of the maintenance/modification.

The Persistent UAS

Flight Service Costs

A breakdown of the costs for an unmanned aerial system conducting a flight/mission service which a customer would be interested in, taken from reference [86].

- **UAS Use**
 - Cost to the Flight Service Mission for the use of the UA (unmanned aircraft) i.e. the aircraft is part of the UAS (unmanned aerial system).
- **Ground Equipment Use**
 - Cost to the Flight Service for use of the associated Ground Equipment (e.g. Control Station) for the UA.
- **Insurance**
 - Cost of the all Insurance to the Flight Service (e.g. Public Liability)
- **Flight Consumables**
 - Cost of Consumables used during the sortie(s) of the UAS during the Flight Service (e.g. Fuel)
- **Communication Services**
 - Cost of the Communication Services used During the Flight Service e.g. CS to UAS, payload data.
- **Facilities Use**
 - Cost of the use of Facilities for the Flight Service e.g. (Landing Fees).
- **Labour**
 - Cost of Burdened Labour to the Flight Service (e.g. UA-P, maintenance crew).
- **Transportation**
 - Cost of Transportation of the UAS to and from the location of the Flight Service (not during a Sortie) (e.g. road freight costs, cost of flying the UA to the location).
- **Other Material & Services**
 - e.g. Spare Parts, Security Contracts
- **Per Diem & Related Costs.**
 - e.g. Cost of Accommodation for Labour at the Flight Service Location.

Business Requirements

- **Availability**
 - The ratio of up time to total time (up time plus down time).
- **Documentation and Standards**
 - **Design Documentation**
 - Documentation produced during the design process
 - **Operational Documentation**
 - Documentation needed for and produced during operation
 - **Maintenance Documentation**

- Documentation needed for and produced during maintenance
- **System Ease of Operation**
 - How easy the system is to operate
- **Total Cost of Operation**
 - The total cost of operating the UAS
- **Safety**
 - The condition of being protected from or unlikely to cause danger, risk, or injury.
- **Marketing**
 - The action or business of promoting and selling products or services, including market research and advertising
- **Innovation Leadership**
 - The ability to develop new novel technologies and development into products.
- **Legislation**
 - The laws applicable to the design, manufacture and operation of the unmanned aerial system.

Operational Requirements

- **System Downtime**
 - The amount of time the system is unavailable.
- **Platform (UAS) Reliability**
 - The reliability of the unmanned aerial system as a whole (the aircraft and all other equipment needed to fly the aircraft, e.g. control station)
- **Mission Success**
 - Whether the mission/fight service has been completed as planned.
- **Demand of Personnel**
 - The number of personnel and the hours they are required for to operate the unmanned aerial system.
- **Readiness**
 - **Deployability**
 - The time taken to get the unmanned aerial system from where it currently is (e.g. storage) to where the flight/mission service is to take place (on station).
 - **Time to Take-Off**
 - The time it takes to get the unmanned aerial system is ready for take-off when it is on station/

Maintenance Requirements

- **Spares**
 - Spare parts and their location
- **Fault Detection Reliability**
 - **Fault Detection Rate**
 - The percentage of faults detected when there is a fault.
 - **False Positive Alarm Rate**
 - The percentage of faults detected when there is no fault.
 - **False Negative Alarm Rate**
 - The percentage of no fault detected when there is a fault.
- **Repair Reliability**
 - The reliability of any repair work conducted.
- **Mean Time Between Removal**
 - The average time it takes to remove a faulty component or part, from the unmanned aerial vehicle.
- **Mean Time To Repair**
 - The average time it takes to repair the unmanned aerial vehicle.
- **Average Turnaround Time**
 - The average time needed for loading, unloading, and servicing.
- **Average Delayed Time**
 - **Technical**
 - The average time the unmanned aerial vehicle is delayed due to a technical issue (e.g. maintenance action)
 - **Logistic**
 - The average time the unmanned aerial vehicle is delayed due to a logistical issue (e.g. waiting for a spare part)
- **Repair Level**
 - The location which the repair needs to take place (e.g. side of runway, in a hanger/under cover, main repair base, etc.)
- **Mean Time To Diagnose**
 - The average time it takes to diagnose a problem with the unmanned aerial vehicle
- **Personnel Required**
 - The maintenance personnel required to perform maintenance actions.
- **Auxiliary Equipment**
 - Any equipment needed for the maintenance of the unmanned aerial vehicle (e.g. specialist tools, jigs, winches)

- **Frequency of Scheduled Maintenance**
 - The frequency maintenance of the unmanned aerial system been planned (aka: planned maintenance).

IVHM Requirements

- **Performance Indicators**
 - **Measurable features that can be used (on their own or in combination) to assess the condition of the vehicle, system, sub-system, or component.**
- **Sensitivity**
 - **“Measure of how sensitive a technique is to input changes or external disturbances. Can be assessed against any performance metric of interest.”[100]**
- **Conditioning of Data**
 - **Manipulation of the data to make it more manageable or useful.**
- **Store Data**
 - **Ability to store and access data from the IVHM system.**
- **Transfer Data within the Vehicle**
 - **The ability to transfer data between systems within the vehicle.**
- **Transfer Data from the Vehicle**
 - **The ability to transfer data between the vehicle and other systems external to the vehicle.**
- **Diagnostics Analysis**
 - **The ability to accurately use diagnostic tools on the vehicle and its systems.**
- **Prognostics Analysis**
 - **The ability to accurately use prognostic tools on the vehicle and its systems.**
- **Fleet Analysis**
 - **The ability to accurately use diagnostic and prognostic tools on the fleet of vehicles.**
- **Response to the IVHM**
 - **Measures put in place to react to a fault or impending failure detected by the IVHM system. The response can be fully automated or a procedure to be followed by the aircrew or maintenance personnel.**
- **Management of Spare Parts**

- Services which comprise the necessary activities to supply and store spare parts.
- **Reconfigure IVHM in Service**
 - Capability to reconfigure, change, or add capabilities to an IVHM system during the life cycle of the vehicle.

IVHM Enablers

- **Degradation Traceability**
 - Ability to detect degradation in a component, part, or system.
- **Detectability of Impending Failure**
 - Ability to detect a failure before the failure happens.
- **Performance Monitoring**
 - Ability to monitor the performance of the aircraft.
- **Standard Data Format**
 - A standardized format that the data must conform to.
- **Availability of Communications**
 - The amount of bandwidth available for the vehicle to send information off board.
- **Accuracy and Precision of Captured Data**
 - Accuracy and precision of the data use as input for the IVHM system captured through different sensors.
- **Availability and Accuracy of Historical Maintenance Data**
 - Information held (e.g. maintenance reports, databases) on the maintenance history of the individual and fleet of aircraft.
- **Availability and Accuracy of Operational Data**
 - Information on the operation of the aircraft (e.g. mission logs, weather conditions).
- **Availability and Accuracy of Failure Data**
 - Information held on failures which have accrued.
- **Failure Mode Knowledge**
 - Information pertaining to all known failure modes (e.g. symptoms, consequences, etc.)
- **Maintenance Staff Availability**
 - The availability of maintenance staff to carry out maintenance actions.
- **Flexibility of Schedules**
 - The amount of leeway in current schedules for the aircraft.

C. Populated IVHM-RD Forms

		Business Requirements									
		Importance Rank	Availability	Depth of Maintenance Documentation	System Ease of Operation	Total Cost of Operation	Safety	Marketing	Sustain Innovation Leadership	Compliance with Legislation	
Costs	Operating Costs	Cost of Fuel	5	0.83 (1.17) [6] (75%)	0.00 (0.00) [7] (88%)	0.00 (0.00) [7] (88%)	9.00 (0.00) [8] (100%)	0.14 (0.38) [7] (88%)	2.43 (3.15) [7] (88%)	0.86 (1.07) [7] (88%)	0.29 (0.49) [7] (88%)
		Cost of Consumables (excl. Fuel)	2	0.83 (1.17) [6] (75%)	0.14 (0.38) [7] (88%)	0.00 (0.00) [7] (88%)	8.25 (2.12) [8] (100%)	0.29 (0.49) [7] (88%)	1.57 (1.40) [7] (88%)	1.43 (1.51) [7] (88%)	0.14 (0.38) [7] (88%)
		Depreciation of the Asset	4	2.00 (3.94) [5] (63%)	2.00 (3.63) [6] (75%)	0.50 (0.55) [6] (75%)	6.75 (3.11) [8] (100%)	1.67 (3.61) [6] (75%)	1.43 (1.51) [7] (88%)	0.86 (1.46) [7] (88%)	0.50 (1.22) [6] (75%)
		Cost of Aircrew	2	3.60 (4.93) [5] (63%)	0.17 (0.41) [6] (75%)	3.88 (4.36) [8] (100%)	7.13 (3.56) [8] (100%)	0.86 (1.46) [7] (88%)	0.33 (0.52) [6] (75%)	0.00 (0.00) [6] (75%)	2.71 (4.31) [6] (75%)
		Cost of Mission Planning	1	3.00 (4.65) [6] (75%)	0.50 (1.22) [6] (75%)	2.25 (3.11) [8] (100%)	5.25 (4.06) [8] (100%)	0.88 (1.36) [8] (100%)	0.67 (1.21) [6] (75%)	0.17 (0.41) [6] (75%)	1.00 (1.55) [6] (75%)
		Cost of Insurance	2	0.60 (1.34) [5] (63%)	1.50 (3.67) [6] (75%)	1.00 (1.55) [6] (75%)	5.25 (4.06) [8] (100%)	3.14 (4.14) [7] (88%)	0.67 (0.52) [6] (75%)	0.00 (0.00) [6] (75%)	4.00 (4.10) [6] (75%)
		Cost of Communications	1	1.00 (1.55) [6] (75%)	0.43 (1.13) [7] (88%)	2.00 (3.12) [8] (100%)	5.25 (4.06) [8] (100%)	1.43 (3.36) [7] (88%)	2.00 (3.27) [6] (75%)	0.83 (1.17) [6] (75%)	0.17 (0.41) [6] (75%)
		Cost of Ground Equipment	2	1.20 (1.64) [5] (63%)	0.67 (1.21) [6] (75%)	4.00 (4.24) [8] (100%)	8.00 (2.83) [8] (100%)	0.00 (0.00) [6] (75%)	0.83 (1.17) [6] (75%)	1.14 (1.35) [7] (88%)	0.50 (1.22) [6] (75%)
	Maintenance Costs	Cost of Maintenance Facilities	4	3.50 (4.42) [6] (75%)	3.17 (4.54) [6] (75%)	2.00 (3.12) [8] (100%)	7.25 (3.28) [8] (100%)	0.57 (1.13) [7] (88%)	0.50 (0.55) [6] (75%)	0.71 (1.11) [7] (88%)	2.17 (3.54) [6] (75%)
		Cost of Parts	3	5.00 (3.83) [7] (88%)	1.50 (3.67) [6] (75%)	1.86 (3.34) [7] (88%)	8.25 (2.12) [8] (100%)	0.57 (1.13) [7] (88%)	1.17 (1.47) [6] (75%)	1.00 (1.00) [7] (88%)	0.86 (1.46) [7] (88%)
		Cost of Labour	2	4.67 (3.44) [6] (75%)	2.71 (3.09) [7] (88%)	2.57 (3.21) [7] (88%)	8.25 (2.12) [8] (100%)	0.57 (1.13) [7] (88%)	2.33 (3.44) [6] (75%)	1.29 (1.25) [7] (88%)	3.43 (4.04) [7] (88%)
		Cost of Delivery and Storage of Parts	3	4.14 (3.44) [7] (88%)	2.14 (3.34) [7] (88%)	0.57 (1.13) [7] (88%)	4.75 (3.62) [8] (100%)	0.57 (1.13) [7] (88%)	0.67 (1.21) [6] (75%)	0.71 (1.11) [7] (88%)	0.00 (0.00) [6] (75%)
	Deployment Costs	Cost of the Transportation of the Aircraft	1	1.40 (1.52) [5] (63%)	0.00 (0.00) [6] (75%)	0.50 (0.55) [6] (75%)	4.75 (3.62) [8] (100%)	0.00 (0.00) [6] (75%)	0.83 (1.17) [6] (75%)	0.50 (0.55) [6] (75%)	0.67 (1.21) [6] (75%)
		Cost of the Use of Facilities at Destination	1	2.57 (3.21) [7] (88%)	0.67 (1.21) [6] (75%)	1.75 (3.11) [8] (100%)	6.25 (3.85) [8] (100%)	1.71 (3.40) [7] (88%)	1.50 (3.67) [6] (75%)	0.17 (0.41) [6] (75%)	2.14 (3.34) [7] (88%)
		Cost of Deploying Personnel	1	2.71 (3.09) [7] (88%)	0.50 (1.22) [6] (75%)	1.25 (1.49) [8] (100%)	6.25 (3.85) [8] (100%)	1.71 (3.40) [7] (88%)	0.67 (1.21) [6] (75%)	0.17 (0.41) [6] (75%)	1.67 (3.61) [6] (75%)
Raw Score			87.32	41.55	63.98	231.38	38.40	37.10	21.02	59.17	
Raw Percentage			15.06%	7.16%	11.03%	39.90%	6.62%	6.40%	3.63%	10.20%	
Percentage of Maximum			37.74%	17.96%	27.65%	100.00%	16.60%	16.03%	9.09%	25.57%	
Importance Rank			2	1	2	5	1	1	1	2	

Figure 9-6 Populated Persistent UAS Business House

		Operations Requirements					
		System Downtime	Platform Reliability	Mission Success Rate	Demand of Personnel	Deployability	Operational Readiness
Business Requirements	Availability ²	8.14 (2.27) [7] {100%}	8.00 (2.45) [6] {86%}	3.17 (3.13) [6] {86%}	1.67 (1.03) [6] {86%}	4.43 (3.21) [7] {100%}	9.00 (0.00) [7] {100%}
	Depth of Maintenance ¹	5.50 (3.99) [6] {86%}	5.50 (3.99) [6] {86%}	2.17 (1.33) [6] {86%}	4.50 (3.67) [6] {86%}	5.60 (4.67) [5] {71%}	5.17 (4.31) [6] {86%}
	Documentation						
	System Ease of Operation ²	2.60 (3.78) [5] {71%}	2.00 (1.41) [5] {71%}	5.71 (4.19) [7] {100%}	5.40 (3.29) [5] {71%}	4.40 (4.34) [5] {71%}	5.67 (3.72) [6] {86%}
	Total Cost of Operation ⁵	5.50 (3.99) [6] {86%}	7.29 (2.93) [7] {100%}	3.67 (4.27) [6] {86%}	4.33 (3.72) [6] {86%}	2.33 (3.44) [6] {86%}	4.83 (4.58) [6] {86%}
	Safety ¹	0.20 (0.45) [5] {71%}	3.43 (2.70) [7] {100%}	1.00 (1.22) [5] {71%}	3.33 (4.41) [6] {86%}	4.80 (4.02) [5] {71%}	4.80 (4.02) [5] {71%}
	Marketing ¹	3.00 (3.67) [5] {71%}	3.00 (3.29) [6] {86%}	5.57 (4.39) [7] {100%}	4.20 (4.55) [5] {71%}	2.50 (3.51) [6] {86%}	3.50 (4.42) [6] {86%}
	Sustain Innovation Leadership ¹	1.67 (1.51) [6] {86%}	1.67 (1.51) [6] {86%}	4.20 (4.55) [5] {71%}	2.00 (1.41) [5] {71%}	3.00 (3.67) [5] {71%}	3.00 (3.67) [5] {71%}
Compliance with Legislation ²	1.67 (1.51) [6] {86%}	1.00 (1.10) [6] {86%}	1.40 (1.52) [5] {71%}	3.40 (3.29) [5] {71%}	3.17 (3.13) [6] {86%}	2.83 (3.25) [6] {86%}	
Raw Score	59.35	70.02	49.03	49.83	45.22	69.97	
Raw Percentage	17.28%	20.39%	14.28%	14.51%	13.17%	20.37%	
Percentage of Maximum	84.76%	100.00%	70.02%	71.17%	64.58%	99.92%	
Importance Rank	3	5	2	2	1	5	

Figure 9-7 Populated Persistent UAS Operations House

		Maintenance Requirements										
		Importance	Availability of Spares	Fault Detection Rate	False Positives Rate	False Negatives Rate	Reliability of Repairs	Mean Time To Replace	Average Turnaround Time	Mean Time To Diagnose	Personnel Required	Auxiliary Equipment Required
Characteristics/Requirements	System Downtime	3	7.20 (2.90) [10]{100%}	5.22 (3.67) [9]{90%}	3.56 (3.28) [9]{90%}	4.75 (3.62) [8]{80%}	6.33 (3.16) [9]{90%}	7.80 (2.53) [10]{100%}	5.80 (3.43) [10]{100%}	6.60 (3.10) [10]{100%}	4.78 (3.23) [9]{90%}	4.78 (3.23) [9]{90%}
	Platform Reliability	5	2.25 (2.96) [8]{80%}	6.20 (3.68) [10]{100%}	4.75 (3.62) [8]{80%}	5.86 (3.98) [7]{70%}	7.00 (3.00) [9]{90%}	1.75 (2.96) [8]{80%}	2.22 (2.73) [9]{90%}	5.75 (3.54) [8]{80%}	3.38 (2.50) [8]{80%}	3.33 (3.39) [9]{90%}
	Mission Success Rate	2	4.00 (4.24) [8]{80%}	3.44 (3.40) [9]{90%}	4.00 (3.00) [9]{90%}	3.38 (2.50) [8]{80%}	7.00 (3.27) [10]{100%}	2.38 (3.02) [8]{80%}	2.13 (3.04) [8]{80%}	2.50 (2.93) [8]{80%}	2.50 (2.93) [8]{80%}	2.50 (2.93) [8]{80%}
	Demand of Personnel	2	2.50 (2.93) [8]{80%}	4.67 (3.39) [9]{90%}	3.88 (3.36) [8]{80%}	6.00 (3.87) [7]{70%}	5.63 (3.74) [8]{80%}	6.67 (3.61) [9]{90%}	6.67 (3.61) [9]{90%}	6.67 (3.61) [9]{90%}	9.00 (0.00) [10]{100%}	4.50 (3.93) [8]{80%}
	Deployability	1	5.60 (3.66) [10]{100%}	4.25 (3.01) [8]{80%}	4.43 (3.21) [7]{70%}	5.57 (3.21) [7]{70%}	5.00 (3.00) [9]{90%}	5.00 (3.00) [9]{90%}	5.67 (3.16) [9]{90%}	4.33 (2.65) [9]{90%}	5.44 (3.43) [9]{90%}	5.80 (3.43) [10]{100%}
	Operational Readiness	5	5.44 (3.43) [9]{90%}	4.78 (3.23) [9]{90%}	3.25 (2.49) [8]{80%}	5.00 (3.38) [8]{80%}	6.11 (3.48) [9]{90%}	6.33 (3.16) [9]{90%}	6.60 (3.10) [10]{100%}	6.33 (3.16) [9]{90%}	5.78 (3.93) [9]{90%}	5.78 (3.93) [9]{90%}
Raw Score			78.67	91.03	70.85	92.86	114.81	86.90	84.76	102.88	88.54	79.69
Raw Percentage			8.83%	10.22%	7.95%	10.42%	12.89%	9.75%	9.51%	11.55%	9.94%	8.94%
Percentage of Maximum			68.53%	79.29%	61.71%	80.88%	100.00%	75.69%	73.83%	89.62%	77.12%	69.41%
Importance Rank			2	3	1	3	5	2	2	4	3	2

Figure 9-8 Populated Persistent UAS Maintenance House

		IVHM Requirements											
		Sense		Acquire		Transfer		Analyse			Act		
		Performance Indicators	Sensitivity	Conditioning of Data	Store Data	Transfer Data within the Vehicle	Transfer Data from the Vehicle	Diagnostics Analysis	Prognostics Analysis	Fleet Analysis	Response to the IVHM	Management of Spare Parts	Reconfigure IVHM in Service
Maintenance Requirements	Availability of Spares ²	5.00 (4.52) [6] (67%)	3.86 (3.76) [7] (78%)	1.00 (1.55) [6] (67%)	2.00 (3.63) [6] (67%)	2.17 (3.54) [6] (67%)	4.29 (4.54) [7] (78%)	3.67 (4.27) [6] (67%)	4.25 (4.10) [8] (89%)	3.50 (3.63) [8] (89%)	3.50 (3.63) [8] (89%)	6.38 (3.74) [8] (89%)	2.43 (3.15) [7] (78%)
	Fault Detection Rate ³	6.67 (3.61) [9] (100%)	7.13 (3.56) [8] (89%)	4.44 (3.57) [9] (100%)	4.44 (3.57) [9] (100%)	4.63 (3.78) [8] (89%)	6.57 (4.16) [7] (78%)	7.33 (3.39) [9] (100%)	6.57 (4.16) [7] (78%)	7.71 (3.40) [7] (78%)	6.13 (4.05) [8] (89%)	2.00 (3.27) [7] (78%)	4.89 (4.01) [9] (100%)
	False Positives Rate ¹	6.38 (3.74) [8] (89%)	4.86 (4.02) [7] (78%)	4.13 (4.12) [8] (89%)	2.38 (2.88) [8] (89%)	2.63 (2.83) [8] (89%)	3.83 (4.12) [6] (67%)	7.88 (3.18) [8] (89%)	6.50 (3.99) [6] (67%)	6.50 (3.99) [6] (67%)	4.86 (4.02) [7] (78%)	1.43 (1.51) [7] (78%)	4.38 (3.96) [8] (89%)
	False Negatives Rate ³	6.38 (3.74) [8] (89%)	6.00 (3.87) [7] (78%)	4.13 (4.12) [8] (89%)	2.38 (2.88) [8] (89%)	2.88 (2.75) [8] (89%)	4.83 (4.58) [6] (67%)	7.88 (3.18) [8] (89%)	7.50 (3.67) [6] (67%)	7.50 (3.67) [6] (67%)	4.57 (4.24) [7] (78%)	3.67 (4.27) [6] (67%)	5.13 (4.22) [8] (89%)
	Reliability of Repairs ⁵	7.50 (3.67) [6] (67%)	3.00 (3.00) [7] (78%)	2.17 (3.54) [6] (67%)	1.17 (1.47) [6] (67%)	0.83 (1.17) [6] (67%)	1.33 (1.37) [6] (67%)	3.50 (3.63) [8] (89%)	3.57 (3.91) [7] (78%)	5.71 (4.19) [7] (78%)	4.17 (3.92) [6] (67%)	5.50 (3.99) [6] (67%)	1.67 (1.51) [6] (67%)
	Mean Time To Replace ²	5.57 (4.39) [7] (78%)	3.00 (2.78) [8] (89%)	0.86 (1.07) [7] (78%)	2.00 (3.27) [7] (78%)	1.29 (1.25) [7] (78%)	1.86 (1.46) [7] (78%)	4.29 (4.54) [7] (78%)	4.29 (4.54) [7] (78%)	6.43 (4.39) [7] (78%)	2.86 (2.97) [7] (78%)	5.11 (3.82) [9] (100%)	1.86 (1.46) [7] (78%)
	Average Turnaround Time ²	6.00 (4.65) [6] (67%)	3.00 (3.00) [7] (78%)	2.14 (3.18) [7] (78%)	2.14 (3.18) [7] (78%)	3.71 (3.77) [7] (78%)	7.13 (3.56) [8] (89%)	5.71 (4.19) [7] (78%)	5.71 (4.19) [7] (78%)	4.57 (4.24) [7] (78%)	6.86 (3.76) [7] (78%)	6.00 (3.87) [7] (78%)	3.71 (3.77) [7] (78%)
	Mean Time To Diagnose ⁴	6.57 (4.16) [7] (78%)	3.88 (3.36) [8] (89%)	2.88 (2.75) [8] (89%)	3.63 (3.50) [8] (89%)	3.63 (3.50) [8] (89%)	5.38 (4.00) [8] (89%)	7.11 (3.76) [9] (100%)	6.57 (4.16) [7] (78%)	6.00 (3.87) [7] (78%)	6.13 (4.05) [8] (89%)	3.57 (3.91) [7] (78%)	2.57 (3.05) [7] (78%)
	Personnel Required ³	3.67 (4.27) [6] (67%)	2.71 (3.09) [7] (78%)	1.17 (0.98) [6] (67%)	2.17 (3.37) [6] (67%)	2.33 (3.44) [6] (67%)	3.71 (3.77) [7] (78%)	5.50 (3.82) [8] (89%)	5.25 (4.06) [8] (89%)	5.29 (3.55) [7] (78%)	5.67 (3.72) [6] (67%)	4.67 (3.44) [6] (67%)	2.83 (3.25) [6] (67%)
	Auxiliary Equipment Required ²	2.57 (3.21) [7] (78%)	2.43 (3.15) [7] (78%)	1.00 (1.00) [7] (78%)	0.86 (0.38) [7] (78%)	0.86 (1.07) [7] (78%)	4.43 (4.39) [7] (78%)	3.88 (4.36) [8] (89%)	3.88 (4.36) [8] (89%)	2.00 (3.27) [7] (78%)	3.13 (3.83) [8] (89%)	2.29 (3.25) [7] (78%)	0.86 (1.07) [7] (78%)
Raw Score	158.57	107.45	65.67	63.67	66.84	112.75	151.03	144.86	153.57	131.96	113.76	79.25	
Raw Percentage	11.75%	7.96%	4.87%	4.72%	4.95%	8.36%	11.19%	10.74%	11.38%	9.78%	8.43%	5.87%	
Percentage of Maximum	100.00%	67.76%	41.41%	40.15%	42.15%	71.10%	95.24%	91.35%	96.85%	83.22%	71.74%	49.98%	
Importance Rank	5	3	1	1	1	3	5	4	5	4	3	2	

Figure 9-9 Populated Persistent UAS IVHM Requirements House

Research Programme Criteria										
	Cost		Research Areas			Research Impact			Long Lasting Benefits	
	Acquire	Operate	Low Maintenance Technologies	Non-conventional Flight Control	Technology Integration	Originality	Academic Quality	Business Quality	Educational Tool	Publicity Tool
Acquire		-0.2	-0.2	0.6	0.6	1.0	1.0	-0.2	0.2	0.2
Operate	0.2 (2) [5]{100%}		0.2	0.6	0.2	1.0	1.0	0.6	0.6	0.2
Low Maintenance Technologies	0.2 (2) [5]{100%}	-0.2 (2) [5]{100%}		0.6	0.2	0.6	0.6	0.6	-1.0	-0.2
Non-conventional Flight Control	-0.6 (1) [5]{100%}	-0.6 (1) [5]{100%}	-0.6 (1) [5]{100%}		0.2	-0.3	-0.3	0.3	-1.0	-1.0
Technology Integration	-0.6 (1) [5]{100%}	-0.2 (2) [5]{100%}	-0.2 (2) [5]{100%}	-0.2 (2) [5]{100%}		-0.3	-0.3	0.3	-0.3	-1.0
Originality	-1.0 (0) [5]{100%}	-1.0 (0) [5]{100%}	-0.6 (1) [5]{100%}	0.3 (1) [3]{60%}	0.3 (1) [3]{60%}		-1.0	-0.3	-1.0	-1.0
Academic Quality	-1.0 (0) [5]{100%}	-1.0 (0) [5]{100%}	-0.6 (1) [5]{100%}	0.3 (1) [3]{60%}	0.3 (1) [3]{60%}	1.0 (0) [3]{60%}		-0.3	-0.3	-1.0
Business Quality	0.2 (2) [5]{100%}	-0.6 (1) [5]{100%}	-0.6 (1) [5]{100%}	-0.3 (1) [3]{60%}	-0.3 (1) [3]{60%}	0.3 (1) [3]{60%}	0.3 (1) [3]{60%}		-0.3	-0.3
Educational Tool	-0.2 (2) [5]{100%}	-0.6 (1) [5]{100%}	1.0 (0) [5]{100%}	1.0 (0) [3]{60%}	0.3 (1) [3]{60%}	1.0 (0) [3]{60%}	0.3 (1) [3]{60%}	0.3 (1) [3]{60%}		-0.3
Publicity Tool	-0.2 (2) [5]{100%}	-0.2 (2) [5]{100%}	0.2 (2) [5]{100%}	1.0 (0) [3]{60%}	1.0 (0) [3]{60%}	1.0 (0) [3]{60%}	1.0 (0) [3]{60%}	0.3 (1) [3]{60%}	0.3 (1) [3]{60%}	
Raw Score	-3.0	-4.6	-1.4	3.9	2.9	5.3	2.6	1.7	-2.9	-4.5
Importance Rank	1	1	2	5	4	5	4	4	1	1

Figure 9-10 Populated Demon UAS Research Programme Criteria House

		Experiment Capability																	
		Mission/Experiment					Demon Availability				Resource Availability				Documentation				
		Importance Rank	Collect Operational Data	Collect Operating Conditions	Monitor Performance	Capture Experimental/ Test Data	UAS Ease of Operation	Time Between Reconfigure/Mod.	Per-Flight/Experiment Checks	Unscheduled Maintenance	Repair Time	Availability of Spares/Parts	Staff Availability	Tool/Equipment Availability	Lab/Workshop Availability	CAA Documentation/Airworthiness	Design/Modification	Research/Publication	
Research Programme Criteria	Cost	Acquire	1	6.75 (3.86) [4]{100%}	5.00 (4.62) [4]{100%}	3.75 (2.99) [4]{100%}	6.00 (3.46) [4]{100%}	4.00 (3.46) [4]{100%}	6.50 (3.00) [4]{100%}	5.50 (4.12) [4]{100%}	3.00 (4.24) [4]{100%}	4.50 (3.87) [4]{100%}	2.50 (3.32) [4]{100%}	6.25 (4.27) [4]{100%}	6.25 (4.27) [4]{100%}	8.50 (1.00) [4]{100%}	6.50 (3.79) [4]{100%}	1.25 (2.50) [4]{100%}	
		Operate	1	7.25 (3.50) [4]{100%}	7.00 (4.00) [4]{100%}	7.25 (3.50) [4]{100%}	7.00 (4.00) [4]{100%}	5.25 (2.87) [4]{100%}	5.25 (3.86) [4]{100%}	5.75 (3.20) [4]{100%}	7.25 (2.87) [4]{100%}	7.25 (2.87) [4]{100%}	7.50 (3.00) [4]{100%}	9.00 (0.00) [4]{100%}	8.75 (0.50) [4]{100%}	8.75 (0.50) [4]{100%}	7.75 (2.50) [4]{100%}	7.75 (2.50) [4]{100%}	2.75 (3.77) [4]{100%}
	Research Areas	Low Maintenance Technologies	2	2.50 (1.00) [4]{100%}	3.25 (2.06) [4]{100%}	3.25 (3.86) [4]{100%}	8.25 (1.50) [4]{100%}	2.00 (1.83) [4]{100%}	3.75 (3.77) [4]{100%}	4.50 (3.00) [4]{100%}	7.00 (2.83) [4]{100%}	8.50 (1.00) [4]{100%}	4.25 (3.20) [4]{100%}	4.25 (2.50) [4]{100%}	5.00 (2.83) [4]{100%}	3.75 (1.50) [4]{100%}	2.50 (1.00) [4]{100%}	4.50 (3.00) [4]{100%}	3.50 (4.36) [4]{100%}
		Non-conventional Flight Control	5	5.50 (3.00) [4]{100%}	8.25 (1.50) [4]{100%}	8.75 (0.50) [4]{100%}	8.50 (1.00) [4]{100%}	7.75 (2.50) [4]{100%}	6.00 (3.46) [4]{100%}	3.00 (0.00) [4]{100%}	2.50 (1.00) [4]{100%}	2.50 (1.00) [4]{100%}	2.25 (0.96) [4]{100%}	3.75 (2.99) [4]{100%}	3.00 (1.63) [4]{100%}	3.75 (1.50) [4]{100%}	2.50 (1.00) [4]{100%}	4.50 (3.00) [4]{100%}	9.00 (0.00) [4]{100%}
		Technology Integration	4	3.00 (2.45) [4]{100%}	1.75 (1.50) [4]{100%}	3.25 (2.87) [4]{100%}	6.00 (3.83) [4]{100%}	5.75 (3.95) [4]{100%}	8.75 (0.50) [4]{100%}	7.25 (2.87) [4]{100%}	5.00 (4.62) [4]{100%}	4.75 (4.35) [4]{100%}	3.25 (3.86) [4]{100%}	2.75 (3.50) [4]{100%}	2.50 (1.91) [4]{100%}	2.75 (2.36) [4]{100%}	6.00 (3.46) [4]{100%}	7.50 (3.00) [4]{100%}	9.00 (0.00) [4]{100%}
	Research Impact	Originality	5	2.75 (0.50) [4]{100%}	4.00 (2.00) [4]{100%}	2.75 (0.50) [4]{100%}	5.00 (2.83) [4]{100%}	5.75 (4.27) [4]{100%}	2.00 (1.15) [4]{100%}	1.75 (1.50) [4]{100%}	1.75 (1.50) [4]{100%}	2.50 (1.00) [4]{100%}	0.00 (0.00) [4]{100%}	0.75 (0.50) [4]{100%}	0.00 (0.00) [4]{100%}	0.00 (0.00) [4]{100%}	0.00 (0.00) [4]{100%}	2.25 (4.50) [4]{100%}	9.00 (0.00) [4]{100%}
		Academic Quality	4	8.75 (0.50) [4]{100%}	5.75 (3.20) [4]{100%}	8.50 (1.00) [4]{100%}	6.00 (3.46) [4]{100%}	2.50 (1.73) [4]{100%}	1.00 (2.00) [4]{100%}	3.00 (0.00) [4]{100%}	2.00 (1.15) [4]{100%}	2.00 (1.41) [4]{100%}	0.75 (0.96) [4]{100%}	3.00 (4.24) [4]{100%}	1.00 (1.41) [4]{100%}	1.00 (1.41) [4]{100%}	2.00 (3.37) [4]{100%}	4.00 (4.69) [4]{100%}	9.00 (0.00) [4]{100%}
		Business Quality	4	5.25 (2.87) [4]{100%}	3.75 (3.77) [4]{100%}	8.00 (2.00) [4]{100%}	8.00 (2.00) [4]{100%}	3.75 (1.50) [4]{100%}	3.00 (2.83) [4]{100%}	3.00 (2.83) [4]{100%}	4.00 (2.00) [4]{100%}	4.00 (2.00) [4]{100%}	3.50 (2.52) [4]{100%}	3.50 (2.52) [4]{100%}	3.25 (2.87) [4]{100%}	3.50 (3.32) [4]{100%}	8.75 (0.50) [4]{100%}	7.25 (2.87) [4]{100%}	4.50 (3.00) [4]{100%}
	Long Lasting Benefits	Educational Tool	1	5.75 (3.20) [4]{100%}	5.50 (3.00) [4]{100%}	5.75 (3.20) [4]{100%}	6.00 (3.46) [4]{100%}	5.00 (2.83) [4]{100%}	3.00 (2.45) [4]{100%}	0.25 (0.50) [4]{100%}	1.75 (1.50) [4]{100%}	1.75 (1.50) [4]{100%}	5.75 (3.77) [4]{100%}	5.50 (3.00) [4]{100%}	7.25 (2.87) [4]{100%}	7.25 (2.87) [4]{100%}	7.00 (2.83) [4]{100%}	8.50 (1.00) [4]{100%}	8.75 (0.50) [4]{100%}
		Publicity Tool	1	4.75 (4.92) [4]{100%}	1.75 (1.50) [4]{100%}	5.25 (4.50) [4]{100%}	2.50 (1.00) [4]{100%}	1.50 (1.73) [4]{100%}	0.00 (0.00) [4]{100%}	1.50 (1.73) [4]{100%}	1.50 (1.73) [4]{100%}	1.50 (1.73) [4]{100%}	1.50 (1.73) [4]{100%}	0.75 (0.50) [4]{100%}	0.50 (0.58) [4]{100%}	0.50 (0.58) [4]{100%}	1.75 (1.50) [4]{100%}	3.25 (2.06) [4]{100%}	9.00 (0.00) [4]{100%}
Raw Score			138.75	132.00	165.00	185.50	135.25	113.25	98.75	92.75	100.00	67.00	89.50	74.75	78.00	109.50	143.75	208.75	
Raw Percentage			7.18%	6.83%	8.54%	9.60%	7.00%	5.86%	5.11%	4.80%	5.17%	3.47%	4.63%	3.87%	4.04%	5.67%	7.44%	10.80%	
Percentage of Maximum			66.47%	63.23%	79.04%	88.86%	64.79%	54.25%	47.31%	44.43%	47.90%	32.10%	42.87%	35.81%	37.37%	52.46%	68.86%	100.00%	
Importance Rank			3	3	4	4	3	2	2	2	2	1	2	1	1	2	3	5	

Figure 9-11 Populated Demon UAS Experiment Capability House

		IVHM Requirements														
		Sense		Acquire		Transfer		Analysis			Act					
		Importance Rank	Performance Indicators	Sensitivity	Conditioning of Data	Store Data	Transfer Data within the Vehicle	Transfer Data from the Vehicle	Diagnostics Analysis	Prognostics Analysis	Fleet Analysis	Response to the IVHM	Management of Spare Parts	Reconfigure IVHM in Service		
Experiment Capability	Mission/Experiment	Collect Operational Data	3	4.75 (3.50) [4][100%]	2.75 (1.26) [4][100%]	2.00 (1.15) [4][100%]	5.50 (3.00) [4][100%]	5.50 (4.12) [4][100%]	5.50 (4.12) [4][100%]	3.25 (4.03) [4][100%]	1.75 (1.50) [4][100%]	0.25 (0.50) [4][100%]	3.00 (0.00) [4][100%]	2.50 (1.00) [4][100%]	2.50 (1.00) [4][100%]	
		Collect Operating Conditions	3	4.50 (3.00) [4][100%]	4.75 (2.87) [4][100%]	4.00 (3.46) [4][100%]	7.00 (2.83) [4][100%]	7.50 (3.00) [4][100%]	9.00 (0.00) [4][100%]	3.75 (3.77) [4][100%]	2.25 (1.50) [4][100%]	0.25 (0.50) [4][100%]	2.50 (1.00) [4][100%]	2.00 (1.15) [4][100%]	2.50 (1.00) [4][100%]	2.50 (1.00) [4][100%]
		Monitor Performance	4	6.25 (3.20) [4][100%]	5.00 (2.83) [4][100%]	4.50 (3.00) [4][100%]	7.00 (2.83) [4][100%]	7.25 (2.87) [4][100%]	6.00 (3.46) [4][100%]	3.75 (3.77) [4][100%]	2.25 (1.50) [4][100%]	2.25 (4.50) [4][100%]	2.50 (1.00) [4][100%]	2.50 (1.00) [4][100%]	2.50 (1.00) [4][100%]	2.50 (1.00) [4][100%]
		Capture Experimental/Test Data	4	4.50 (3.00) [4][100%]	4.00 (3.46) [4][100%]	4.00 (3.46) [4][100%]	6.00 (3.46) [4][100%]	6.00 (3.46) [4][100%]	6.00 (3.46) [4][100%]	3.50 (3.79) [4][100%]	2.00 (1.15) [4][100%]	0.25 (0.50) [4][100%]	1.50 (1.00) [4][100%]	1.50 (1.00) [4][100%]	4.00 (3.46) [4][100%]	4.00 (3.46) [4][100%]
		UAS Ease of Operation	3	4.00 (3.46) [4][100%]	1.50 (1.73) [4][100%]	1.50 (1.73) [4][100%]	3.75 (3.77) [4][100%]	2.50 (1.00) [4][100%]	4.50 (3.00) [4][100%]	3.25 (4.03) [4][100%]	1.50 (1.73) [4][100%]	0.00 (0.00) [4][100%]	2.50 (1.00) [4][100%]	1.75 (1.50) [4][100%]	2.50 (1.00) [4][100%]	2.50 (1.00) [4][100%]
	Demon Availability	Time Between Reconfigure/Mod	2	1.00 (1.41) [4][100%]	0.75 (0.50) [4][100%]	0.50 (0.58) [4][100%]	1.00 (1.41) [4][100%]	0.75 (1.50) [4][100%]	0.75 (1.50) [4][100%]	0.75 (0.50) [4][100%]	0.50 (0.58) [4][100%]	1.00 (1.41) [4][100%]	1.25 (1.26) [4][100%]	2.75 (4.19) [4][100%]	4.00 (3.46) [4][100%]	4.00 (3.46) [4][100%]
		Per-Flight/Experiment Checks	2	2.75 (2.36) [4][100%]	1.50 (1.00) [4][100%]	1.00 (1.41) [4][100%]	2.25 (1.50) [4][100%]	1.50 (1.73) [4][100%]	2.25 (1.50) [4][100%]	1.00 (1.41) [4][100%]	0.75 (1.50) [4][100%]	1.00 (1.41) [4][100%]	2.50 (1.00) [4][100%]	2.50 (4.36) [4][100%]	4.00 (3.46) [4][100%]	4.00 (3.46) [4][100%]
		Unscheduled Maintenance	2	5.00 (2.83) [4][100%]	4.00 (3.46) [4][100%]	4.00 (3.46) [4][100%]	2.00 (1.15) [4][100%]	2.00 (1.15) [4][100%]	2.00 (1.15) [4][100%]	4.50 (3.00) [4][100%]	4.00 (3.46) [4][100%]	2.25 (4.50) [4][100%]	4.50 (3.00) [4][100%]	5.25 (2.87) [4][100%]	4.25 (3.20) [4][100%]	4.25 (3.20) [4][100%]
		Repair Time	2	1.50 (1.73) [4][100%]	1.00 (1.41) [4][100%]	0.50 (0.58) [4][100%]	0.25 (0.50) [4][100%]	0.50 (0.58) [4][100%]	1.00 (1.41) [4][100%]	2.50 (4.36) [4][100%]	2.50 (4.36) [4][100%]	2.25 (4.50) [4][100%]	3.75 (3.77) [4][100%]	3.75 (3.77) [4][100%]	2.25 (1.50) [4][100%]	2.25 (1.50) [4][100%]
		Availability of Spares/Parts	1	0.25 (0.50) [4][100%]	0.25 (0.50) [4][100%]	0.25 (0.50) [4][100%]	1.00 (1.41) [4][100%]	0.25 (0.50) [4][100%]	0.25 (0.50) [4][100%]	2.00 (1.15) [4][100%]	3.25 (4.50) [4][100%]	0.75 (1.50) [4][100%]	6.75 (4.50) [4][100%]	6.75 (4.50) [4][100%]	1.75 (1.50) [4][100%]	1.75 (1.50) [4][100%]
	Resource Availability	Staff Availability	2	0.25 (0.50) [4][100%]	0.00 (0.00) [4][100%]	0.00 (0.00) [4][100%]	0.00 (0.00) [4][100%]	0.00 (0.00) [4][100%]	0.25 (0.50) [4][100%]	0.25 (0.50) [4][100%]	0.25 (0.50) [4][100%]	0.25 (0.50) [4][100%]	3.75 (3.77) [4][100%]	1.75 (1.50) [4][100%]	3.75 (3.77) [4][100%]	3.75 (3.77) [4][100%]
		Tool/Equipment Availability	1	0.25 (0.50) [4][100%]	0.00 (0.00) [4][100%]	0.00 (0.00) [4][100%]	0.25 (0.50) [4][100%]	0.00 (0.00) [4][100%]	0.25 (0.50) [4][100%]	0.25 (0.50) [4][100%]	0.25 (0.50) [4][100%]	0.25 (0.50) [4][100%]	3.75 (3.77) [4][100%]	4.75 (4.92) [4][100%]	3.75 (3.77) [4][100%]	3.75 (3.77) [4][100%]
		Lab/Workshop Availability	1	0.25 (0.50) [4][100%]	0.00 (0.00) [4][100%]	0.00 (0.00) [4][100%]	0.00 (0.00) [4][100%]	0.00 (0.00) [4][100%]	0.00 (0.00) [4][100%]	0.00 (0.00) [4][100%]	0.00 (0.00) [4][100%]	0.00 (0.00) [4][100%]	6.75 (4.50) [4][100%]	6.75 (4.50) [4][100%]	3.75 (3.77) [4][100%]	3.75 (3.77) [4][100%]
	Documentation	CAA Documentation/Airworthiness	2	1.50 (1.73) [4][100%]	1.50 (1.73) [4][100%]	0.00 (0.00) [4][100%]	0.75 (1.50) [4][100%]	0.00 (0.00) [4][100%]	0.25 (0.50) [4][100%]	0.75 (1.50) [4][100%]	0.75 (1.50) [4][100%]	0.75 (1.50) [4][100%]	2.25 (1.50) [4][100%]	0.25 (0.50) [4][100%]	2.25 (4.50) [4][100%]	2.25 (4.50) [4][100%]
		Design/Modification	3	5.50 (4.12) [4][100%]	4.75 (4.92) [4][100%]	1.75 (1.50) [4][100%]	1.75 (1.50) [4][100%]	2.25 (1.50) [4][100%]	2.25 (1.50) [4][100%]	3.00 (0.00) [4][100%]	2.50 (1.00) [4][100%]	2.25 (4.50) [4][100%]	3.75 (3.77) [4][100%]	4.50 (3.00) [4][100%]	3.75 (3.77) [4][100%]	3.75 (3.77) [4][100%]
Research/Publication		5	4.00 (2.00) [4][100%]	3.25 (2.06) [4][100%]	2.25 (2.50) [4][100%]	4.75 (4.35) [4][100%]	2.75 (3.50) [4][100%]	2.00 (2.00) [4][100%]	8.50 (1.00) [4][100%]	7.25 (3.50) [4][100%]	2.25 (4.50) [4][100%]	6.75 (4.50) [4][100%]	0.25 (0.50) [4][100%]	3.75 (3.77) [4][100%]	3.75 (3.77) [4][100%]	
Raw Score			144.00	111.25	85.25	143.50	129.75	140.25	142.00	106.25	45.50	138.25	100.25	128.75		
Raw Percentage			10.18%	7.86%	6.02%	10.14%	9.17%	9.91%	10.04%	7.51%	3.22%	9.77%	7.08%	9.10%		
Percentage of Maximum			100.00%	77.26%	59.20%	99.65%	90.10%	97.40%	98.61%	73.78%	31.60%	96.01%	69.62%	89.41%		
Importance Rank			5	4	3	5	4	5	5	3	1	5	3	4		

Figure 9-12 Populated Demon UAS IVHM Requirements House

		IVHM Enablers													
		Sense			Acquire	Transfer	Analysis				Act				
		Importance Rank	Degradation Traceability	Detectability of Impending Failure	Performance Monitoring	Standard Data Format	Availability of Communications	Accuracy & Precision of Captured Data	Availability & Accuracy of Historical Maintenance Data	Availability & Accuracy of Operational Data	Availability & Accuracy of Failure Data	Failure Mode Knowledge	Maintenance Staff Availability	Flexibility in Schedules	
IVHM Requirements	Sense	Performance Indicators	5	9.00 (0.00) [4][100%]	9.00 (0.00) [4][100%]	9.00 (0.00) [4][100%]	2.50 (1.00) [4][100%]	2.75 (0.50) [4][100%]	8.50 (1.00) [4][100%]	2.50 (4.36) [4][100%]	1.75 (2.06) [4][100%]	1.50 (2.38) [4][100%]	8.50 (1.00) [4][100%]	0.00 (0.00) [4][100%]	0.00 (0.00) [4][100%]
		Sensitivity	4	9.00 (0.00) [4][100%]	8.50 (1.00) [4][100%]	6.50 (3.00) [4][100%]	4.00 (3.46) [4][100%]	2.75 (0.50) [4][100%]	8.50 (1.00) [4][100%]	2.50 (4.36) [4][100%]	3.00 (4.24) [4][100%]	3.00 (4.24) [4][100%]	6.25 (3.77) [4][100%]	0.00 (0.00) [4][100%]	0.00 (0.00) [4][100%]
	Acquire	Conditioning of Data	3	5.50 (4.12) [4][100%]	3.25 (3.30) [4][100%]	5.25 (2.87) [4][100%]	3.75 (3.77) [4][100%]	4.00 (3.46) [4][100%]	7.00 (4.00) [4][100%]	2.50 (4.36) [4][100%]	3.25 (4.03) [4][100%]	3.75 (3.77) [4][100%]	1.50 (1.73) [4][100%]	0.25 (0.50) [4][100%]	0.25 (0.50) [4][100%]
		Store Data	5	7.50 (3.00) [4][100%]	7.25 (2.87) [4][100%]	6.75 (2.87) [4][100%]	4.50 (3.00) [4][100%]	4.50 (5.20) [4][100%]	2.25 (4.50) [4][100%]	6.75 (4.50) [4][100%]	7.00 (4.00) [4][100%]	7.50 (3.00) [4][100%]	4.50 (3.00) [4][100%]	1.50 (1.73) [4][100%]	1.00 (1.41) [4][100%]
	Transfer	Transfer Data within the Vehicle	4	7.00 (4.00) [4][100%]	6.75 (2.87) [4][100%]	3.50 (2.52) [4][100%]	7.50 (3.00) [4][100%]	7.50 (3.00) [4][100%]	0.25 (0.50) [4][100%]	0.25 (0.50) [4][100%]	2.00 (1.15) [4][100%]	2.50 (1.00) [4][100%]	1.00 (1.41) [4][100%]	0.00 (0.00) [4][100%]	0.25 (0.50) [4][100%]
		Transfer Data from the Vehicle	5	7.00 (4.00) [4][100%]	6.75 (2.87) [4][100%]	5.50 (3.00) [4][100%]	4.50 (3.00) [4][100%]	9.00 (0.00) [4][100%]	0.25 (0.50) [4][100%]	0.25 (0.50) [4][100%]	2.00 (1.15) [4][100%]	2.50 (1.00) [4][100%]	1.00 (1.41) [4][100%]	1.75 (1.50) [4][100%]	2.00 (1.15) [4][100%]
	Analyse	Diagnostics Analysis	5	6.50 (3.00) [4][100%]	8.50 (1.00) [4][100%]	8.25 (1.50) [4][100%]	0.50 (0.58) [4][100%]	5.50 (4.12) [4][100%]	8.50 (1.00) [4][100%]	5.50 (3.00) [4][100%]	4.50 (3.00) [4][100%]	8.50 (1.00) [4][100%]	8.75 (0.50) [4][100%]	0.75 (1.50) [4][100%]	3.50 (1.00) [4][100%]
		Prognostics Analysis	3	6.75 (4.50) [4][100%]	3.75 (3.77) [4][100%]	3.75 (3.77) [4][100%]	0.25 (0.50) [4][100%]	5.25 (4.50) [4][100%]	6.75 (4.50) [4][100%]	6.75 (4.50) [4][100%]	6.75 (4.50) [4][100%]	6.75 (4.50) [4][100%]	6.75 (4.50) [4][100%]	0.75 (1.50) [4][100%]	5.25 (4.50) [4][100%]
		Fleet Analysis	1	2.25 (4.50) [4][100%]	2.25 (4.50) [4][100%]	2.25 (4.50) [4][100%]	2.25 (4.50) [4][100%]	0.25 (0.50) [4][100%]	2.25 (4.50) [4][100%]	2.25 (4.50) [4][100%]	3.00 (4.24) [4][100%]	3.00 (4.24) [4][100%]	3.00 (4.24) [4][100%]	0.75 (1.50) [4][100%]	2.25 (4.50) [4][100%]
	Act	Response to the IVHM	5	6.25 (3.20) [4][100%]	7.50 (3.00) [4][100%]	5.75 (3.77) [4][100%]	0.50 (0.58) [4][100%]	5.00 (4.62) [4][100%]	5.25 (4.50) [4][100%]	5.25 (4.35) [4][100%]	6.00 (3.46) [4][100%]	7.50 (3.00) [4][100%]	7.50 (3.00) [4][100%]	6.75 (4.50) [4][100%]	4.50 (3.00) [4][100%]
		Management of Spare Parts	3	2.00 (2.45) [4][100%]	4.50 (3.00) [4][100%]	3.00 (0.00) [4][100%]	0.25 (0.50) [4][100%]	5.50 (4.12) [4][100%]	4.75 (4.92) [4][100%]	6.50 (4.36) [4][100%]	5.75 (3.77) [4][100%]	3.00 (1.63) [4][100%]	3.00 (1.63) [4][100%]	6.75 (4.50) [4][100%]	5.75 (3.20) [4][100%]
		Reconfigure IVHM in Service	4	4.00 (3.46) [4][100%]	4.25 (3.20) [4][100%]	4.00 (3.46) [4][100%]	2.50 (4.36) [4][100%]	4.00 (3.46) [4][100%]	7.00 (4.00) [4][100%]	7.50 (3.00) [4][100%]	4.00 (3.46) [4][100%]	4.50 (3.00) [4][100%]	4.25 (3.20) [4][100%]	3.75 (3.77) [4][100%]	4.00 (3.46) [4][100%]
Raw Score			306.25	309.75	270.50	133.50	235.25	244.50	191.75	192.50	221.00	234.00	92.75	108.00	
Raw Percentage			12.06%	12.20%	10.65%	5.26%	9.26%	9.63%	7.55%	7.58%	8.70%	9.21%	3.65%	4.25%	
Percentage of Maximum			98.87%	100.00%	87.33%	43.10%	75.95%	78.93%	61.90%	62.15%	71.35%	75.54%	29.94%	34.87%	
Importance Rank			5	5	4	2	4	4	3	3	3	4	1	1	

Figure 9-13 Populated Demon UAS IVHM Enablers House

D. Most Agreed and Contested Relationships

	Degradation Traceability	Detectability of Impending Failure	Performance Monitoring	Standard Data Format	Availability of Communications	Accuracy & Precision of Captured Data	Availability & Accuracy of Historical Maintenance Data	Availability & Accuracy of Operational Data	Availability & Accuracy of Failure Data	Failure Mode Knowledge	Maintenance Staff Availability	Flexibility in Schedules
Performance Indicators	0.00	0.00	0.00	1.00	0.50	1.00	4.36	2.06	2.38	1.00	0.00	0.00
Sensitivity	0.00	1.00	3.00	3.46	0.50	1.00	4.36	4.24	4.24	3.77	0.00	0.00
Conditioning of Data	4.12	3.30	2.87	3.77	3.46	4.00	4.36	4.03	3.77	1.73	0.50	0.50
Store Data	3.00	2.87	2.87	3.00	5.20	4.50	4.50	4.00	3.00	3.00	1.73	1.41
Transfer Data within the Vehicle	4.00	2.87	2.52	3.00	3.00	0.50	0.50	1.15	1.00	1.41	0.00	0.50
Transfer Data from the Vehicle	4.00	2.87	3.00	3.00	0.00	0.50	0.50	1.15	1.00	1.41	1.50	1.15
Diagnostics Analysis	3.00	1.00	1.50	0.58	4.12	1.00	3.00	3.00	1.00	0.50	1.50	1.00
Prognostics Analysis	4.50	3.77	3.77	0.50	4.50	4.50	4.50	4.50	4.50	4.50	1.50	4.50
Fleet Analysis	4.50	4.50	4.50	4.50	0.50	4.50	4.50	4.24	4.24	4.24	1.50	4.50
Response to the IVHM	3.20	3.00	3.77	0.58	4.62	4.50	4.35	3.46	3.00	3.00	4.50	3.00
Management of Spare Parts	2.45	3.00	0.00	0.50	4.12	4.92	4.36	3.77	1.63	1.63	4.50	3.20
Reconfigure IVHM in Service	3.46	3.20	3.46	4.36	3.46	4.00	3.00	3.46	3.00	3.20	3.77	3.46

Figure 9-14 Most Agreed and Contested Relationships for the Demon UAS Enablers House

	Degradation Traceability	Detectability of Impending Failure	Performance Monitoring	Standard Data Format	Availability of Communications	Accuracy & Precision of Captured Data	Availability & Accuracy of Historical Maintenance Data	Availability & Accuracy of Operational Data	Availability & Accuracy of Failure Data	Failure Mode Knowledge	Maintenance Staff Availability	Flexibility in Schedules
Performance Indicators	3.29	2.45	0.00	1.10	3.03	0.00	4.67	4.31	3.90	3.29	4.93	3.78
Sensitivity	4.24	4.24	3.99	4.92	4.34	3.99	4.02	4.02	4.02	4.02	1.26	1.26
Conditioning of Data	4.03	4.03	3.77	4.55	5.20	3.99	4.50	4.50	5.20	4.24	0.58	0.58
Store Data	4.24	4.24	4.02	4.67	3.77	3.67	3.29	3.29	3.67	1.73	0.58	0.58
Transfer Data within the Vehicle	3.78	4.27	3.13	3.67	3.99	4.12	3.78	4.12	4.76	3.39	0.58	0.58
Transfer Data from the Vehicle	3.29	3.92	2.95	3.67	3.40	4.12	4.76	4.31	4.76	3.39	4.03	4.92
Diagnostics Analysis	2.68	0.00	4.34	4.34	4.24	0.00	4.00	3.29	3.29	2.45	4.03	4.36
Prognostics Analysis	3.10	2.45	3.49	4.50	4.24	2.45	3.10	3.29	3.10	3.10	3.49	4.76
Fleet Analysis	3.00	0.00	4.50	4.02	4.58	2.45	2.45	2.45	2.68	2.68	3.03	4.03
Response to the IVHM	0.00	0.00	3.49	3.63	4.24	2.68	3.00	4.00	3.00	3.00	3.29	1.52
Management of Spare Parts	3.46	0.82	3.79	1.26	4.03	3.46	3.90	4.12	4.38	4.10	3.29	4.03
Reconfigure IVHM in Service	4.12	3.90	3.58	4.34	4.50	4.12	4.62	4.10	4.62	3.74	3.46	3.77

Figure 9-15 Most Agreed and Contested Relationships for the Persistent UAS Enablers House