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# Integrated Helicopter Survivability

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**Cranfield Defence and Security**

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# ABSTRACT

A high level of survivability is important to protect military personnel and equipment and is central to UK defence policy. Integrated Survivability is the systems engineering methodology to achieve optimum survivability at an affordable cost, enabling a mission to be completed successfully in the face of a hostile environment. "Integrated Helicopter Survivability" is an emerging discipline that is applying this systems engineering approach within the helicopter domain. Philosophically the overall survivability objective is 'zero attrition', even though this is unobtainable in practice.

The research question was: "How can helicopter survivability be assessed in an integrated way so that the best possible level of survivability can be achieved within the constraints and how will the associated methods support the acquisition process?"

The research found that principles from safety management could be applied to the survivability problem, in particular reducing survivability risk to as low as reasonably practicable (ALARP). A survivability assessment process was developed to support this approach and was linked into the military helicopter life cycle. This process positioned the survivability assessment methods and associated input data derivation activities.

The system influence diagram method was effective at defining the problem and capturing the wider survivability interactions, including those with the defence lines of development (DLOD). Influence diagrams and Quality Function Deployment (QFD) methods were effective visual tools to elicit stakeholder requirements and improve communication across organisational and domain boundaries.

The semi-quantitative nature of the QFD method leads to numbers that are not real. These results are suitable for helping to prioritise requirements early in the helicopter life cycle, but they cannot provide the quantifiable estimate of risk needed to demonstrate ALARP.

The probabilistic approach implemented within the Integrated Survivability Assessment Model (ISAM) was developed to provide a quantitative estimate of 'risk' to support the approach of reducing survivability risks to ALARP. Limitations in available input data for the rate of encountering threats leads to a probability of survival that is not a real number that can be used to assess actual loss rates. However, the method does support an assessment across platform options, provided that the 'test environment' remains consistent throughout the assessment. The survivability assessment process and ISAM have been applied to an acquisition programme, where they have been tested to support the survivability decision making and design process.

The survivability 'test environment' is an essential element of the survivability assessment process and is required by integrated survivability tools such as ISAM. This test environment, comprising of threatening situations that span the complete spectrum of helicopter operations requires further development. The 'test environment' would be used throughout the helicopter life cycle from selection of design concepts through to test and evaluation of delivered solutions. It would be updated as part of the through life capability management (TLCM) process.

A framework of survivability analysis tools requires development that can provide probabilistic input data into ISAM and allow derivation of confidence limits. This systems level framework would be capable of informing more detailed survivability design work later in the life cycle and could be enabled through a MATLAB® based approach.

Survivability is an emerging system property that influences the whole system capability. There is a need for holistic capability level analysis tools that quantify survivability along with other influencing capabilities such as: mobility (payload / range), lethality, situational awareness, sustainability and other mission capabilities.

It is recommended that an investigation of capability level analysis methods across defence should be undertaken to ensure a coherent and compliant approach to systems engineering that adopts best practice from across the domains. Systems dynamics techniques should be considered for further use by Dstl and the wider MOD, particularly within the survivability and operational analysis domains. This would improve understanding of the problem space, promote a more holistic approach and enable a better balance of capability, within which survivability is one essential element.

There would be value in considering accidental losses within a more comprehensive 'survivability' analysis. This approach would enable a better balance to be struck between safety and survivability risk mitigations and would lead to an improved, more integrated overall design.

# ACKNOWLEDGEMENTS

# CONTRIBUTIONS OF THE CANDIDATE

This research draws upon existing and developing knowledge and understanding within the survivability domain. The candidate works within a team and consequently methodologies, models and techniques are often developed as part of a team effort. The candidate's personal contributions to new knowledge in this discipline are as follows ('novel' contributions have been marked with an asterisk):

- Research and organisation of relevant material into one place and combining this with new ideas to further understanding within the helicopter survivability field:

  - Survivability 'level' definitions with respect to helicopters (Section 1.4.3).

  - Literature search on helicopter threats and survivability attributes (Chapter 2).

  - Literature search on analytical methods, including Quality Function Deployment (QFD) and the Analytical Hierarchy Process (AHP) (Section 3.11).

- Application of a systems engineering approach to helicopter survivability and development of a survivability assessment process* (Chapter 4).

- The idea to apply the concept of reducing risk to 'as low as reasonably practicable' (ALARP) to the survivability problem* (Chapter 4).

- Application of the QFD method to the problem and the development of a new 'hybrid' risk and QFD based approach (Section 4.6.2).

- The idea to use a probabilistic fault tree method set around the pillars of survivability to evaluate a survivability metric and the subsequent development of the Integrated Survivability Assessment Model (ISAM)* (Section 4.8).

- Lessons learnt in terms of the utility of the different methods resulting from their application to the helicopter acquisition process. (Chapters 4 and 5).

# TABLE OF CONTENTS

# TABLE OF FIGURES

# TABLE OF TABLES

# NOMENCLATURE

## Probability related terms

| | |
|---|---|
| N | Number of missions |
| p | Unweighted probability of survival |
| $P_H$ | Probability of hit |
| $P_K$ | Probability of kill |
| $p_r$ | Probability of encountering a threat on a mission |
| $P_R$ | Probability of recovering mission capability |
| $P_S$ | Probability of survival |
| r | Rate of encounter |

## Power required for general forward flight terms

| | |
|---|---|
| $A = \pi R^2$ | Area of rotor disc (m$^2$) |
| b | Number of rotor blades |
| c | Average chord (m) |
| $c_f$ | Coefficient of flat plate drag |
| $C_T = \dfrac{T}{\rho A (\Omega R)^2}$ | |

| | |
|---|---|
| $f = c_f m^{\frac{2}{3}}$ | Flat plate drag area (m$^2$) |
| g | Acceleration due to gravity (m/s$^2$) |
| k | Induced power correction factor |
| m | Mass (kg) |
| n | |
| P | Power (W) |
| P$_c$ | Power required to climb (W) |
| $PF = \rho A (\Omega R)^3$ | Power factor |
| P$_{installed}$ | Installed power (W) |
| P$_{realistic}$ | Realistic power (W) |
| P$_{required}$ | Required power (W) |
| $\Delta$P | Power margin (W) |
| R | Rotor disc radius (m) |
| T | Rotor thrust (N) |
| V | Flight velocity (m/s) |
| V$_c$ | Climb velocity (m/s) |
| W | Aircraft weight (N) |
| $\delta$ | Blade average drag coefficient |
| $\mu$ | Advance ratio |
| $\rho$ | Air density (kg/m$^3$) |
| $\sigma = \dfrac{bc}{\pi R}$ | Rotor solidity (blade area / rotor disc area) |
| $\Omega$ | Rotor angular velocity (rad/s) |

# Abbreviations

| | |
|---|---|
| AAA | Anti-Aircraft Artillery |
| ACS | Aircraft Combat Survivability |
| AD | Air Defence |
| AEW | Airborne Early Warning |
| AFV | Armoured Fighting Vehicle |
| AGP | Aircraft Gateway Processor |
| AHP | Analytical Hierarchy Process |
| ALARP | As Low As Reasonably Practicable |
| ALM | Air and Littoral Manoeuvre |
| AMS | Acquisition Management System |
| AOF | Acquisition Operating Framework |
| AP | Armour-Piercing |
| ASE | Aircraft Survivability Equipment |
| ASW | Anti-Submarine Warfare |
| ATGW | Anti-Tank Guided Weapon |
| ATIRCM | Advanced Threat Infrared Countermeasure |
| AUM | All Up Mass |
| AVS | Air Vehicle Specification |
| AWC | Air Warfare Centre |
| BBC | British Broadcasting Corporation |
| BLOS | Beyond Line Of Sight |
| BOI | Board Of Inquiry |
| $C^2$ | Command and Control |
| $C^3I$ | Command, Control, Communications and Information |
| $C^4ISTAR$ | Command Control Communications Computers Intelligence Surveillance Target Acquisition and Reconnaissance |

| | |
|---|---|
| C$^4$I | Command Control Communications Computers and Intelligence |
| CADMID | Concept Assessment Demonstration Manufacture In-service Disposal |
| CAS | Close Air Support |
| CAS | Combat Air Support |
| CASEVAC | Casualty Evacuation |
| CBRN | Chemical Biological Radiological Nuclear |
| CBRR | Chemical Biological Radioactive Respirator |
| CC&D | Camouflage, Concealment and Deception |
| CDAS | Common Defensive Aids Suite |
| CFIT | Controlled Flight Into Terrain |
| CI | Consistency Index |
| CIFMEA | Combat-Induced Failure Mode and Effects Analysis |
| CIRCM | Common Infrared Countermeasure |
| CM | Countermeasure |
| CMDS | Countermeasure Dispensing System |
| CMWS | Common Missile Warning System |
| COEIA | Combined Operational Effectiveness Investment Appraisal |
| COP | Combined Operating Picture |
| COTS | Commercial Off The Shelf |
| CR | Consistency Ratio |
| CRV | Canadian Rocket Vehicle |
| CSAR | Combat Search and Rescue |
| CSRD | Contracted System Requirement Document |
| DAAvn | Directorate of Army Aviation |
| DARS | Directorate of Aviation Regulation and Safety |
| DAS | Defensive Aids Suite |
| DASC | Defensive Aids Suite Controller |
| DASC | Defence Aviation Safety Centre |

| | |
|---|---|
| dBA | Decibel, A-weighted |
| DEC | Directorate of Equipment Capability |
| DERA | Defence Evaluation and Research Agency |
| DEW | Directed-Energy Weapon |
| DG(S&A) | Director General Scrutineering and Analysis |
| DIRCM | Directed Infrared Countermeasure |
| DIS | Defence Industrial Strategy |
| DLOD | Defence Lines of Development |
| DNAE | Day Night Adverse Environment |
| DNAW | Day Night Adverse Weather |
| DoD | Department of Defense (US) |
| DPA | Defence Procurement Agency |
| DRIL | Detect Recognise Identify and Locate |
| DSTL | Defence Science and Technology Laboratory |
| DSTO | Defence Science and Technology Organisation |
| DT&E | Developmental Test and Evaluation |
| DTIC | Defence Technology and Innovation Centre |
| DVE | Degraded Visual Environment |
| EA | Electronic Attack |
| ECC | Equipment Capability Customer |
| ED | Electronic Defence |
| EM | Electromagnetic |
| EMP | Electromagnetic Pulse |
| EO | Electro-Optic |
| FIR | Far Infrared |
| FLIR | Forward Looking Infrared |
| FLOT | Forward Line of Own Troops |
| GAO | General Accounting Office |

| | |
|---|---|
| GLONASS | Global Navigation Satellite System |
| GNSS | Global Navigation Satellite Systems |
| GPS | Global Positioning System |
| HE | High Explosive |
| HEAT | High Explosive Anti-Tank |
| HELIACT | HELIcopter Acoustic Contouring Tool |
| HFI | Hostile Fire Indicator |
| HIDAS | Helicopter Integrated Defensive Aids Suite |
| HMG | Heavy Machine Gun |
| HMI | Human Machine Interface |
| HOQ | House Of Quality |
| HSE | Health and Safety Executive |
| HUMS | Health and Usage Monitoring System |
| IADS | Integrated Air Defence System |
| IED | Improvised Explosive Device |
| IFF | Identify Friend or Foe |
| IFV | Infantry Fighting Vehicle |
| II | Image Intensification |
| INCOSE | International Council on Systems Engineering |
| INS | Inertial Navigation System |
| IR | Infrared |
| IRA | Irish Republican Army |
| IRCM | Infrared Countermeasure |
| IRLS | Infrared Line Scan |
| IRST | Infrared Search and Track |
| ISA | International Standard Atmosphere |
| ISAAC | Integrated Survivability Analysis and Assessment Code |
| ISAM | Integrated Survivability Assessment Model |

| | |
|---|---|
| ISTAR | Intelligence Surveillance Targeting, Acquisition and Reconnaissance |
| ITEA | Integrated Test Evaluation and Acceptance |
| JATAS | Joint and Allied Threat Awareness System |
| JHC | Joint Helicopter Command |
| JSP | Joint Service Publication |
| KIA | Killed In Action |
| KSR | Key System Requirement |
| KUR | Key User Requirement |
| LADAR | Laser Radar |
| LIDAR | Light Detection and Ranging |
| LOS | Line Of Sight |
| LOSBR | Line of Sight Beam Riding |
| LVL | Low Visibility Landing |
| LWR | Laser Warning Receiver |
| MAIS | Major Automated Information System |
| MANPAD | Man Portable Air Defence |
| MANPADS | Man Portable Air Defence System |
| MARSG | MOD Aviation Regulatory and Safety Group |
| MASH | Mobile Army Surgical Hospital |
| MAW | Missile Approach Warner |
| MBT | Main Battle Tank |
| MCDA | Multi Criteria Decision Analysis |
| MCLOS | Manual Command to Line Of Sight |
| MDA | Mission Decision Aiding |
| MDAP | Major Defense Acquisition Programs |
| MDSS | Mission Decision Support Systems |
| MEDIVAC | Medical Evacuation |
| MIR | Middle Infrared |

| MISSION | Maritime Integrated Survivability Simulation |
| --- | --- |
| MITL | Man In The Loop |
| MJP | Military Judgement Panel |
| MMI | Man Machine Interface |
| MOD | Ministry of Defence |
| MOTS | Military Off The Shelf |
| MTI | Moving Target Indication |
| MVA | Multiattribute Value Analysis |
| MWC | Maritime Warfare Centre |
| NASA | National Aeronautics and Space Administration |
| NATO | North Atlantic Treaty Organisation |
| NAVAIR | Naval Air Systems Command |
| NEC | Network Enabled Capability |
| N-EMP | Nuclear Electromagnetic Pulse |
| NEO | Non-combatant Evacuation Operation |
| NIR | Near Infrared |
| NOE | Nap Of the Earth |
| NVG | Night Vision Goggles |
| OA | Operational Analysis |
| ORBAT | Order of Battle |
| OSDI | Open Systems Development Initiative |
| OSJTF | Open Systems Joint Task Force |
| OT&E | Operational Test and Evaluation |
| PD | Pulse Doppler |
| PLC | Public Limited Company |
| PN | Proportional Navigation |
| PPE | Personal Protective Equipment |
| PRF | Pulse Repetition Frequency |

| | |
|---|---|
| QFD | Quality Function Deployment |
| RAF | Royal Air Force |
| RAH | Reconnaissance Attack Helicopter |
| RAM | Radar Absorbing Material |
| RAO | Research Acquisition Organisation |
| RAP | Recognised Air Picture |
| RCS | Radar Cross Section |
| RF | Radio Frequency |
| RLP | Recognised Land Picture |
| RMP | Recognised Maritime Picture |
| RN | Royal Navy |
| RPG | Rocket Propelled Grenade |
| RWR | Radar Warning Receiver |
| SA | Situational Awareness |
| SACLOS | Semi-Automatic Command to Line of Sight |
| SAM | Surface to Air Missile |
| SAR | Search and Rescue |
| SAR | Synthetic Aperture Radar |
| SAS | Special Air Service |
| SEA | South East Asia |
| SEAD | Suppression of Enemy Air Defence |
| SEIC | Systems Engineering and Innovation Centre |
| SEPP | Systems Engineering Problem-solving Paradigm |
| SPIE | Society of Photo-Optical Instrumentation Engineers |
| SRD | System Requirement Document |
| SRL | System Readiness Level |
| SSM | Soft Systems Methodology |
| STA | Surveillance and Target Acquisition |

| | |
|---|---|
| STAR | System Threat Assessment Report |
| T&E | Test and Evaluation |
| TDP | Technology Demonstrator Programme |
| TLCM | Through Life Capability Management |
| TLMP | Through Life Management Plan |
| TREBAT | Technology Research Elements Benefits Analysis Tool |
| TRL | Technology Readiness Level |
| TTPs | Tactics, Techniques and Procedures |
| TV | Television |
| UAV | Uninhabited Aerial Vehicle |
| UHF | Ultra High Frequency (300 MHz to 3 GHz) |
| UK | United Kingdom |
| UOR | Urgent Operational Requirement |
| URD | User Requirement Document |
| US | United States |
| USA | United States of America |
| USSR | Union of Soviet Socialist Republics |
| USUR | Urgent Statement of User Requirement |
| UV | Ultra-Violet |
| V&V | Verification and Validation |
| VHF | Very High Frequency (30 MHz to 300 MHz) |
| XIR | Extreme Infrared |

# GLOSSARY

| | |
|---|---|
| Acquisition | "Acquisition translates industrial capacity into effective military capability. Acquisition is defined as: The activities of setting and managing requirements, negotiating and letting contracts, project and technology management, support and termination or disposal based on a through life approach to acquiring military capability" (Ministry of Defence 2007a). |
| Capability | "Capability is the enduring ability to generate a desired operational outcome or effect, and is relative to the threat, physical environment and the contributions of coalition partners. Capability is not a particular system or equipment" (Ministry of Defence 2007a). |
| Defence lines of development (DLOD) | The defence lines of development (DLOD) provide a pan-defence taxonomy to enable the coherent, through-life development and management of defence capability. The lines of development are: training, equipment, personnel, information, concepts and doctrine, organisation, infrastructure and logistics. Interoperability is an overriding theme (Ministry of Defence 2008a). |
| Detection | "Detection is the discovery by any means of the presence of something of potential military interest" (Richardson et al 1997). |
| Identification | "Identification is the stage in the [target] acquisition process in which the target is established as being friend or foe and its type" (Richardson et al 1997). |

| | |
|---|---|
| Open system architecture | An open systems architecture has "clearly and completely defined interfaces, which support interoperability, portability and scalability" (Kiczuk and Roark 1995). |
| Paradigm | "A conceptual framework within which scientific theories are constructed" (Schwarz 1991). |
| Recognition | "Recognition is the classification of the object of potential military interest by its appearance or behaviour" (Richardson et al 1997). |
| Requirement | "A requirement is an unambiguous statement of the capability that the system must deliver. It is expressed in operational terms (what the system will do) rather than solutions (how the system will do it)" (Elliot and Deasley 2007). |
| Surveillance | "Surveillance is the continuous systematic watch over the battlefield area to provide timely information for combat intelligence" (Richardson et al 1997). |
| System | "An integrated set of elements, subsystems, or assemblies that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements" (INCOSE 2010). |
| Systems engineering | "Systems engineering is the general term for the methods used to provide optimally engineered, operationally effective, complex systems. Systems engineering balances capability, risk, complexity, cost and technological choices to provide a solution which best meets the customer's needs" (Ministry of Defence 2005a). |
| Target acquisition | "Target acquisition is defined as the detection, recognition, identification and location of a target in sufficient detail to permit the effective deployment of weapons" (Richardson et al 1997). |
| Through life capability management | "Through life capability management translates the requirements of Defence policy into an approved programme that delivers the required capabilities, through-life, across all Defence Lines of Development" (Ministry of Defence 2007a). |

| Validation | "Have we built the right system?" (Buede 2000). |
| --- | --- |
| | Examines whether the right system has been developed and whether the system meets the needs of the stakeholders. |
| Verification | "Have we built the system right?" (Buede 2000). |
| | Examines whether the system was built correctly, i.e. meets the requirements specified during the design stage. |

# 1    INTRODUCTION

This chapter provides the context to the study. It explains the importance of helicopter survivability at the political, strategic and tactical level and provides supporting evidence from past operations. The chapter then sets out the research question and associated objectives. A thesis outline provides the 'research storyboard' that introduces each element of the research and links it to appropriate chapters, so assisting the reader in navigating through the work. Relevant survivability definitions have been identified and in some cases developed to help the reader to understand the subsequent work.

## 1.1    Context to the study

A high level of survivability is important to protect military personnel and equipment and is central to UK defence policy. Survivability is a key enabler in the delivery of effects based operations. The Defence White Paper, (Ministry of Defence 2003a), highlights the importance of protection of the Armed Forces: "Increased protection for our Armed Forces on operations is an area of continued importance and an important strategic enabler." The Dstl Technical Strategy, (Dstl 2004), states that "protection" is one of the means by which the broader objective of survivability is achieved. Survivability provides the capability to operate in areas that would otherwise be denied, as well as reducing attrition and protecting the lives of service personnel. "Integrated Survivability" is a prominent theme in both the Defence Industrial Strategy (Ministry of Defence 2005a) and the Defence Technology Strategy (Ministry of Defence 2006).

Past operations have shown that helicopters have been targeted by terrorists for operational gains and that losses have been exploited through the media for maximum political effect. In Northern Ireland during 1977, the Irish Republican Army (IRA) in South Armagh announced that enemy helicopters were a "priority target," and their tactics included concentrating on those aircraft believed to be carrying troops. Pro IRA newspapers at the time would then exploit these hostile actions to bolster the morale of IRA volunteers and sympathisers and to try to sway public opinion. The IR News, (Anon. 1988a), and the An Phoblacht Republican News, (Anon. 1988b), featured the shooting down of an Army Lynx on 23 June 1988, in a "spectacular attack." The attack was also recorded by the terrorists on video. This example demonstrates the importance of helicopter survivability and that the requirement for survivability can be driven by political as well as operational considerations.

There are also many examples of support helicopters having transported payloads of significant and strategic value. The loss of such a platform would have had a significant impact upon military capability as well as morale. During the Falklands war, a Sea King crashed resulting in the deaths of 22, including 18 Special Air Service (SAS) troopers from 'D' Squadron (Blakeway 1992). Whilst the cause was thought to be non-hostile (an engine failure because of the ingestion of a sea bird), (Paul and Spirit 2002), it demonstrates the payload that could be transported and the impact of such a loss. 29 personnel were killed in 1994 when a Chinook crashed on the Mull of Kintyre en route from Northern Ireland to Inverness (BBC 2010). Whilst this was an accident, it again demonstrates the significance of a single helicopter loss.

Ten helicopters, including three Chinooks, six Wessex and one Lynx were lost when the 'Atlantic Conveyor' was sunk by an Argentinean Exocet (Blakeway 1992). This was a great

loss of air mobility leading to campaign plan changes. Troops were marched into battle as a result. This resulted in a significant impact upon survivability at the force level. Helicopter losses can therefore impact upon the delivery of military effect at the campaign level.

In Iraq, recent figures show that most of the coalition lives lost in helicopter crashes are as the result of hostile action (119), closely followed by non-hostile causes (114). The helicopter losses caused by hostile action are responsible for 3.3% of coalition hostile losses (Kneisler and White 2008). The US DoD have stated that 69 US helicopters have crashed in Iraq since 2003 (Yates 2008). Apparently 36 of these were a result of hostile fire (Campbell and O'Hanlon 2008). Without a constant focus on survivability, it is likely that coalition losses would be far higher. Helicopter losses, the resulting loss of life, loss of operational capability and the cost of repair are important reasons why work in this area is so important.

In Iraq, the coalition experience has been that helicopters provide a safer means of transporting troops compared with road vehicles (Harris 2006). There have been many instances of road vehicles attacked by IED, by far the biggest single cause of US troop deaths (1 692, 40.8%) (Campbell and O'Hanlon 2008). However, insurgents have been increasingly targeting helicopters because they believe they are carrying a significant number of troops and because a helicopter crash is likely to be fatal (Harris 2006).

In Afghanistan, a significant proportion of coalition fatalities are as a result of helicopter crashes (13%), of these most are as a result of non-hostile causes (74%), compared with hostile (26%) (Kneisler and White 2008). Afghanistan has much more challenging terrain to operate within compared with Iraq. This leads to a significant proportion of troop movements by helicopter, so increasing troops' exposure within helicopters. Helicopters are also more likely to have a non-hostile crash (compared with Iraq) because of the terrain being more difficult to fly and land within. The threat to helicopters in Afghanistan and the consequence of their loss is high. In 2006, The Parachute Regiment almost had to retreat from Musa Qala as a consequence of a shortage of helicopters. Their commander, Brigadier Ed Butler was quoted as saying that: "the threat to helicopters from very professional Taliban fighters and particularly mortar crews was becoming unacceptable. We couldn't guarantee that we weren't going to lose helicopters" (Coghlan 2006). The National Audit Office (2004) has also identified a shortage of helicopter lift capability, further highlighting the impact of losing such valuable assets.

There is a growing emphasis upon manoeuvre and the "manoeuvrist approach" in delivery of military effect. This involves: "momentum, shock, surprise, and tempo to shatter an adversary's cohesion and will to fight" (National Audit Office 2004). Helicopters represent an important part of this capability because they possess good range, speed and flexible

deployment options. Helicopters operate within the full spectrum of operations from peacekeeping through to warfighting. This concept of employment often requires helicopters to operate close to the ground at slow speed or in the hover. This makes helicopters susceptible to a wide spectrum of threats ranging from ground-based weapons right through to sophisticated anti-aircraft systems.

Figure 1-1 shows some historical data on aircraft loss rates over the last sixty years. The general loss rate trend is downwards, consistent with the shift from attritional to more modern warfare, where near zero loss rates are expected. Most of these statistics relate to fixed wing, although of particular note are the helicopter losses sustained by the US during the South East Asia (SEA) conflict. The numbers in brackets relate to the actual numbers of aircraft lost.
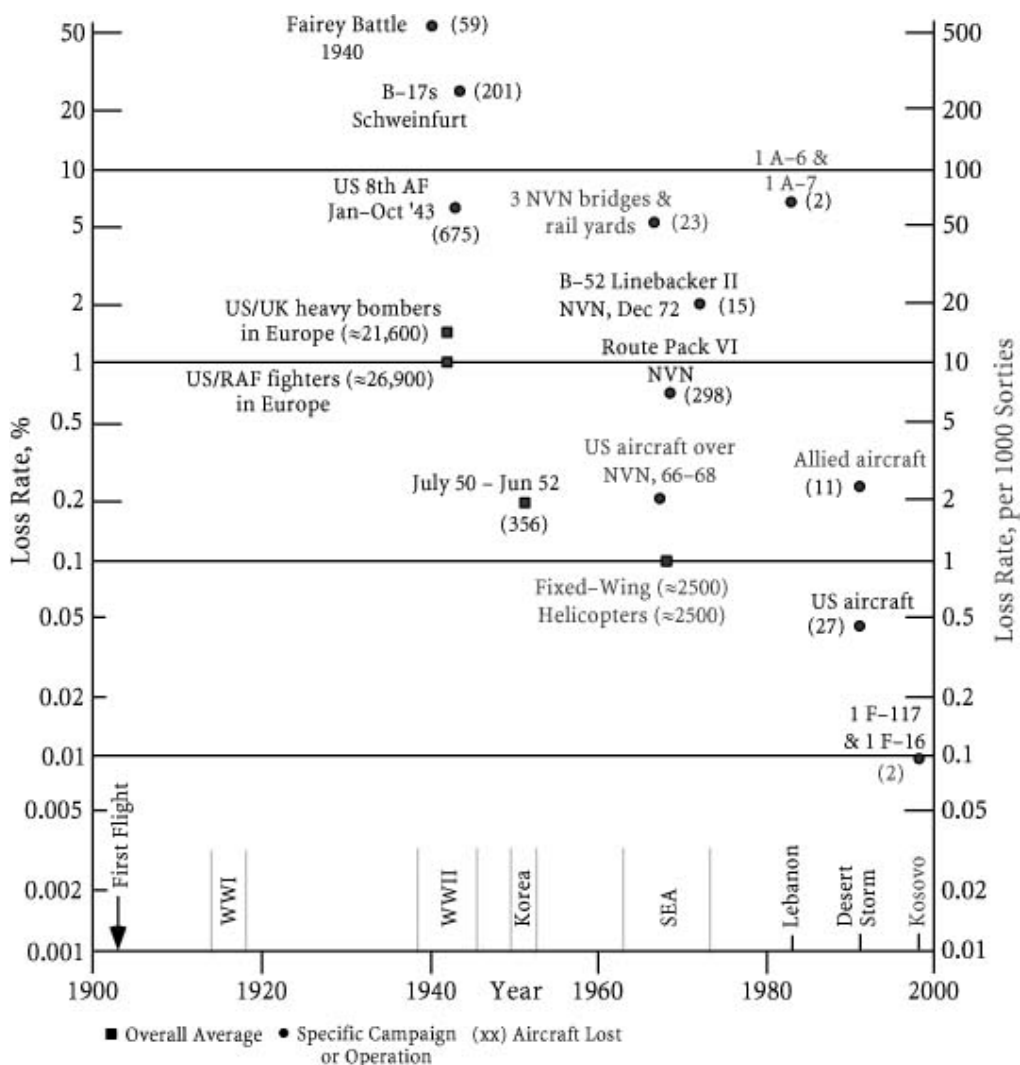


**Figure 1-1 – Historical aircraft losses from: "The Fundamentals of Aircraft Combat Survivability Analysis and Design," by Dr. Robert Ball (2003). Reprinted by kind permission of the American Institute of Aeronautics and Astronautics, Inc.**

Survivability has traditionally been considered within individual technical areas and at an individual platform level. A systems engineering approach is required to understand survivability as a whole taking into account the mission. This project aims to work towards this objective whilst being consistent with the following Dstl research aspiration:

"Establish a framework of understanding and models that allows an integrated approach to survivability planning, embracing susceptibility, vulnerability and recoverability and able to take account of all relevant lines of development" (Dstl 2004).

## 1.2 Aim and objectives

### 1.2.1 Aim

The aim of this work is to answer the following research question: "How can helicopter survivability be assessed in an integrated way so that the best possible level of survivability can be achieved within the constraints and how will the associated methods support the acquisition process?"

### 1.2.2 Objectives

The project aim will be realised through completion of the following objectives:

1. To research and develop the necessary definitions and background theory.

2. To carry out a literature search to develop knowledge and understanding of threats to military helicopters, survivability attributes and systems engineering.

3. To identify, develop and evaluate the processes and methods that could be applicable in evaluating the performance of an integrated helicopter survivability system. These methods and system engineering techniques will be critically appraised.

4. Investigate how effective balance of investment decisions can be made in survivability, throughout the concept, assessment, demonstration, manufacture, in-service and disposal, (CADMID) phases of the acquisition cycle.

5. Make conclusions and recommendations regarding the preceding work and evaluate potential application to the future acquisition of integrated helicopter survivability.

## 1.3 Thesis Outline

Chapter 1 provides initial context to the study, essential survivability definitions and defines the research question. The research needs to be conducted to enable the development of the integrated survivability toolset necessary to design the maximum level of protection possible for our military personnel, the aircraft and the mission.

The problem is that aircraft face a wide range of threats that are constantly evolving. In addition, predicting future scenarios is difficult and our aircraft procurement process takes a long time. Furthermore, aircraft have long service lives, sometimes in excess of 30 years. Consequently, aircraft are often used in theatres and in roles that they were not originally designed for and hence require appropriate survivability upgrade to deal with the changing threat as well as equipment obsolescence[1]. Until recently, survivability measures have been added in a non-integrated and ad-hoc manner. This work aims to provide a methodology and toolset to improve this situation.

The problem includes many diverse aspects that will need to be considered, such as: a wide range of helicopter concept of operations, a changing threat environment and varied survivability measures with interdependencies. These areas are introduced in Chapter 2 and provide essential background and context to the problem.

In order to deliver a more integrated analysis, the research approach examines techniques from the systems engineering, risk and quality domains. Chapter 3 reviews these areas and assesses their relevance to the problem. A number of methods were then selected to tackle the problem:

- System dynamics and the central 'influence diagram' method.

- Quality Function Deployment (QFD).

- The Analytical Hierarchy Process (AHP).

- Probabilistic methods.

In Chapter 4, the research work experimented with these methods in combination with the understanding gained in Chapters 2 and 3 and assessed the utility of the different approaches. The following research outputs were developed by the author and discussed:

- A helicopter survivability assessment process (Section 4.1.2) that situated the survivability modelling within the context of reducing survivability risk to as low as reasonably practicable (ALARP).

- A helicopter survivability influence diagram (Section 4.4) to capture the wider survivability related issues and defence lines of development (DLODs).

- A helicopter survivability QFD model (Section 4.6).

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[1] For example, the UK Apache helicopter was originally procured for anti-armour operations against Soviet and Warsaw Pact forces over the German plains. By the time the contract was placed in 1996, the threat had changed (NAO 2002). It was not employed in this specific scenario and is now being used in a close air support role against a different threat within mountainous Afghanistan (Macy 2008).

- A probabilistic tool called the Integrated Survivability Assessment Model (ISAM)[2] (Section 4.8).

The probabilistic tool provided a promising approach for quantifying survivability risk and was used in a case study to further assess its suitability in answering the research question. Supporting methods to provide input data to the probabilistic approach were developed, including a method to calculate the rate of encountering threats, taking into account military judgement and threat information (Section 4.8.2).

The discussion (Section 4.10) identifies the lessons learnt from the research outputs and discusses how the methods could be applied at the different stages of a military helicopter's lifecycle. Wider issues such as the rationale for considering combat losses separately from accidental losses are also discussed.

Chapter 5 presents the conclusions arising from the research outputs and how they are related to the research question. The recommendations arising from the conclusions are also presented and related to future research needs.

## 1.4 Definitions

### 1.4.1 Survivability

The following definition for "survivability" has been formally stated within the Dstl Technical Strategy, (Dstl 2004), and has been adopted across all the survivability domains within Dstl:

"Survivability can be defined as the ability to complete a mission successfully in the face of a hostile environment, and may be broken down into three elements: susceptibility, vulnerability and recoverability:"

- Susceptibility is the extent to which own forces are likely to be found, targeted and hit by a weapon system employed against them;

- Vulnerability determines the consequences of being hit;

- Recoverability is the extent to which mission capability can be restored following damage.

Figure 1-2 illustrates the Dstl definition. For the purposes of this study, the Dstl definition of survivability has been adopted; moreover, it is currently the only formal UK definition in existence and is consistent with definitions used by the US and NATO. It is likely that this definition will develop in the future to include force level considerations. It is anticipated

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[2] The ISAM concept and design was the author's idea. The ISAM software was developed by a colleague.

that these force level considerations will bring in enabling technology such as network enabled capability (NEC)[3].
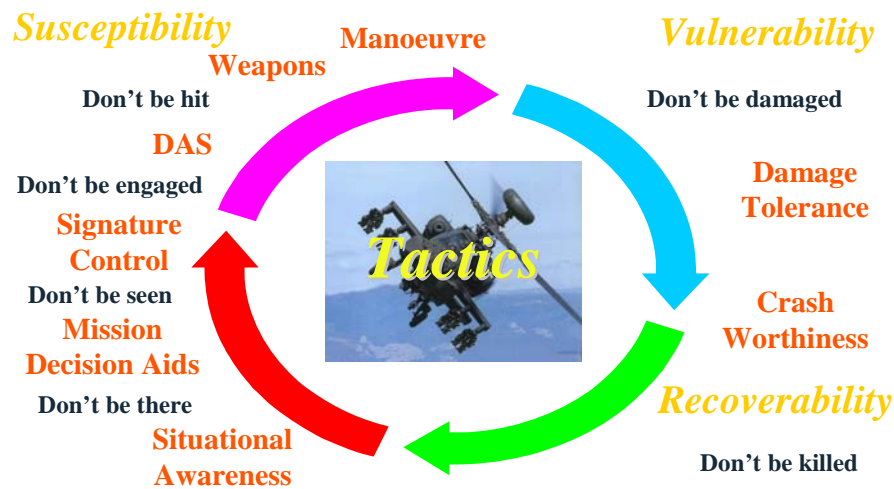


**Figure 1-2 - Integrated mission survivability, (Wickes 2005).**

There are many other definitions for "survivability," most of which originate from the US, and these have been included within Appendix A. The definition of survivability used for the current work only includes losses as a result of direct hostile action and does not consider losses as a consequence of "operational mishaps"; for example, controlled flight into terrain, (including wires) or airworthiness and safety defects. There is a 'grey area' when an aircraft is forced to fly at low level to reduce its susceptibility to threats and then flies into the terrain because of pilot error. This example would be classed as an 'operational mishap' even though it occurred within the context of a hostile environment.

The US lost a total of 4869 rotary wing aircraft in Vietnam between 1962 and 1973, see Table 1-1. 2587 were a result of hostile action and almost as many (2282) because of operational mishaps (Ball 2003). Equivalent statistics for UK helicopter losses to hostile action are not available, although some published data is available. A number of recent UK helicopter losses have been reported as accidents and operational mishaps. For example, 'brownout' or degraded visual environment (DVE) is a common safety problem experienced in Iraq and Afghanistan (Ministry of Defence 2007b). Appendix B provides further details of recent UK helicopter incidents and Appendix C provides statistics of RAF helicopter accident rates from 1980 - 2004.

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[3] NEC is defined as "the enhancement of capability through the effective linkage of platforms and people through a network" (Ministry of Defence 2003a). JSP777 states that: "NEC is about the coherent integration of sensors, decision-makers, weapon systems and support capabilities to achieve the desired military effect" (Ministry of Defence 2005b).

**Table 1-1 - US helicopter losses during the Vietnam conflict, 1962 – 1973, (Ball 2003, Summers 2005).**

| Cause | Aircraft losses | Fatalities | Sorties | $P_s$ % |
|---|---|---|---|---|
| Hostile action | 2587 | 4906 | 36,125,000 | 99.993 |
| Accidents | 2282 | N/A | 36,125,000 | 99.994 |

The safety community sometimes refer to "survivability" when they describe the ability of an aircraft to survive a crash, i.e. "crashworthiness". However, "crashworthiness" is just one attribute contributing to survivability within the overall "survive within the hostile environment" definition. A crash in the non-hostile context could be as a result of pilot error or aircraft failure, rather than because of direct hostile action. The three elements of survivability are explained in the following sub-sections.

*Susceptibility*

Susceptibility is defined as: "the extent to which own forces are likely to be found, targeted and hit by a weapon system employed against them" (Dstl 2004). Reducing system susceptibility is achieved by:

- Avoiding an encounter with the threat (depending on the mission objectives), i.e. 'don't be there.' Examples that promote this idea include the effective use of: mission planning and C4ISTAR (command, control, communication, computers, intelligence, surveillance, target acquisition and reconnaissance).

- Preventing the threat from detecting the system (this may also depend on the mission objective): i.e. if the aircraft must be there then 'don't be seen.' Examples include the use of tactics (e.g. flight altitude dependent upon threat) and stealth (e.g. infrared (IR) and radio frequency (RF) signature control).

- Preventing the threat from engaging the system, i.e. if the aircraft is seen then 'don't be engaged.' Examples include: signature control and tactics (e.g. manoeuvre and nap-of-the-earth (NOE) flight).

- Preventing the threat from hitting the system, i.e. if the aircraft is engaged then 'don't be hit.' Examples include: a defensive aids suite (DAS) consisting of threat warning, control and countermeasure techniques.

*Vulnerability*

Vulnerability "determines the consequences of being hit." Reducing system vulnerability is achieved by:

- Tolerating an effect of the hostile environment, i.e. if the aircraft is hit then 'don't be damaged.' Examples include: armour and self sealing fuel tanks.

- Tolerating damage to the crew and passengers, i.e. if the aircraft is damaged then 'don't be killed.' Examples include: crew body armour and fire-fighting equipment.

*Recoverability*

Increasing system recoverability is achieved by;

- Containing damage and recovering a level of warfighting capability after damage, i.e. if the aircraft is damaged then 'be recoverable.' Examples include: single engine performance to enable escape to safety in the event of one engine being destroyed and having a crashworthy structure and fuel system.

Recoverability is considered from the point where the platform has sustained damage. The maritime domain has the greatest emphasis on recoverability, because a ship is not just a weapons platform, but also the home for a hundred or more sailors. When a ship sustains damage there is often time and a chance of recovery before sinking. A criticality rating is used to determine the seriousness of an incident, which then defines the minimum manpower required to deal with it. The distinction between vulnerability and recoverability can sometimes be difficult to determine. On a ship, vulnerability is dependent upon the design and build, whilst recoverability is a function of people and equipment. Within the maritime domain there are seven pillars for recoverability: situational awareness (within the ship); containment; prosecution; restoration; escape and evacuation; external assistance and management (Thornton 2008). Management is the most important because it brings together the right resources at the right time. These pillars can also be applied to the air and land domains, albeit on a smaller scale.

The recoverability definition also depends upon which survivability level (see Section 1.4.3) is being considered. At the platform level, recoverability will include platform attributes such as: crew egress, communications, crashworthiness and fire suppression. At the mission level, recoverability embraces the requirement for troops to get out of an aircraft if it is brought down and continue the mission. At the force level, recoverability has a broader remit, which will include attributes such as: combat search and rescue (CSAR) capability and aircrew escape and evasion training. The force level will include recovery of crews even if platforms are non-recoverable, i.e. damage category 5 or greater (a total platform loss).

Availability of trained aircrew rather than numbers of operational aircraft can be the most limiting factor affecting tempo of operations.

*Survivability equation*

A mission can be considered as a number of events that have a certain likelihood of occurrence. Some events can even be considered to have an element of randomness, for example, a 'pop-up' threat. For this reason, survivability is often expressed as a probability of survival and is denoted as $P_s$. The meaning and value of $P_s$ will depend upon the situation being considered; for example, it could refer to the probability of surviving a mission or the probability of surviving an engagement. See Ball (2003), for a comprehensive set of survivability equations at engagement (one-on-one), mission (many-on-many) and campaign levels.

The probability of survival, $P_s$ can be expressed as follows:

$$P_s = 1 - \left[ P_H \times P_{K|H} \times (1 - P_{R|K}) \right]$$

$P_H$ is the probability of a hit, i.e. the probability that the system is unable to avoid the hostile environment (susceptibility);

$P_{K|H}$ is the probability of a kill given a hit, i.e. the probability that a system kill will be achieved if the system has failed to avoid the hostile environment (vulnerability); and

$P_{R|K}$ is the probability of recoverability given a kill, i.e. the probability that mission capability can be restored following damage, within an operationally relevant timescale, if a system kill has been achieved (recoverability).

### 1.4.2    *Integrated survivability*

"Integrated survivability is the systems engineering methodology to achieve optimum survivability at an affordable cost, enabling a mission to be completed successfully in the face of a hostile environment" (Ministry of Defence 2006). "Integrated Helicopter Survivability" is an emerging discipline that is applying this systems engineering approach within the helicopter domain. This involves understanding the emergent system properties, how the overall system interacts with its environment and the effect of this upon survivability. Survivability is a system characteristic that contributes to delivering the overall military effect. It enables the military to deliver the mission in a man-made hostile environment and so operate in areas that would otherwise be denied.

Many platform systems (for example: communications systems, IR suppression, defensive aids suites and terrain following radar), either intentionally or unintentionally, improve or reduce the survivability of the platform. An integrated systems engineering approach is

required to understand the relative contributions of all aspects of the system design, to the overall survivability of the system. Survivability considerations are not only limited to the equipment line: "A truly integrated approach to survivability should take into account all relevant lines of development[4], including concepts and doctrine, training and sustainability as well as equipment capability" (Dstl 2004). This point emphasises the fact that survivability is set within an overall context of military capability.

Improvements to aircraft safety can also provide a survivability benefit, for example, improved "crashworthiness". Any survivability solution should not increase the risk of losing the aircraft to a non-hostile action and should be balanced at the whole system level. For example, adding ballistic protection may reduce vulnerability, but if the weight penalty is too high then susceptibility could be increased because of the adverse effect upon manoeuvrability or agility. Overall system effectiveness could also be reduced because the weight penalty would reduce payload and range capabilities. Ball (2003), emphasises this point: "A military aircraft cannot be effective if it is not survivable. However, a survivable aircraft is not necessarily an effective aircraft."

Ultimately the wider capability trade-offs need to be evaluated at a higher level than survivability in isolation. This work aims to develop understanding within the helicopter survivability domain and the resulting output could potentially be used within higher level trade-off tools.

### 1.4.3    Levels of survivability

It is appropriate to recognise different 'levels' of survivability depending upon where the system boundary is drawn; however, this study was unable to find existing survivability level definitions. Four levels are proposed to provide decomposition of the survivability definition from force to crew level. These definitions are all framed "in the face of a hostile environment," to be consistent with the overarching Dstl survivability definition. Figure 1-3 attempts to illustrate the concept of survivability levels for a force, although it is recognised that this is still developmental.

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4 The defence lines of development (DLOD) provide a pan-defence taxonomy to enable the coherent, through-life development and management of defence capability. The lines of development were updated in 2005 to: training, equipment, personnel, information, concepts and doctrine, organisation, infrastructure and logistics (Ministry of Defence 2005a). Interoperability is an overriding theme (Ministry of Defence 2008a).
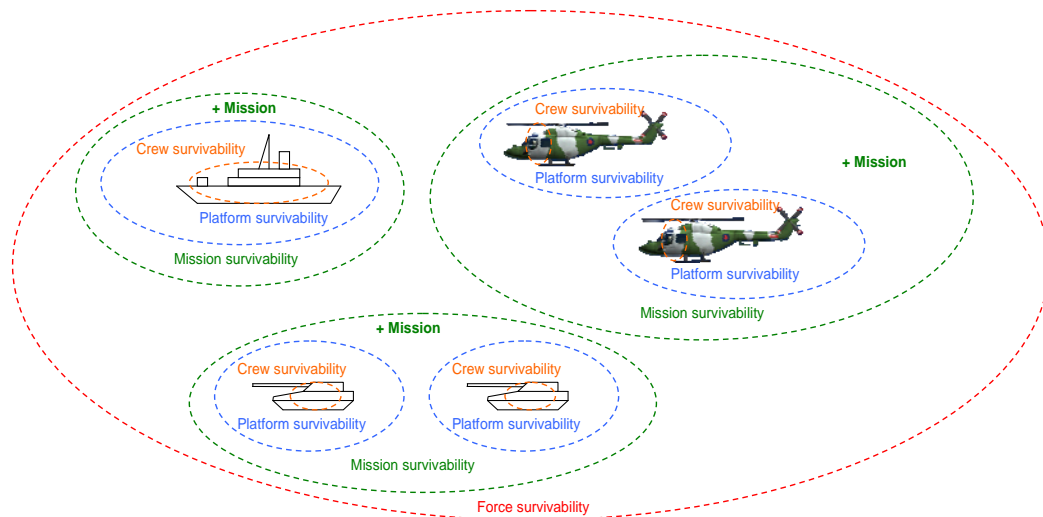
**Figure 1-3 - Survivability Levels.**

*Force level*

Survival at the force level recognises that force-level survivability could be affected by a mix of air, land and naval platforms surviving and being able to undertake a mission or missions that would influence overall force level campaign objectives. Survivability at the force level would be provided by mutual provision of components of the survivability solution (e.g. mutual protection) by the force. This could be defined as: "Survivability of the force to a level that it can carry out the overall campaign objectives." Force-level survivability subsumes mission level, which then subsumes platform level and which in turn subsumes crew level.

*Mission level*

At a mission level the successful mission delivery requires survival of platform capability. This could be defined as: "the survivability required by the platform to carry out its mission and return to base." Successfully delivering payload (e.g. troops) would be considered as part of the mission. As crew are an essential part of the platform system, survival of the crew would also be expected in order to achieve "mission level survivability." There is some debate on this issue, as the mission could be considered 'successful' even if some aircrew were killed or injured.

*Platform level*

Survival of the platform and crew. This could be defined as: "the platform returns to base and no crew member is killed in action (KIA) or critically injured." This could arguably be considered the minimum required operational level of survivability. Platform survivability

could be achieved by compromising the mission, for example by shedding payload to enable a defensive manoeuvre.

*Crew level*

Survival of the crew. If it is not possible to achieve "platform survivability," then this is the lowest level of survivability that would be desirable. This could be defined as: "no crew member is KIA or critically injured."

## 1.5    Summary

This chapter has provided the context to the study. It has set out the research question and associated objectives. A thesis outline provides the 'research storyboard' that introduces each element of the research and links it to appropriate chapters, so assisting the reader in navigating through the work. Relevant survivability definitions have been identified and in some cases developed to help the reader to understand the subsequent work.

A high level of survivability is important to protect military personnel and equipment and is central to UK defence policy. Survivability also provides the capability to operate in areas that would otherwise be denied, so enabling the mission. A helicopter loss can have devastating human consequences as well as serious consequences militarily and politically.

Helicopters are an important part of air manoeuvre[5] capability and consequently deploy to the full spectrum of operations from peacekeeping through to warfighting. They are often required to operate low and slow in a hostile environment. This makes helicopters susceptible to a wide spectrum of threats ranging from ground-based weapons right through to sophisticated anti-aircraft systems.

Given that protection of our helicopters and personnel is so important, the best possible level of survivability must be provided within the constraints of: cost, time, technical risk, space power and weight. In response to this requirement, the aim of this work is to answer the following research question: "How can helicopter survivability be assessed in an integrated way so that the best possible level of survivability can be achieved within the constraints and how will the associated methods support the acquisition process?"

To help the reader to understand the subsequent work, the two overarching survivability definitions have been identified as follows:

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[5] Air manoeuvre is defined as: "Those operations primarily within the land scheme of manoeuvre, seeking decisive advantage by the exploitation of the third dimension by combined-arms forces centred around rotary-winged aircraft, within a joint framework" (Ministry of Defence 2003b).

"Survivability can be defined as the ability to complete a mission successfully in the face of a hostile environment, and may be broken down into three elements: susceptibility, vulnerability and recoverability:" (Dstl 2004)

- Susceptibility is the extent to which own forces are likely to be found, targeted and hit by a weapon system employed against them;

- Vulnerability determines the consequences of being hit;

- Recoverability is the extent to which mission capability can be restored following damage.

"Integrated Survivability is the systems engineering methodology to achieve optimum survivability at an affordable cost, enabling a mission to be completed successfully in the face of a hostile environment" (Ministry of Defence 2006).

The chapter has defined different 'levels' of survivability that recognise the strategic and tactical elements to the above overarching definitions.

# 2     COMBAT HELICOPTER SURVIVABILITY

This chapter provides essential background material to help to define the problem. It introduces the wide range of combat helicopter roles, the evolving threats that can be used against them and the survivability attributes that can be adopted to defeat those threats. This knowledge and understanding of the problem is used later on in conjunction with the systems engineering material (Chapter 3) to identify suitable research approaches and methods to develop further in Chapter 4.

## 2.1     Military use of helicopters

Military helicopters are used extensively in a wide variety of roles in support of the battlefield. Their high utility continues to be demonstrated in Iraq and Afghanistan as is widely published in the press. Indeed they are a valuable asset militarily and are in high demand. This utility has been the result of a gradual iterative development of the requirement, equipment and associated concepts and doctrine since the early 20th century.

The idea to use a helicopter for observation on the battlefield dates back to 1916. The early designs were unsuccessful and it was not until the 1930s that there was significant interest in the idea. These early designs were actually autogiros and so could not hover. The British and the US evaluated a number of aircraft and concluded that autogiros were not suitable for battlefield use because of their limited performance and payload. In 1937 Germany demonstrated the first landing using auto-rotation in a Fa 61. This was an important step in demonstrating inherent safety in helicopter design. During the Second World War autogyros were used more than helicopters for army observation and communications duties. Germany built the first helicopter to be used operationally, the Flettner Fl 282 Kolibri, which was used for naval reconnaissance and anti-submarine patrol (Everett-Heath 1992).

The first rescue of aircrew behind enemy lines was carried out by the US in 1944 in a Sikorsky R-4. It was not until post the Second World War that helicopter capability passed that of autogyros and the role developed into movement of men and materiel. In 1946 the US appreciated the need for a marine helicopter to achieve dispersion and rapid concentration for amphibious forces in order to reduce the risk during a nuclear scenario. At the same time the British identified requirements for: observation, heavy lift, anti-submarine warfare (ASW) and search and rescue (SAR) (Everett-Heath 1992).

The utility of helicopters was gradually realised and developed during the subsequent conflicts, including: The Korean War (1950-53), The Malayan Emergency (1948 – 1960), Algeria (1954-62), Vietnam (1961-73), Borneo (1963-66), Aden (1964-68), Afghanistan (1979-89), Iran-Iraq (1980-88), The Falklands (1982) and The Gulf War (1991) to the present day.

The Korean War was the first conflict to use helicopters in a large scale, mainly in the medical evacuation role. US Army and Air Force helicopters flew in support of the Mobile Army Surgical Hospitals (MASH) rescuing casualties (approximately 30 000) and conducting combat rescue of 996 aircrew that had been shot down. The US Marines conducted the first tactical lift of men and materiel within the combat zone and in four hours inserted 224 troops and almost 18 000 pounds of payload (Dunstan 2003).

The British conducted the first extensive use of helicopters for counter-insurgency warfare during the Malayan Emergency. 26 Navy and RAF helicopters were used to insert and extract troops (including SAS) within remote jungle areas, casualty evacuation, reconnaissance, crop contamination and dropping leaflets (Dunstan 2003).

During the Algerian War, French forces used helicopters in the air assault role. They also developed armed helicopters, mounting 20 mm cannon, rocket pods, machine guns and anti-tank missiles to suppress ground fire (Dunstan 2003).

The US continued to develop their helicopter tactics and doctrine during the Vietnam conflict. In 1964 the 11th Air Assault Division (Test) confirmed the airmobile concept as a method to improve tactical mobility. The US developed armed helicopters for escort and fire suppression of landing zones. The concept was taken further with the development of dedicated helicopter gunships for close fire support of troops on the ground. Even the Chinook had a 'Go-Go Bird' gunship variant equipped with extra armour, grenade launchers, cannon, rocket launchers and machine guns (Dunstan 2003).

Helicopters were used extensively by British forces during the Falklands War, particularly for moving men and ammunition forward. However, the loss of the Atlantic Conveyor with ten helicopters onboard restricted the 'air manoeuvre' operation significantly. Some momentum was lost with troops having to march across difficult terrain into battle (Blakeway 1992).

The load-lifting role and tactical flexibility provided by helicopters has contributed greatly to the success of the land battle. Helicopters provide the means to move troops, equipment and artillery quickly across difficult terrain, so reducing the conflict duration and number of casualties (Everett-Heath 1992). It is evident that the range of helicopter roles has increased extensively as the concept of 'air manoeuvre' has developed.

Helicopter roles or tasks can be grouped into the broader roles identified in Table 2-1. It should be noted that some tasks, for example combat search and rescue (CSAR), span two or more of the broader roles.

**Table 2-1 – Combat helicopter roles and tasks**

| Role | Task |
|------|------|
| Find | Observation |
| | Reconnaissance |
| | Communications |
| | Command and control |
| | Anti-submarine warfare (ASW) |
| | Airborne early warning (AEW) |
| | Mine sweeping (e.g. MH-53E) |
| | Search and rescue (SAR) |
| | Combat search and rescue (CSAR) |
| Lift | Troop movement (insertion & extraction) |
| | Non-combatant evacuation operations (NEO) |
| | Materiel movement (inc. weapons, ammunition, vehicles) |
| | Leaflet drops and psychological warfare tasks |
| | Resupply |
| | Towing boats |
| | Casualty and medical evacuation (CASEVAC / MEDEVAC) |
| Attack | Ground attack (e.g. anti-armour) |
| | Close air support (CAS) |
| | Bombing (e.g. 'Hind' and 'HIP' in Afghanistan during 1979 – 89) |
| | Minelaying |
| | Air-to-air combat (e.g. anti-helicopter) |
| | Escort |
| | Stop and search |

## 2.2 Threats to helicopters

The purpose of this section is to identify possible threats to helicopters, develop understanding of the problem and to help to inform the development of the methods in Chapter 4. Understanding the threat environment is fundamental to understanding the survivability problem.

A system can be considered to be a threat if it has the opportunity, the intent and the capability to attack a helicopter. The threat environment definition is a useful starting point and must consider the operational context, taking into account the aircraft role. Threats to helicopters include: small arms, heavy machine guns (HMGs), anti-aircraft artillery (AAA),

rocket propelled grenades (RPGs), anti-tank guided weapons (ATGWs), man-portable air-defence systems (MANPADS), armed helicopters and tactical and strategic surface to air missile (SAM) systems. These threats can operate autonomously, or in groups, or they can be part of a larger scale integrated air defence system (IADS), complete with surveillance sensors, command centres and weapon firing platforms (Ball 2003).

Historical records show that during the Vietnam conflict, American forces sustained a very high number of helicopter losses because of hostile action. The numbers of helicopters lost by threat category were stated by the Comptroller, Officer of the Secretary of Defense and are set out in Table 2-2[6] (Everett-Heath 1992).

**Table 2-2 – Number of US helicopter combat loses in Vietnam by threat category from 1962 – 1973 (Everett-Heath 1992, Dunstan 2003).**

| Threat | Number of helicopters lost |
|---|---|
| Small arms and AAA | 2373 |
| Fighter aircraft (MIGs) | 2 |
| SAMs | 7 |
| Destroyed on the ground (attacks on helicopter bases) | 205 |

During the 1979-1989 war in Afghanistan, it is estimated that around 500 helicopters were lost; however, there are no statistics published by the Russians. It is likely that around half of these were lost as a consequence of the challenging terrain and the risk of flying at low-level. Significant hostile losses were a result of small arms, machine guns and cannon. SA-7, Blowpipe and Stinger also achieved kills, with Stinger being the most successful SAM. Helicopters were also lost on the ground because of attacks on bases by the Mujaheddin (Everett-Heath 1992). Lake (2009) suggests that 333 Russian helicopters were destroyed by MANPADS and heavy-calibre machine guns.

### 2.2.1 *Small arms*

"A gun is a device, including any stock, carriage, or attachment from which projectiles, rounds, or high-explosive shells are propelled by the force of an explosive reaction" (Ball 2003). "Small arms are man-portable, individual, and crew-served guns (weapon systems) that fire projectiles up to and including 20 mm in diameter" (Ball 2003). Tracer rounds are often mixed with ball or armour piercing ammunition to help the gunner to guide the rounds on to the target. Small arms include: pistols, shoulder-fired rifles, carbines, assault rifles, submachine guns and light and heavy machine guns. Typical projectile calibres in

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[6] See the appendices in Dunstan (2003) for further Vietnam helicopter statistics.

millimetres are: 5.56, 7.62, 12.7, 14.5 and 20. The most widely proliferated of all small arms is the AK-47 assault rifle and it is estimated that around 100 million of these weapons have been manufactured worldwide.

Historical records show that small arms achieved a high number of helicopter kills in Vietnam and during the 1979 – 1989 Afghanistan conflict (Everett-Heath 1992). This threat remains dangerous today. An RAF Chinook received damage from 7.62 mm and .50 calibre rounds in Afghanistan in May 2008. One .50 calibre round hit the gearbox and was fortunately deflected by a nut. Had the round entered the gearbox it could have destroyed it, causing catastrophic damage (Loveless 2009).

### 2.2.2  *Anti-aircraft artillery*

Guns firing projectiles over 20 mm in calibre can be classed as anti-aircraft artillery (AAA) and can be further categorised into: light AAA (21 - 59 mm), medium AAA (60 - 99 mm) and heavy AAA (≥100 mm). AAA often includes a high explosive element that provides a blast and fragmentation effect upon impact or after a set time (Ball 2003). AAA is a highly prolific threat and has achieved many helicopter kills, including during the Vietnam conflict, see Table 2-2.

AAA can be manually aimed or RF guided, for example in the case of the Russian 'Shilka' ZSU-23-4[7] (Janes 2008a). The ZSU-23-4 is a tracked, self-propelled gun system that has four 23 mm cannon firing 800 to 1000 rounds per barrel per minute. The system uses a 'Gun Dish' radar to search, detect and then automatically track a target. An optical sight can be used to augment the radar system. Night vision and ammunition upgrades are available to improve the passive night time capability and to improve range and lethality (Jane's 2008a). AAA and SAM systems can also be combined on a single weapon platform to engage aircraft at low and medium level. Examples include the 2S6 based Tunguska (SA-19 'Grison') and Pantsir-S1 (SA-22 'Greyhound'). These systems are rapidly re-deployable and can be fired on the move (Jane's 2009).

### 2.2.3  *Rocket propelled grenade*

Rocket propelled grenades (RPGs) consist of a hand-held, shoulder launcher and unguided rockets fitted with an explosive warhead. They were originally designed as infantry weapons used to destroy armoured vehicles. The RPG-7 variant was introduced by the Russians in 1962. The PG-7 grenade is ejected from the launcher by a boost charge. At approximately 11 m downrange, the sustainer motor fires taking the rocket to around 300 m/s. Accuracy is

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[7] ZSU is the Russian abbreviation for: 'Zenitnaia Samokhodnaia Ustanovka,' meaning 'self-propelled anti-aircraft mount'.

improved by a set of canted fins that fold out after launch, inducing a spin stabilisation to limit dispersion. The weapon self-destructs at around 900 m (Department of Defense 1976).

Historically, RPGs have also been effective against helicopters, especially when they are hovering or on the ground. Out of 380 incidents involving RPGs during the Vietnam conflict (until 1971), 128 helicopters were destroyed. Other weapons hit 54 times as many aircraft compared with RPGs, however only nine times as many aircraft were destroyed (Dunstan 2003). RPGs have also been adapted by guerrilla and terrorist organisations to improve their effectiveness against helicopters. This was demonstrated when two US MH-60 Black Hawk helicopters were destroyed by Somali gunners in October 1993 (Hunter 2002). "As demonstrated in Somalia, even nations without complex integrated air defense systems have demonstrated the capability to inflict casualties on technologically superior opponents" (Rodrigues 1999). The US recognise the importance of this threat and have recently conducted live-fire testing of complete AH-1 helicopter platforms against RPGs (O'Connell 2006).

RPGs are still a very real threat as experienced during operation HERRICK, where the Taleban have targeted UK helicopters with RPGs (BBC 2006). In one such attack, the BBC (2006) reported that four RPGs were fired at helicopters from one location. An RAF Chinook carrying a VIP party was severely damaged by RPG during a mission in May 2008. As a result, one hydraulic system failed and a large portion of a rear rotor blade was destroyed, making the aircraft extremely difficult to control (Barrie 2009 and Loveless 2009).

### 2.2.4 *Anti-tank guided weapons*

An anti-tank guided weapon (ATGW) is designed to damage or destroy armoured targets, although the "weapons are evolving to meet emerging battlefield requirements" (Foss 2009). The first ATGW, the air launched XH-7 was fielded by German forces towards the end of the Second World War (Rouse 2000).

First generation ATGW systems use a manual command to line of sight (MCLOS) guidance system and are short range (Foss 2009). MCLOS requires the operator to steer the missile to the target typically using a joy stick or pressure switch. The steering commands are sent via a wire or radio link. The missile usually has a flare at the rear to help the operator track the weapon and subsequently superimpose the missile "over the top" of the target until impact occurs. MCLOS ATGWs have the advantage of being relatively cheap and resistant to enemy countermeasures. The disadvantages are that the operator must be highly skilled and requires frequent training (Rouse 2000).

Second generation ATGW systems use a semi-automatic command to line of sight (SACLOS) guidance system, have increased range and are more reliable than first generation systems (Foss 2009). SACLOS requires the operator to track the target using a telescopic sight with a graticule. An automatic missile tracking system is boresighted to the target tracker or aligned to it via a servo system. The missile usually has a tracking beacon and when the missile is launched, the automatic target tracker detects any deviation from the LOS. Errors are processed by the tracking system, which then outputs the correct command to the missile via the command link (Rouse 2000).

Third generation ATGW systems can use beam riding or homing techniques and can attack the target from above. Line of sight beam riding (LOSBR) systems require the operator to track the target in the same way as a second generation system and a laser beam is directed along the LOS. A rearward facing laser receiver maintains the missile within the laser beam and hence the LOS. Fire-and-forget systems using an imaging infrared seeker have also been developed, such as the Raytheon/Lockheed Martin Javelin (Foss 2009). Third generation systems can have a 'soft launch' that reduces the signature when firing, so improving operator survivability (Rouse 2000).

ATGWs can also be integrated on to land vehicles and helicopters. Armoured fighting vehicles (AFVs) are capable of firing certain types of ATGWs from the main gun (e.g. Soviet T-64B and T-80) or from a turret-mounted launcher. Infantry fighting vehicles (IFVs) can have ATGW supplementing the main armament, for example the Russian BMP-1 or BMP-2 can have AT-3 'Sagger' and AT-5 'Spandrel' integrated, respectively (Foss 2009).

ATGWs are developing to deal with a wider range of targets such as buildings, bunkers and light armour, requiring the use of a range of warheads including tandem HEAT and thermobaric. Night vision equipment can also be fitted to improve engagement opportunities (Foss 2009). ATGWs generally fly relatively slowly because of the 'man-in-the-loop' guidance; however, they are effective against slow moving and hovering helicopters (Rouse 2000).

### 2.2.5 *Man-portable air-defence systems*

Man-portable air-defence systems (MANPADS) are a type of surface-to-air missile (SAM) consisting of a launcher, a grip stock and a missile. The missile consists of guidance, warhead, control and propulsion systems. MANPADS usually use passive IR homing with proportional navigation[8] (PN) for guidance to intercept a target (Rouse 2000). Taking the

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[8] How PN works: A seeker continually tracks the target and determines the sight line from the missile to the target. The missile guidance system measures the rate at which the sight line is changing in three dimensions. The rate of change of the missile trajectory is made proportional to the rate of change of the sight line in order to make the rate change to zero. Eventually the missile achieves a constant heading because the rate of change of

SA-7 as an example, a shoulder launcher fires the Grail missile that uses passive infrared homing for guidance and has a high explosive (HE) warhead with a contact fuze. A solid fuel boost and sustain motor provide a maximum range of approximately 3 500 m. The SA-7 can be used against aircraft flying from altitudes of 50 - 3 000 m and can be fired from the ground or from a vehicle (Ball 2003).

MANPADS are highly mobile, simple to use, reliable and rapidly deployable (Spassky et al 2004). Recent MANPADS developments include the Igla-S SA-24 'Grinch,' which offers; dual-band (1.3 – 1.5 μm and 3 – 5 μm) guidance, an improved firing range (up to 6 000 m) and warhead lethality compared with the Igla-1 (SA-16) (Jane's 2008b). MANPADS can also be laser-beam-riding, for example the MANPADS version of the Starstreak high velocity missile (Anon. 2006a). These systems use the same LOSBR principles as third generation ATGWs, see Section 2.2.4.

In the hands of the Mujaheddin, Stinger was used to destroy more helicopters than any other SAM used in Afghanistan (1979 – 1989), with the SA-7 and Blowpipe also achieving a few kills (Everett-Heath 1992). Schroeder (2007) reports that 269 Afghan government and Soviet aircraft were destroyed by Stinger between 1986 and 1988. In one example, on 26 September 1986 the Mujaheddin used Stinger to engage three 'Hind' helicopters out of a group of four near Jalalabad in quick succession (Everett-Heath 1992). More recently in Iraq, there have been reports that MANPADS attacks have been responsible for a number of coalition helicopter losses (Schroeder 2007).

Approximately 300 Shorts Blowpipe missiles and 900 General Dynamics Stinger Basic missiles were received by the Mujaheddin (Everett-Heath 1992) and it is reported that many of these then proliferated in the 1990s to guerrilla and terrorist groups around the world (Hunter 2002). Proliferation of the SA-series of MANPADS increased beyond that of Stinger after the collapse of the USSR (Hunter 2002). "According to threat documents, worldwide proliferation of relatively inexpensive, heat-seeking missiles is dramatically increasing the risk associated with providing airlift support in remote, poorly developed countries" (Rodrigues 1999). In 2004 it was estimated that one million MANPADS had been produced since the 1950s and 500 000 to 750 000 were still in existence, with around 1% of these outside government control (Schroeder 2007).

### 2.2.6   *Radio frequency surface to air missiles*

Radar systems detect targets by transmitting radio-frequency (RF) energy and then measuring the radar return from the target. Non-coherent radars work by transmitting non-

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the sight line is forced to zero (assuming that the target maintains a straight course and neither objects change speed) and hits the target (Rouse 2000).

coherent RF energy and then measuring the amplitude of the return from the target. Coherent radars function by detecting the amplitude and phase of the return signal. The phase of the received signal is compared with a stable reference oscillator in the radar system to determine the received vector (Scheer and Kurtz 1993).

RF SAMs are often part of a 'layered' air defence system. A typical system uses radar to carry out the surveillance, target acquisition and guidance functions. The surveillance and target acquisition (STA) subsystems carry out the DRIL process (detect, recognise, identify and locate) (Rouse 2000). STA radars are usually centimetric or millimetric. Centimetric systems have longer ranges and millimetric systems provide greater resolution (Rouse 2000). Once the DRIL process has been carried out the missile is fired and guided towards the target. RF SAMs usually use semi-active homing with PN for guidance. The target is illuminated by radio energy from the target illuminating radar. The passive missile seeker then tracks the target using the reflected energy. Semi-active homing has the advantage that significant illuminating power can be directed at the target without increasing the size, weight and cost of the missile (Rouse 2000).

Two applications of coherent radar used in threat systems are moving target indication (MTI) and pulse doppler (PD) configurations. The purpose of MTI radar is to reject fixed, stationary and slow-moving targets such as buildings, hills and trees and to display signals from fast moving targets such as aircraft (Skolnik 1990). MTI radar identifies moving targets from fixed targets or stationary clutter by detecting the doppler frequency shift provided by the reflected signal from a moving target. The phase of the incoming signal is compared with the phase of a reference oscillator within the radar system. If the phase of the received pulse has changed then the target has moved (Skolnik 1990). A high band pass filter process is typically used to cancel out direct current associated with clutter and stationary targets, whilst passing the fluctuating vector linked with the moving target (Scheer and Kurtz 1993).

PD radar systems calculate the radial component of velocity of the moving target by measuring the doppler frequency using Fourier processing (Scheer and Kurtz 1993). PD radar systems have the following characteristics: they have a high pulse repetition frequency (PRF) and they use coherent processing to reject clutter in the main beam to improve target detection and classification (Skolnik 1990). PD radar systems are generally used to detect moving targets in a high clutter environment. PD radar systems can be classified into medium and high-PRF categories. Low-PRF PD radar systems are also known as 'MTI.' The characteristics of these radar types are compared inTable 2-3.

**Table 2-3 - Radar comparison (Skolnik 1990).**

| System | Slow moving target rejection | Can measure radial target velocity | Range measurement |
|---|---|---|---|
| MTI – Low PRF | Poor | No | Unambiguous |
| PD – Med PRF | Good | Yes | Ambiguous |
| PD – High PRF | Good | Yes | Ambiguous |

The tactical Tor SA-15 'Gauntlet' is an example of a coherent threat. The STA functions are carried out by pulse-doppler, three-dimensional, electronically scanning array radars. The SA-15 has an estimated maximum range of 12 km and a minimum engagement range of 1.5 km. It fires a vertically-launched Gauntlet missile equipped with a 15 kg HE fragmentation warhead. The altitude range is 10 – 6 000 m (Ball 2003). The system is highly mobile and has a TV engagement system that can be used to complement the radar system. Tor-M1 and M2 upgrades are available and the system has proliferated to a number of countries around the world (Jane's 2009b).

Longer range 'strategic' RF SAM systems include the Russian S-300PMU2 (SA-20 'Gargoyle') that has a range of up to 200 km and can intercept targets as low as 10 m in altitude (Spassky et al 2004). Many land based systems also have naval variants, for example: SA-8 (SA-N-4), SA-10 (SA-N-6) and SA-15 (SA-N-9) (Jane's 2009b).

## 2.2.7 *Armed vehicles*

Armed vehicles, such as four wheel drives and pickup trucks, can be retro-fitted with small arms and AAA, or used to carry RPGs and MANPADS. Armoured vehicles such as armoured personnel carriers and main battle tanks carry heavier weapons. Soviet tanks carry a pintle-mounted 14.5 mm heavy machine gun specifically for the purpose of attacking helicopters. The T-64B and T-80 main battle tank main guns are also capable of firing ATGWs and conventional shells (Everett-Heath 1992).

## 2.2.8 *Helicopters*

Air-to-air combat is not a primary role of helicopters, however, if two sides in a ground battle employed helicopters, then it is possible that these platforms would face each other. Everett-Heath (1992) proposes four levels of helicopter air combat. The first is defensive where helicopters are armed with a self-defence weapon, such as a machine gun to be used only if attacked. This level is appropriate for transport helicopters. The second level applies to attack, anti-tank and reconnaissance helicopters, whereby they would use their air-to-ground weapons in an air-to-air role. The third level applies to helicopters fitted with air-to-

air missiles; for example, Apache fitted with Stinger (Rouse 2000). The fourth level applies to helicopters designed specifically for air-to-air combat, but to date there are no contenders in this category. The 'Hind' could engage helicopters, but limitations including poor manoeuvrability would put it at a disadvantage (Everett-Heath 1992).

### 2.2.9 Fixed-wing aircraft

According to Everett-Heath (1992), fixed-wing aircraft are not a primary threat to helicopters because they cannot fly as low, or slowly, or turn as sharply as a helicopter. Modern fixed wing assets are likely to have a "look down, shoot down capability" that could be used against helicopters (Everett-Heath 1992).

### 2.2.10 Mortars and rockets

Helicopter landing sites and bases can be mortared, as experienced by the US in Vietnam (Dunstan 2003), or attacked with rockets. Mortars have more recently been used against coalition airbases in Iraq and apparently used to specifically target helicopters (Knights 2007).

### 2.2.11 Mines

Anti-personnel and anti-vehicle mines are indiscriminate and could explode if landed on by a helicopter. In addition, possible helicopter landing sites could be mined. Specific anti-helicopter mine systems have been designed to protect the forward line of own troops (FLOT) from the armed helicopter threat posed during the Cold War. These mines could be deployed relatively quickly by multiple launch rocket systems, fixed wing, helicopters, ground vehicles or by hand (Tilllery and Buc 1989). Acoustic anti-helicopter mines have been under development that are designed to detect and identify helicopters and then fire upwards when the helicopter is sufficiently close (Everett-Heath 1992). Anti-helicopter mines were apparently used in Iraq and were deployed around likely landing zones and other predictable flight paths. RF proximity fuses from artillery or anti-aircraft shells were used as a firing switch (Knights 2007).

### 2.2.12 Improvised explosive devices

There are many examples of 'low technology' and improvised threats as used in asymmetric warfare. According to newspaper reports, aerial and ground-based improvised explosive devices (IEDs) have been used to target helicopters in Iraq, with aerial IEDs being used to target helicopters over known flight paths (Harris 2006). Other tactics can include ambushing patrol vehicles with a roadside bomb and then targeting medical evacuation helicopters that attend to recover casualties (Harris 2006).

### 2.2.13 Wires and obstacles

Wires are a significant risk to helicopters as they are very difficult for pilots to see, particularly in low light or degraded visual conditions. There have been 50 wire strike incidents during the past 30 years, 27 of which happened on operations (Ministry of Defence 2007b). In September 2004, an Army Lynx Mk9 crashed killing all six people on board. Eyewitnesses claimed that it flew into power lines (BBC 2004). Purposely laid wires and obstacles are a potential threat to helicopters. In Afghanistan the sport of kite fighting is popular with opponents using wire-tethered kites. These could pose a risk to helicopters operating in the area. Wire-tethered barrage balloons and wires mounted on buildings and roof tops are another potential hazard.

### 2.2.14 Lasers

Lasers were developed in the 1960s and have since found many military applications including rangefinding and target designation. "Lasers are devices that generate or amplify coherent radiation at wavelengths in the infrared, visible and ultra-violet regions of the electromagnetic spectrum," hence the name 'laser' (light amplification by stimulated emission of radiation) (Richardson et al 1997). There are four main types of laser used for medium and high power military applications: solid-state, chemical, fibre and free electron devices (Skinner 2008).

Conventional lasers are capable of damaging or disturbing sensors at ranges of up to 10 km (Frater and Ryan 2001). Even low-energy lasers constitute a threat to sensors and human eyes, and could therefore, pose a risk to helicopter pilots (Everett-Heath 1992). International law does not allow the intentional blinding of personnel by laser devices: "It is prohibited to employ laser weapons specifically designed, as their sole combat function or as one of their combat functions, to cause permanent blindness to unenhanced vision, that is to the naked eye or to the eye with corrective eyesight devices" (International Committee of the Red Cross 1996 cited in Frater and Ryan 2001).

The US DoD is developing solid-state lasers that can achieve enough power to destroy an aircraft (around 100 kW). Northrop Grumman and United Defense are developing the air defence system Talon, a vehicle-mounted 100 kW solid-state laser (Skinner 2008). Low-power laser 'dazzling' systems have also been trialled by the US in Iraq and Afghanistan.

### 2.2.15 Radio frequency directed energy weapons

Radio-frequency directed-energy weapons (RF DEW) function by transmitting radio-frequency electromagnetic energy to a target at a power level that disrupts or damages electronic systems (Frater and Ryan 2001). This could potentially cause an aircraft to operate

erratically or completely lose control resulting in a crash. This effect is not new because the nuclear electromagnetic pulse (N-EMP) associated with a nuclear explosion can also cause similar damage. Frater and Ryan (2001) state that RF DEW can be considered to be high-powered transmitters (up to 10 GW) that operate up to 100 GHz. RF DEW has technical limitations in that it is difficult to focus the RF energy at longer ranges and so there is significant potential to cause collateral damage to friendly forces or even the weapon platform itself (Frater and Ryan 2001). Reportedly the largest investment in RF weapons and countermeasures has been in Russia and the US (Frater and Ryan 2001). Boeing is apparently researching the use of non-lethal microwave weapons onboard helicopters to disable people (Warwick 2006).

### 2.2.16  *Chemical, biological, radiological and nuclear*

NATO air forces were well prepared for chemical, biological, radiological and nuclear (CBRN) threats during the Cold War. Helicopter aircrew may need to consider the possibility of flying into a chemically- or biologically-contaminated area in flight. Airbases are a particular problem as they are large, fixed areas that can be easily targeted.

### 2.2.17  *Other*

Other threats include asymmetric and improvised devices not already categorised. For example, in Vietnam the Viet Cong booby trapped possible helicopter landing sites. They would set spears to puncture the belly of a helicopter and set bows and arrows that were triggered by the rotor downwash (Dunstan 2003).

### 2.2.18  *Surveillance and target acquisition threats*

Surveillance threats do not achieve a platform kill in their own right, but could cue other assets as part of an IADS. Surveillance and target acquisition (STA) threats could however, achieve a mission kill, for example if STA assets were to detect and identify a helicopter on a covert mission. STA threats can be grouped into six main categories (Richardson et al 1997):

- Optical and electro-optic systems that include: sights, telescopes, binoculars, video cameras and image processing systems.

- Image-intensification systems that include: three generations of image-intensification devices and low-light TV. Note that commercially available second generation night vision devices combined with MANPADS provide even poor countries with a night time air-defence capability (Rodrigues 1999).

- Thermal imaging systems that include: infrared line scan (IRLS) and infrared search and track (IRST) systems.

- Laser systems that include: laser range finders, laser target designators and laser radar (LADAR).

- Radar systems that include: surveillance radar, target tracking radar and synthetic aperture radar (SAR)[9].

- Acoustic systems that include: seismic sensors and acoustic arrays used to direction find and characterise the helicopter range and type.

## 2.3 Helicopter survivability attributes

Attributes within this context refer to functions, equipment, techniques and tactics that provide a survivability benefit. These have been defined to help the reader to understand what components make up an integrated survivability capability and to inform the development of the methods in Chapter 4.

### 2.3.1 Mission decision support systems

Navigation is an essential aviation requirement enabling an aircraft to achieve the mission objectives. Navigation doesn't directly lead to flight safety because it only "tells you" where you are. Navigation "is essentially about travel and finding the way from one place to another and there are a variety of means by which this may be achieved" (Anderson 1966 cited in Titterton and Weston 1997). Navigation contributes to the 'don't be there' function, enabling the aircraft to be navigated along a route of least risk to known threats. A navigation system determines position, velocity and usually attitude (Titterton and Weston 2004). Some systems also resolve the attitude, acceleration and angular rate (Groves 2008).

'Don't be there' requires the ability to navigate and to have good intelligence of enemy threat positions. Early pioneers of military aviation used their observation, map reading skills, a compass and pencil to navigate. Threat positions were established by sight from observation posts on the ground and in the air. Terrestrial radio navigation systems were introduced during the Second World War to assist with navigation. The first inertial guidance systems were initially developed by German scientists in WW2 for the V2 rocket. The inertial navigation system (INS) was rapidly developed for military air and naval applications after the war as sensor accuracy improved. "Inertial navigation is the process whereby the measurements provided by gyroscopes and accelerometers are used to determine the position of the vehicle in which they are installed. By combining the two sets of measurements, it is possible to define the translational motion of the vehicle within the

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[9] SAR is a sideways looking device typically used for airborne ground mapping because of its high resolution. The technique uses the vehicle motion in combination with signal processing to generate an effective long antenna (Skolnik 1981, Skolnik 1990). SAR can be used for military reconnaissance in the day, at night and in poor weather conditions and has been used by the US on Global Hawk and Predator UAVs (Hewish 2004). SAR is effective at detecting slow moving (below 70 knots) and stationary objects (Hewish 2004).

inertial reference frame and so calculate its position within that frame" (Titterton and Weston 1997).

More recently global navigation satellite systems (GNSS) were developed to improve further position accuracy. Examples include: the US global positioning system (GPS), GLONASS[10] and Galileo, the European GPS (Groves 2008). More capable systems integrate INS and GNSS using the complementary characteristics of each technology to bound the navigation errors. This provides "a continuous, high-bandwidth, complete navigation solution with high long- and short-term accuracy" (Groves 2008).

Mission decision support systems (MDSS)[11] are intended to improve the crew's decision making and reduce workload. Examples of such systems include mission planning systems that can be updated in flight. Inputs to such a system include the mission plan, positional and attitude information, inputs from own platform sensors and inputs from off-board sensors such as intelligence, surveillance, targeting, acquisition and reconnaissance (ISTAR) assets. The system could provide processing to allow an optimised route to be calculated using various algorithms including inter-visibility. Inter-visibility analyses the flight path over terrain to determine in which positions the aircraft can be acquired by the threat. This approach can be used to establish a route of least risk. This could include flying at low-level, using terrain to mask the aircraft from the threat. The potential exists for real time re-routing to avoid threats once the technology is at a sufficient level of maturity and reliability: This could provide the ability to route around a 'pop-up' threat to enable the platform to remain within the 'don't be there' or 'don't be seen' pillars.

### 2.3.2   *Situational awareness*

*Sensors*

A platform's own sensors provide valuable situational awareness (SA). Examples include:

- Direct vision optics.

- Image intensifiers (II) such as night vision goggles (NVGs).

- Low-light TV.

- Thermal imaging.

- Multi- and hyper-spectral sensing.

- Radar.

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[10] GLONASS is the Russian global navigation satellite system that was developed in parallel with the US GPS (Groves 2008).
[11] Mission decision support systems were previously referred to as: mission decision aiding (MDA) systems.

- Radio frequency interferometer.

- Light detection and ranging (LIDAR).

*Communications*

Communications systems contribute to providing overall situational awareness and so promote survivability by contributing to the 'don't be there' and 'don't be seen' pillars. Communications systems vary in their capability to transmit information (voice and data) insecurely or securely at a certain range, for example, beyond line of sight (BLOS). A communication system can be used at a simple level so that a pilot could verbally advise his wingman of a hostile action. At a more comprehensive level, a combined operating picture (COP) could be updated via a Link 16 data transmission enabling shared situational awareness (Jane's 2007). The COP consists of layers of information including: the recognised air picture (RAP), the recognised land picture (RLP) and the recognised maritime picture (RMP). These recognised pictures incorporate verified information on the position of enemy (red) and coalition (blue) forces. Communications typically involve receiving and transmitting voice and data information in the electromagnetic (EM) spectrum, for example the very high frequency (VHF) and ultra high frequency (UHF) radio bands. When transmitting, the probability of the enemy detecting the aircraft's position and intent is increased and so a survivability trade-off exists. Communication signals can be transmitted with a reduced risk of compromising the mission using secure anti-jam systems such as Bowman (Janes 2009c).

*Network enabled capability*

At an operational level, network enabled capability (NEC) aims to harness the benefits of networking to enable shared situational awareness. NEC aims to improve the integration of weapon systems, command and control ($C^2$) nodes, and ISTAR systems to enable the military to deliver timely effects-based operations (MOD 2005). This vision of NEC should enhance force protection and reduce fratricide, so improving survivability at the force level. NEC is a long-term vision that is continuing to develop. The understanding of benefits and implications of NEC is being aided by simulation facilities such as Niteworks, a facility run by industry in partnership with MOD.

*Man machine interface*

The man machine interface (MMI) is essential to realise the benefits of bringing together the sensors, communications and NEC. The MMI includes crew data input devices, such as keyboards and tracker balls, and output devices, such as visual displays and audio cueing. The right information must be communicated effectively to the crew at the right time to

enable 'true' situational awareness. The MMI must take into account human factors such as ergonomics and crew workload during a complex mission.

### 2.3.3    *Signature control*

The discipline of camouflage, concealment and deception (CC&D) depends heavily upon signature control and it even exploits signatures. A helicopter platform has a signature made up of a number of characteristics that can reveal its presence. These can be characterised into three groups (Richardson et al 1997):

- Electromagnetic waves such as radio or light waves.

- Mechanical waves such as sound or vibration.

- Other effects such as smoke, dust and smell.

Operationally-relevant signatures within the EM spectrum[12] are grouped into the ultra violet (UV), visible, infrared (IR), optical and radio frequency bands, see Figure 2-1. Detection systems can be categorised as active or passive and can be defined as follows:

- "Active systems are those which radiate energy at the target to illuminate it"

- Passive systems detect energy radiating from the target area. They do not radiate energy at the target.

Signatures can also be grouped into emitted or reflected categories. IR from the exhaust and hot engine parts is an example of an emitted signature, see Figure 2-2. The reflected radar return from the platform is an example of a reflected signature. The signature of a platform can incorporate emitted and reflected components within a band; for example, reflected RF from a radar return and emitted RF from an active terrain-following radar system.

Signatures have to be controlled and signature control techniques must be 'designed in' early in the design process (i.e. at the outset); they are not simply a retrofit, bolt-on attribute. Signatures also need to be controlled operationally through the use of specific equipment configurations, paint schemes and tactics, techniques and procedures (TTPs). Signatures are usually minimised as much as possible in order to reduce the probability of detection (i.e. don't be seen) and to avoid engagement (i.e. don't be engaged). During the design process, signatures must be considered together as part of a careful balancing act, with consideration of the platform role, the mission set and the threat. The financial cost may be too high to achieve anything approaching a 'perfect' solution, in which case 'trades' will need to be made. This can only be undertaken successfully when the whole system and operational

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[12] The various parts of the EM spectrum were discovered by many scientists from the 18th century, but it was Maxwell who made the electromagnetic connection and published the Electromagnetic Theory in 1867 (Hecht 2002). The EM spectrum also includes gamma rays and x-rays.

scenarios are defined. Development costs can be high because the cost of hiring skilled people and the required analysis and test facilities is expensive.
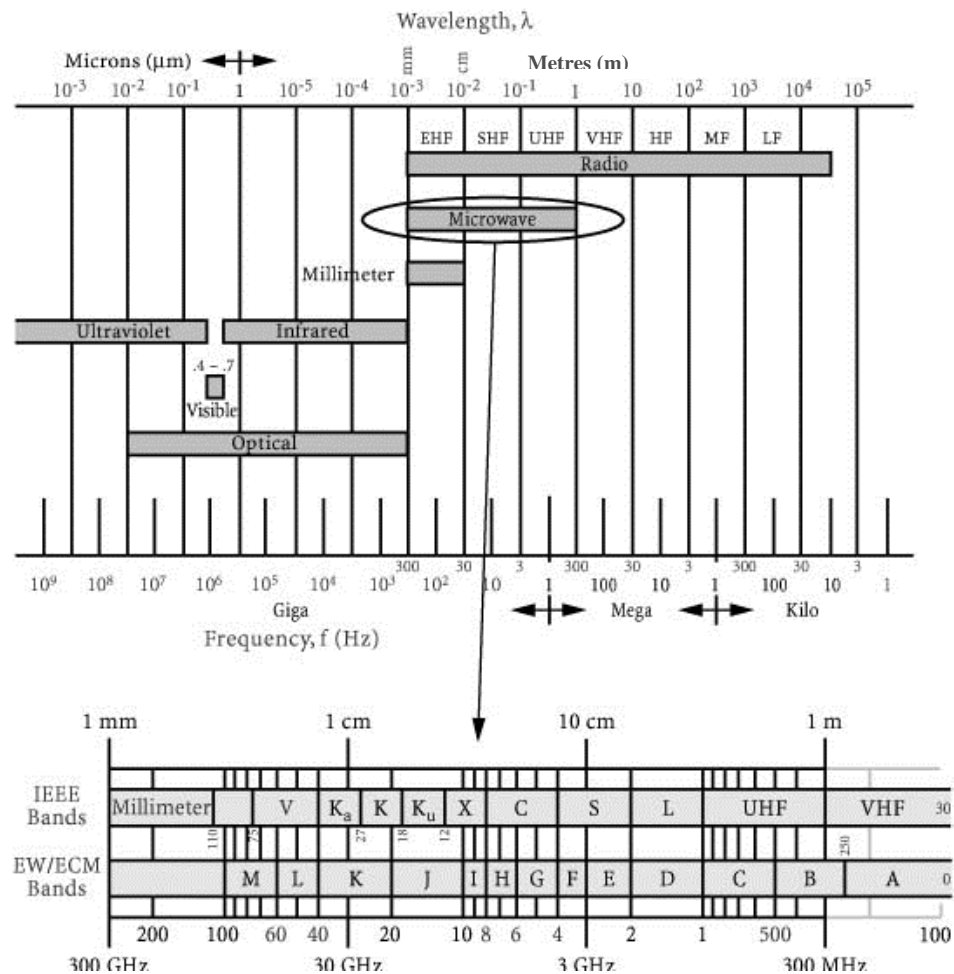


**Figure 2-1 - Part of the EM Spectrum, from: "The Fundamentals of Aircraft Combat Survivability Analysis and Design," by Ball (2003). Reprinted by kind permission of the American Institute of Aeronautics and Astronautics, Inc.**

The US Comanche programme was the most comprehensive example of integrated signature reduction on a helicopter. Unfortunately the programme was cancelled in February 2004 because the US Army considered that the platform would not meet future operational requirements[13] (Anon. 2006b). It is possible, however, that technology developments from the Comanche programme may be integrated into other US helicopter platforms in the future.

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[13] 121 Comanches were due to be built between 2004 and 2011 at a cost of $14.6 billion. The US Army instead decided to allocate the money to buy 796 additional helicopters (including Blackhawk) and to upgrade 1,400 existing platforms (Anon. 2006c). Arguably this decision secured greater overall capability, because the higher number of transport helicopters provided a 'force multiplier' in terms of achieving military effect on the ground.

*Visible signature*

The human eye is a very effective daylight sensor system and consequently it provides a significant detection capability unaided or aided. The human eye sees visible light in the approximate wavelength from 390 nm to 780 nm (Hecht 2002).

Low reflectivity diffuse paints can be used to reduce glint and glare by altering the apparent surface characteristics of a target. This is achieved by changing the scattering and absorption properties of the pigments and dyes (Pollock 1993). Roughened surfaces can also be used to reduce specular reflections. The signature optimisation carried out on the Comanche programme resulted in a visual signature less than the OH-58D 'Little Bird.'

Paints are often used to generate a camouflage scheme that makes it more difficult for an observer to perceive detection or identification of the target. These schemes are usually theatre specific to enable the platform to 'blend in' with its background. Navy helicopters often use a grey scheme to reduce contrast of the platform with respect to the sea and sky backgrounds. The Army and RAF use a green or sand scheme with breakup. Sometimes aircraft are designed to have a high contrast from the background, i.e. to stand out, for example during the Bosnia peace keeping operations where some aircraft were painted white.

*IR signature*

EM radiation is emitted by any object with a temperature of above absolute zero. The IR region of the EM spectrum is divided into the following wavelength bands (Richardson et al 1997):

- Near IR (NIR) 0.7 to 3 $\mu$m.

- Middle IR (MIR) 3 to 6 $\mu$m.

- Far IR (FIR) 6 to 15 $\mu$m.

- Extreme IR (XIR) 15 to 1000 $\mu$m.

IR imaging systems operate in the 3-5 $\mu$m and 8-12 $\mu$m regions because of the combination of the two classical atmospheric transmission windows and the characteristics of the most frequently used IR detectors (Jacobs 1996). The wavelength bands can also be defined with respect to the atmospheric transmission windows.

Aircraft have signatures that are largely characterised by the high volume of hot exhaust gases from the engine(s). These exhaust gases mainly consist of $H_2O$ vapour and $CO_2$. These constituents have high emissivities at the 2.7 and 4.3 $\mu$m spectral regions and hence emit a considerable amount of radiation in these regions. The atmosphere tends to absorb these

wavelengths because it also consists of $H_2O$ vapour and $CO_2$. Because the gases are hotter than the atmosphere, some radiation is emitted outside the regions of high atmospheric absorption and so propagates with much less attenuation (Accetta et al 1993). Figure 2-2 illustrates the effect of dominant engine emissions on the IR signature of a Gazelle helicopter. The coldest regions are represented by dark blue and the hottest areas are red through to white.

The aircraft skin will also have an IR signature corresponding to the emissivity of the material and the operating conditions. Painted surfaces normally have emissivities[14] around 0.9, however, this can change (generally upwards) because of dust, dirt, oil and weathering (Accetta et al 1993).
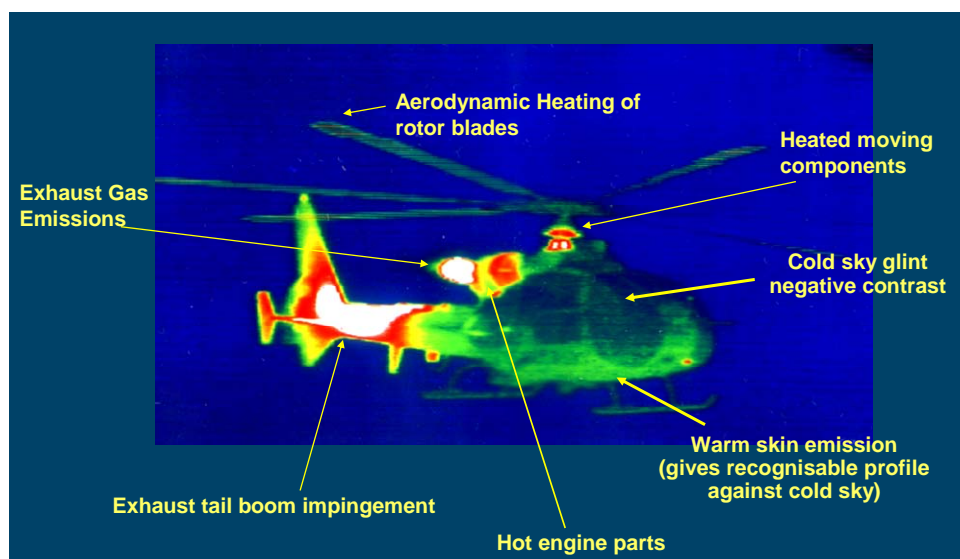


**Figure 2-2 – A thermal image for a Gazelle helicopter.**

Paints and coatings can be used to reduce signature and provide camouflage in the IR band. For camouflage to be effective in the IR band, two conditions must be satisfied: temperature similarity and spatial similarity. Temperature similarity requires that the camouflage presents an apparent target temperature similar to the background. Spatial similarity requires that the shape of the camouflage material presents a thermal pattern that 'fits' into the background (Jacobs 1996).

IR suppression devices are an example of passive signature control to reduce IR signature. These devices typically work by mixing cooler air with the hot exhaust gases and hiding hot engine parts behind fairings (Anon. 2006d). The different generations of suppressor from generation 0 (no suppressor) to generation 4 (advanced suppressor) are introduced in Table 2-4.

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[14] "Emissivity is defined as: "the ratio of the emission of a sample to that of a blackbody at the same temperature and in the same spectral interval" (Accetta et al 1993).

**Table 2-4 - IR suppressor generations (Anon. 2006d).**

| Generation | Characteristic design features |
|---|---|
| 0 | No suppressor. |
| 1 | Suppressor consists of screens and fairings to shield hot engine and exhaust components from direct view. Poor platform integration. |
| 2 | Suppressor consists of screens that also incorporate film and transpiration cooled surfaces. Reasonable platform integration. |
| 3 | Suppressor consists of screens, film and transpiration cooling and also exhaust gas cooling. exhaust gas cooling uses advanced technology to mix the hot gas with cooler air. Good platform integration. |
| 4 | Suppressor is fully integrated within the airframe, e.g. Comanche. |

The Comanche programme developed the first IR suppression system to be fully integrated into a helicopter airframe. The design consisted of IR suppressors that were incorporated within the tail-boom. These worked by mixing the engine exhaust with cooling air passing through inlets above the tail. The mixed exhaust then flowed through slots within an inverted shelf on the sides of the tail-boom. The Comanche design was reported to radiate 25% of the engine heat of other similar size helicopters (Anon. 1999).

'Retro-fit' IR suppressors can be integrated into existing helicopter platforms. The US DoD recently placed a contract upon Rolls Royce to fit IR suppressors to Special Operations Command MH-47 Chinook helicopters. To provide some idea of the cost of this technology, the contract was valued at $19 million for 100 units, with two units fitted to each aircraft (Anon. 2005).

*RF signature*

Radar signature is usually expressed as a radar cross section (RCS). There are two practical methods[15] of reducing helicopter RCS as follows (Knott et al 2004):

- Shaping.

- Use of radar absorbing materials.

"The objective of shaping is to orient the target surfaces and edges to deflect the scattered energy in directions away from the radar" (Knott et al 2004). Shaping is usually used to produce an RCS that is as low as possible in the main threat directions. Optimising the design to reduce RCS in one aspect will typically increase the RCS in another aspect.

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[15] Passive and active cancellation techniques can also be used to reduce RCS, however, they are extremely difficult to implement in practice (Knott et al).

Additionally, there will always be viewing angles at normal incidence where the echo will be relatively high. The design process is, therefore, concerned with optimising the design to reduce RCS in the most important aspects. Consideration of the mission, platform role and the threat has to be made in order to determine these most important viewing angles. It is also important to understand what these angles are to enable optimum flight profiles. Careful design techniques avoid geometrical shapes that act as inner cubes that enhance the RCS over wide angles. Additionally, shapes and cavities that re-radiate are minimised.

Radar absorbing material (RAM) works by absorbing some of the radar energy across its designed bandwidth, so reducing the reflected radar return. It is often used where shaping could not be employed or as a 'retro fit' signature reduction measure. The magnetic and dielectric properties of the RAM can affect how much RF energy is absorbed. Carbon can be used as RAM owing to its imperfect conductivity. Operationally, magnetic absorbers are more commonly used; these typically consist of compounds of iron, such as carbonyl iron and iron oxides. Magnetic absorbers are more compact than dielectric absorbers, but are also heavier. The absorbing material is normally set within a binder or matrix to provide the electromagnetic properties required to perform over a specified range of frequencies (Knott et al 2004).

The US Comanche was a very good example of a low RF signature helicopter platform. The radar cross section was minimised by optimally shaping the fuselage and by mounting the weapons internally.

*Acoustic signature*

"Acoustics is the science of sound, which includes its generation, transmission, and effects" (ANSI 1971) cited in Kutz (1998). Sound is a mechanical pressure wave that can be transmitted in a fluid or a solid.

The acoustic signature of a helicopter can be detected by the unaided human ear, or by listening devices such as tetrahedral arrays that can be used to track acoustically the position of aircraft (QinetiQ 2004). Helicopters can also be detected seismically by sensors embedded in the ground (Richardson et al 1997).

If a helicopter is hovering behind trees to avoid visual detection, it can still be detected acoustically. Acoustic signature is dominated by the main and tail rotors because of the rotor speed and the resulting pressure waves that develop. The number of main and tail rotor blades and the two rotors' speeds are often unique to the helicopter type, making it possible to identify the helicopter. Acoustic detection is very dependent upon the local environment, as it is influenced by factors such as wind, temperature and topography.

Noise contour prediction can be used as part of the mission planning process to optimise safe routing (QinetiQ 2004). On the Apache Block III upgrade programme, Boeing is conducting research to display the acoustic footprint to the crew so that they can fly to minimise detectability (Warwick 2006).

### 2.3.4   Defensive aids suites

A defensive aids suite[16] (DAS) is a system of sensors, controllers and effectors that defends the platform from threats. Sensing may be carried out passively or actively. The control function processes the sensor information and cues the effect, which could be a warning to the crew and/or automatic activation of countermeasures (e.g. flares or chaff). The Helicopter Integrated Defensive Aids System (HIDAS) implemented on the UK Apache is an example of an integrated DAS optimised for helicopters (SELEX Galileo 2008). The system can detect threats and automatically provide countermeasures in typically less than one second (National Audit Office 2002).

*Radar warning*

A radar warning receiver (RWR) is used to detect RF within a given waveband that impinges upon the aircraft. The system must classify, locate and determine the status of threat radar systems and then display this information to the crew. It is important that these threat systems are detected in a timely manner and prioritised to enable the crew to make an appropriate decision. For example, a tracking or fire-control radar signal would have a high priority because this would suggest that a missile was about to be launched, or is already on the way. Timely declaration to the crew would allow them to dispense chaff, manoeuvre and then use terrain masking to avoid further engagements (Ball 2003). The Sky Guardian 2000 RWR manufactured by SELEX Galileo is an example of a helicopter RWR. It provides RF coverage in the C to K band and can also host a programmable DAS controller (DASC) function (SELEX Galileo 2008a).

*Laser warning*

A laser warning receiver (LWR) is designed to warn the platform of imminent attack from fire control or weapon lasers and then the LWR may also activate a countermeasure system (Pollock 1993). LWRs are required to operate over a wide spectral range, from the UV to the far IR, although individual scenarios have specific laser threats that are dominant because of historical evolution and application requirements (Main 1984 cited in Pollock 1993). Lasers can be used on the battlefield for the purposes of determining range or for guidance, as is the

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[16] DAS is commonly referred to as 'aircraft survivability equipment' (ASE) in the US.

case with laser beam riding missiles (Ball 2003). Examples of LWRs include the SELEX Galileo 1223 system and the Goodrich AN/AVR-2A (Puttré et al 2003).

*Missile warning system*

A number of technologies can be used to achieve missile warning. Active radar systems can be used to track the incoming missile. Missiles generate optical emissions during the boost and sustain stages as a by-product of the combustion of fuel (Pollock 1993). UV sensors can be used to detect the missile rocket motor flare at launch and IR sensors can be used to detect the missile plume during flyout (Ball 2003). These sensors track the target and can provide an input to the DAS to allow the crew and/or the system to decide upon the most suitable response. The BAE Systems AN/ALQ-156 is an example of an active pulse-doppler radar missile approach warner (MAW) that works by illuminating an incoming missile and then measuring the RF return (BAE Systems 1992). BAE Systems also produce the passive UV Common Missile Warning System (CMWS) or AN/AAR-57 that is used on a number of UK and US platforms (BAE Systems 2005, Puttré et al 2003 and Wasserbly 2010).

*Hostile fire indication*

Hostile fire indication (HFI) provides warning of ballistic threats, such as small arms, AAA and RPG, enabling crews to take evasive action. BAE Systems is currently developing an acoustic HFI system that uses additional sensors to improve performance (Harding 2009). Thales UK is currently developing the next generation of single-colour IR threat warning system called Elix-IR that aims to incorporate HFI capability, as well as missile warning, and enhanced situational awareness (Thales UK 2008).

*Flares*

Flares are a self protection infrared countermeasure (IRCM) device designed to decoy heat seeking missiles by providing an alternative and more desirable target. Flares are made of a pyrotechnic solid or a pyrophoric liquid or activated metal (Ball 2003). A flare works by emitting radiation in the IR waveband. This seduces the seeker in the IR homing missile, by providing a 'better' target. The separation of the flare from the aircraft draws the missile away from the aircraft, hopefully providing a large enough miss distance. The effectiveness of flares depends upon a number of parameters including: rise time, burn time, power output, spectral distribution, the ejector locations, the time of ejection, the number of flares in a salvo, the interval between salvos, the flare trajectories and the aircraft manoeuvres (Ball 2003). Many modern IR missile seekers incorporate counter-countermeasures technology that may exploit the difference between the spectral radiant intensity in two wavelengths and so differentiate between aircraft and the flare (Ball 2003). An example of a countermeasure dispensing system (CMDS) is the Thales Vicon 78 family of dispensers that is capable of

firing both chaff and flares (Janes 2008c). Flare manufacturers include Chemring Countermeasures who produce a variety of flare cartridges for a range of CMDSs (Puttré et al 2003).

*Chaff*

Chaff was first used during the Second World War (at which time it was code-named Window) and was used by the British to confuse German air defence radar systems. When released into a turbulent airflow, chaff forms a cloud of dipoles that reflect RF energy. This chaff cloud will appear as an extended false target on a radar system, hopefully confusing the threat system, enabling a break of radar lock and so aid escape. The dipoles consist of a thin aluminium foil or a glass fibre coated with zinc or aluminium. The chaff cloud must bloom rapidly so that the radar sees both the aircraft and the chaff in the same range resolution cell or range gate. This rapid blooming is achieved by firing the chaff into the turbulent airflow. For this reason, location of the chaff dispenser is very important and often a compromise, especially as some dispensers fire both chaff and flares. Chaff dispensed from a helicopter close to the ground will settle quickly, resulting in the benefits being short lived. Chaff requirements are that it should provide the necessary RCS, bloom rapidly, remain aloft and move to provide a doppler frequency shift. Chaff is generally effective when the aircraft is within a large cloud and the chaff echo masks the aircraft echo, or when a small chaff cloud decoys a radar tracker, enabling a break lock. Modern radar systems that use pulse doppler or moving-target indication (MTI) signal processing can distinguish between the moving echo from the aircraft and the relatively stationary echo of the chaff cloud, although tracking may be degraded. Some threats can also switch to EO tracking when chaff is detected. An example chaff round is illustrated in Figure 2-3 (Ball 2003).
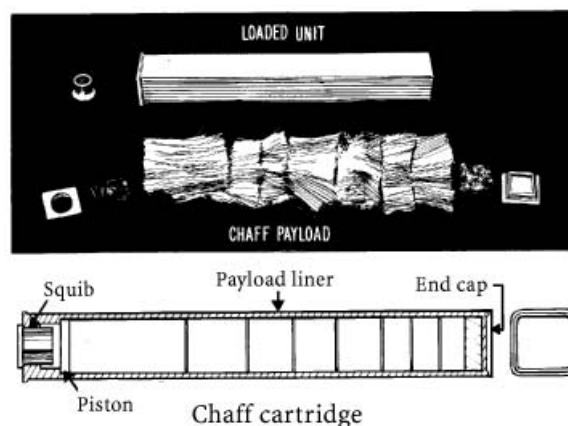


**Figure 2-3 - Chaff cartridge, from: "The Fundamentals of Aircraft Combat Survivability Analysis and Design," by Ball (2003). Reprinted by kind permission of the American Institute of Aeronautics and Astronautics, Inc.**

*Active expendable deceivers*

Active decoys transmit RF with the aim to seduce the threat away from the aircraft. They are either released freely or towed behind aircraft. Towed decoys can then be expended or recovered once used (Ball 2003). The 'Ariel' fibre-optic towed decoy receives signals generated by the aircraft RWR, techniques generator and decoy-interface module (Puttré et al 2003).

To use a towed decoy on a helicopter would pose a number of engineering challenges such as ensuring that the tow line does not interfere with the main or tail rotors. Because helicopters typically operate at low level, an expendable decoy may have limited opportunity to operate before reaching the ground.

*Air launched decoys*

Air launched decoys are expendable air vehicles used to simulate the characteristics of an aircraft including flight path and RCS. They can be powered or unpowered and can incorporate an active radar jammer or deceiver. Typically they would be used to saturate and confuse enemy radar systems such that they switch on and become a target to radar homing weapons (Ball 2003). These countermeasures are more likely to be used by fixed wing aircraft.

*IR jamming*

There are two types of IRCM jammers; omni-directional (staring) and directional (DIRCM). Omni-directional jammers work by deceiving reticle-based IR seekers. They typically consist of a hot source that is mechanically or electrically modulated to create a deception signal, although arc lamps may also be used as the IR source. The IR seeker will see a constant aircraft signature and the pulses from the jammer. The missile modulates this combined signal resulting in the incorrect angular location being resolved. This results in the missile chasing a false target (Ball 2003). The BAE Systems ALQ-157 is an example of an omni-directional IRCM system (BAE Systems 2002).

DIRCM works on a similar principle to omni-directional IRCM jammers, the difference is the directional aspect of the IR energy. A laser can be used as the source, which brings in a number of requirements: the missile must be detected quickly, the laser beam must be slewed to the target, the target must be tracked and the deception signal must be transmitted quickly (Ball 2003). Example DIRCM systems include: the Northrop Grumman / SELEX Galileo AN/AAQ-24 Nemesis and the BAE Systems AN/ALQ-212(V) Advanced Threat IR Countermeasures (ATIRCM) (Puttré et al 2003 and Streetly 2009). The US has recently

launched a Common Infra Red Counter Measure (CIRCM) competition to mature new technology within the DIRCM field (Wasserbly 2010).

*RF jamming*

RF jamming on board the aircraft can provide a self-protection function, known as electronic defence (ED). Off-board jamming can be provided by dedicated electronic attack (EA) aircraft that deny enemy use of the EM spectrum by targeted disruption of communications and sensor operation (Ministry of Defence 2006). Noise jamming works by sending out a signal that masks the radar return from the protected aircraft. The purpose of this is to reduce the effectiveness of the threat's detection and tracking assets. Deception 'jamming'[17] works by creating one or more false targets to confuse the target tracker in an enemy's radar system (Ball 2003).

Electronic surveillance is used to collect data that are then analysed to provide a detailed understanding of threat systems. This is essential to the success of ED and EA (Ministry of Defence 2006). Examples of RF jammers used on helicopters include: Elisra's SPJ-20, the ITT Electronic Systems' AN/ALQ-136(V) and the Northrop Grumman AN/ALQ-162(V) (Streetly 2009).

*DAS architecture*

Upgradeability of survivability systems is important to allow flexibility to adapt the system to changing future environments and requirements. Open architectures can make this possible and are 'crucial' to the successful exploitation of new technology (Ministry of Defence 2006). A helicopter platform may have a thirty-year service life and will require system upgrades through life to maintain capability as part of through life capability management (TLCM).

One way of implementing 'open architectures' is through the use of a DAS controller (DASC). This provides a programmable interface that makes future DAS upgrades easier. The UK developed integrated DAS as part of the HIDAS programme. This is currently in service on the British Army Apache Mk1 and has been selected for the Agusta Westland AW159 Lynx Wildcats (Donaldson 2009). The next generation of integrated DAS is being developed by the UK as part of the Common DAS (CDAS) Technology Demonstrator Programme (TDP) (Barrie 2009).

The importance of upgradeability has also been recognised on the US Apache Block upgrade programme, where open systems architectures have been introduced (Warwick 2006). In response to this requirement, SELEX Galileo has developed the Aircraft Gateway Processor

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[17] Deceivers can be referred to as deception jammers, however they do not actually 'jam,' they spoof or deceive (Ball 2003).

(AGP) DASC that has been selected by the US for the Block II AH64D Apache (SELEX Galileo 2008b). The AGP has many interfaces, enabling integration with a wide range of sensors, effectors, controls and displays. The programmability allows the DAS to be optimised to the mission and enables prioritised tactical responses (Donaldson 2009).

The Joint and Allied Threat Awareness System (JATAS) is another US integrated DAS programme being run by the Naval Air Systems Command (NAVAIR). The idea is to provide an integrated DAS that combines new DAS sub-systems with existing legacy equipments (Donaldson 2009).

### 2.3.5    *Weapons*

Weapons are sometimes referred to as the outer layer of survivability, i.e. to suppress or kill the threat before the threat kills you. This aligns with the well known proverb that "The best form of defence is attack." Effective use of offensive weapons requires weapon overmatch in terms of range and overall capability. The Apache attack helicopter has an offensive capability in the form of: Hellfire missiles, CRV rockets and a 30 mm chain gun. Many support helicopters carry defensive weapons such as a machine gun that can provide a significant psychological deterrent to a potential attacker as well as a suppressive or lethal effect. For example, visible evidence of a door gun, (Figure 2-4) can deter ground forces from an attack. If under attack, suppressive fire combined with manoeuvre can promote the chances of escaping to safety.



**Figure 2-4 - Door gun on board a Royal Navy Lynx (Macready 2005).**

Using lasers to 'dazzle' an attacker is not prohibited under international law ('Vienna Protocol 4'). Apparently Boeing has been developing a laser 'dazzler' to cause temporary 'blindness' to people targeting a helicopter (Warwick 2006). The effect is actually caused by obscuration from scatter within the eye. Boeing also claims to be investigating the use of a helicopter mounted, non-lethal, microwave weapon to disable people (Warwick 2006).

### *2.3.6    Manoeuvre*

Avoidance manoeuvres include flying in radar clutter and avoiding unguided hostile fire. Manoeuvring makes a gunner's task more difficult and leads to greater gunner error. Orientation manoeuvres involve presenting the optimum aspect to the threat to defeat tracking and enhance the effectiveness of countermeasures (Ball 2003). High performance engines such as the 714 engine upgrade on Chinook provide improved performance in terms of manoeuvre, operating altitude, range and payload (Ministry of Defence 2009a).

### *2.3.7    Tactics, techniques and procedures*

Tactics, techniques and procedures (TTPs) are a central survivability attribute and mission enabler. For example, flying at low level or 'nap-of-the-earth' (NOE) can enable a helicopter to avoid detection, by making use of 'terrain masking' and hiding within 'clutter'. Flying at night reduces the chance of detection and acquisition because the effectiveness of the observer's unaided human eye is reduced. Both of these tactics go 'hand-in hand' with day night adverse environment[18] (DNAE) enabling technology, for example moving-map displays and night vision equipment.

Training is an essential survivability component to develop flight crew competence in survivability TTPs. Training in flight simulators allows crews to practice in threatening situations and can help them to develop tactics.

### *2.3.8    Damage tolerance*

Damage tolerance or 'vulnerability reduction' is a survivability attribute that enables the platform to continue to function in the event of it being hit by a weapon. The five main methods to reduce vulnerability are explained below.

*Enlargement*

Components such as power transfer shafts and control rods can be enlarged so that a single hit does not cause catastrophic failure. Shafts and rods can be hollow for maximum strength-to-weight ratio and for enlargement purposes.

*Duplication*

Critical systems will often feature duplication in their design, for example:

- Two pilots.

- Pilot and co-pilot dual controls.

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[18] Day night adverse environment (DNAE) is an updated term that supersedes day night adverse weather (DNAW).

- Redundant load paths in control rods.

- Dual fly-by-wire circuits.

- Dual avionic control systems.

- Twin engines with single engine performance (e.g. 714 engine upgrade on RAF Chinooks).

- Twin spars in the rotor blades (or three in the case of Apache allowing a 30mm hit in any spar).

- Systems with reversionary modes allow the aircraft to operate on a secondary system after loss of the primary system.

- Duplication of navigation systems, for example a pilot could navigate back to base after loss of a global positioning system (GPS) by using the inertial navigation system or even by map and magnetic compass.

*Separation*

Duplicated systems must be separated so that a single hit will not result in both systems being damaged. For example: separation of engines, control rods, control circuits, fuel lines, hydraulic circuits and reservoirs.

*Shielding*

Shielding can be achieved by surrounding critical components with less important ones and by placing armour in strategic locations. The first example of armour in aircraft was used during the First World War when some pilots would sit on a metal pan to protect them from ground fire. Armour was built into some aircraft during the Second World War to protect the pilot and critical engine parts.

Composite lightweight armours were developed in the 1960s to provide protection to aircraft and their crews in Vietnam (Ball 2003). Armour kits were fitted to US Huey helicopters from 1962 to protect crews from small arms fire. These kits were upgraded in 1965 to hard face composite armour which included armoured pilot seats and pilot chest protectors. Aircrews initially wore body armour capable of protecting against shell fragments. This was upgraded by incorporating ceramic plates known as 'chickenplates.' This armour could survive a 7.62 mm armour-piercing (AP) round at 100 m and even defeated .50 calibre on occasion (Dunstan 2003). To this day, armoured seats are usually fitted to military helicopters to provide a high level of protection to a critical system component: the pilot.

*Protection*

Passive protection against the risk of fire and explosion can include self-sealing fuel tanks and purging of dry fuel bays and fuel tank ullage (the space inside a fuel tank above the liquid fuel) with inert gases (e.g. nitrogen). Fuel tanks can also be filled with reticulated foam to prevent a flame front spreading, as is used in Formula-One cars.

Protective coatings for aircrew visors and aircraft sensors can be used to protect against laser threats (Everett-Heath 1992). Aircrew CBRN protection can be provided by a respirator that prevents agents contacting the eyes and skin or entering the respiratory system. Positive pressure is used to keep out agents and is provided by pumped filtered air or oxygen. The UK Cam Lock Ltd Chemical Biological Radioactive Respirator (CBRR) is an example in service with the UK, Canada and US (Jane's 2009d).

Active protection can include health and usage monitoring systems (HUMS) that could, for example, inform the pilot of a loss of transmission oil. This combined with a 'run dry' gearbox could enable escape following gearbox casing damage from AAA. Fires can be actively suppressed through the use of sensor and extinguisher systems.

## 2.3.9 *'Crashworthiness'*

'Crashworthiness' is an attribute that describes how well a platform can protect the crew and passengers during and immediately after a crash. "A survivable accident is one in which the forces transmitted to the occupant through the seat and restraint system do not exceed the limits of human tolerance to abrupt accelerations and in which the structure in the occupant's immediate environment remains substantially intact to the extent that a liveable volume is provided for the occupants throughout the crash sequence" (Waldock 1997) cited in Meo and Vignjevic (2002). Collapsing suspension systems, impact absorbing structures, crew restraint systems and 'crashworthy' seating can all promote crew survivability.

The mechanics involved with a helicopter impacting water are much different from an impact on solid terrain (Meo and Vignjevic 2002). Suspension systems do not provide the protection they would otherwise afford on solid terrain and the sub-floor structure must be capable of retaining integrity, whilst absorbing sufficient crash energy. Crashes into water also provide a risk of submersion, possibly combined with inversion.

The crew must be able to escape after a crash in an environment where there could be a risk from fire and smoke. 'Crashworthy' fuel systems are important to allow the crew time to escape. Immediate egress from the crashed aircraft may require the ability for crew to fight fires and to access escape hatches, possibly guided by emergency egress lighting.

Training such as the 'crash drill' (including the brace position) are important to reduce the effects of disorientation immediately after impact and to reduce the chances of dangerous interactions with the aircraft interior. Simulators are also used in training to teach escape procedures following a helicopter crash and inversion in water

### 2.3.10 Rescue

Even if an aircraft is lost or damaged beyond repair, crew survival is important to meet UK defence policy to protect personnel. Crew survival is also important in operational terms, because available crews can be the limiting factor upon the rate of operations. Operational tempo can be very high at certain critical points within a campaign, so speedy recovery of crashed aircrews is essential. The rescue of aircrew can be categorised as recoverability of capability at the force level.

The financial and time penalties associated with replacing a helicopter and trained crews is very high. The political implications of losing a helicopter and more importantly its crew are also significant and could affect the political will to continue with a campaign. The ability for the crew to survive after the crash and be successfully rescued is important and this requires adequate survival aids, rescue equipment and training. During the Vietnam conflict some helicopter pilots were shot down in excess of a dozen times, with one pilot (CW 2 Steve Hall) shot down four times on a single day (Everett-Heath 1992).

Rescue from the land requires that crew can first evacuate themselves and casualties from the aircraft. Fire-fighting and first-aid equipment and training would be required. The aircraft requires the ability to send a mayday message providing status and position information so that rescuers will know where to search. Good communications with potential rescuers are also required to get casualties treated within the so called 'golden hour.' The concept of a 'golden hour' refers to the first sixty minutes after receiving a major injury. The time between injury and treatment should always be minimised; however, after sixty minutes there is evidence to suggest that the survival rate drops off significantly for patients with severe trauma.

Rescue from the sea poses a number of challenges in addition to those experienced on land, including staying afloat until rescued. Chances of survival will all be increased by adequate provision of immersion suits, life jackets, a life raft, maritime survival equipment and training.

Rescue from hostile territory will be improved by escape and evasion training, good communications with potential rescuers and self protection weapons. Mission planning that incorporates CASEVAC and / or MEDEVAC contingencies would also promote crew survivability.

## 2.4 Discussion

This section identifies and discusses the constituent parts of the problem that will need to be addressed in the research approach developed in Chapter 3.

### *2.4.1 Threats to helicopters*

Military helicopters have a high utility in a wide variety of roles in support of battlefield operations. This flexibility is continually being demonstrated on current operations and consequently helicopters are regarded as a valuable, if not critical military asset. The high demand for helicopter capability in hostile areas puts them at risk. They face an extensive range of possible threats because of the job that they do within a broad range of potential scenarios.

Low-technology threats such as small arms, AAA and RPG are a dangerous threat to helicopters because they are prolific and highly mobile. There are many examples of the asymmetric use of such threats against helicopters historically and more recently in Iraq and Afghanistan. MANPADS are less prolific, but are guided and so potentially more deadly. To date, most recorded helicopter losses have been because of low-technology threats and MANPADS; however, there are many other threats that will be dangerous to helicopters if encountered within future scenarios. These include integrated air-defence systems, comprising sophisticated surveillance systems, fighter aircraft, missile defence systems and automated control systems (Spassky et al 2004).

The historical analysis shows that thousands of combat helicopters and crews have been lost worldwide as a result of hostile action. Most of these losses were sustained by the US during the Vietnam conflict; however, many lives are still being lost because of hostile action on current operations.

Understanding the threat environment provides the context and the starting point for the integrated survivability problem. An assessment will need to be carried out to define the representative threat environment. This is not simply an analysis of whether a threat is present or not within a scenario. The 'threat' definition comprises opportunity, intent and capability. A threat assessment needs to take into account realistic scenarios, missions and threatening situations to adequately characterise the threat. This assessment will need to consider past, current and future operations to ensure that it is comprehensive.

'Threat projection' has limitations because past operations do not often reflect future military requirements. Future predictions are based on assumptions and the associated uncertainties will increase as one tries to predict further and further into the future. However, focusing solely on the 'current war' is likely to leave one unprepared for the next, as has been proven

historically. In other words, it needs to be ensured that the military do not end up in a position where they are 'fighting the last war'.

Threats evolve, sometimes in an asymmetric way and more quickly than a large cumbersome acquisition process can deal with them. Agility and flexibility are, therefore, key characteristics to beat the future threat. 'Be prepared' is also the right approach. For this reason, the right intellectual and industrial survivability capabilities must be maintained to draw on when required.

### 2.4.2 Helicopter survivability attributes

Survivability attributes include functions, equipment, techniques and tactics that provide a survivability benefit. Attributes spanning the whole survivability 'circle' or 'chain' (Figure 1-2) have been introduced and include examples of helicopter applications.

It has been established that survivability is a critical military requirement and an emerging system characteristic (or parameter) resulting from bringing the constituent parts together, for example the integration of a sensor and effecter to form a DAS. Survivability attributes include sub-system and human interactions that are often influenced by TTPs, for example deploying a combination of countermeasures and manoeuvres to defeat certain threats.

Survivability attributes are generally more effective if 'designed in' from the start rather than retrofit; however, airframes can be in service for thirty years, so in reality some retrofit is unavoidable. Furthermore the helicopter procurement cycle takes a long time, by which point the threat and the role may have changed.

The other DLODs (e.g. infrastructure, information and training) are also important to ensure that the wider system works effectively. Survivability attributes are not only specific to the helicopter platform, but also include interactions and interoperability with wider military systems; for example, communications, datalinks, ISTAR and NEC. Consideration of 'human factors' is also important to optimise ergonomics and ease workload during complex situations. Taking an integrated survivability approach includes consideration of defensive as well as offensive capabilities, for example weapons.

In an environment of expeditionary high-tempo operations, extended airframe life and stretched defence budgets (Ministry of Defence 2009b), flexibility is a key aspect. Helicopters must, therefore, be rapidly upgradeable to support future operations and deal with future threats. This places an emphasis on not only the individual sub-systems, but also the architectures that link systems together. 'Open' systems are an important part of this, particularly for DAS. DAS controllers offering interface rich, programmable capability will

contribute to this need by enabling new sub-systems and capabilities to be integrated onto legacy platforms.

It would not be possible or appropriate to fit every survivability attribute on to a helicopter. Given the challenging demands placed upon our helicopters, the right balance of attributes needs to be achieved taking into account the threat, the role and the constraints. This careful balancing act needs to be achieved through the selection of suitable systems engineering methods in Chapter 3 and their further development in Chapter 4.

### 2.4.3 *Constraints*

Most air vehicles and particularly helicopters are constrained by available financial resources, space, mass and power. Additional hardware increases mass, so reducing performance, payload and range and possibly at the expense of mission capability. Newer technology, for example the next generation of DIRCM systems may offer improved survivability at a lower mass burden. Available power is also at a premium on every platform, particularly on older legacy platforms where existing upgrades have 'used up' the available power budget.

Financial constraints are important because if a programme is too expensive it will be stopped or may not even get underway. The US Comanche programme integrated many 'leading edge' survivability attributes; however, it was too expensive and the requirement had changed. Through-life cost needs to be understood and includes allowance for capability sustainment and support, as well as the initial equipment 'buy'.

## 2.5 Summary

Chapter 2 has identified the problems that need to be tackled in order to investigate the research question set out in Chapter 1. These problems are as follows:

### 2.5.1 *Uncertainty*

There are a number of sources of uncertainty that will need to be addressed:

- Threat types and the likelihood of encountering them are difficult parameters to predict because they can change rapidly and in an asymmetric manner. Furthermore, future scenarios are difficult to predict.

- The performance of survivability attributes can be difficult to quantify, particularly for newer technologies at lower technology readiness levels or for existing attributes against new threats.

### 2.5.2    *Helicopter roles*

Helicopters are used in a wide variety of roles and are often used in roles that they were not originally designed for. This is because the acquisition process takes a considerable time to deliver a helicopter capability and by the time a platform comes into service the requirement and threat is likely to have moved on. The problem is compounded by the fact that platforms are often in service for a considerable time and future scenarios are difficult to predict.

### 2.5.3    *Long acquisition cycles*

Helicopter platforms take a long time to procure and system upgrades can often take several years because of design, integration, testing and clearance processes.

### 2.5.4    *Many diverse aspects affect survivability*

There are many diverse aspects affecting survivability across the DLODs, from equipment through to training. Some of these aspects have interactions, for example, adding armour reduces vulnerability against small arms, but this increases mass so reducing manoeuvrability and hence increasing susceptibility. Some aspects may be difficult to quantify, for example the survivability benefit of TTPs and training.

### 2.5.5    *Constraints*

Platforms have constraints such as cost, available electrical power, weight and space. This is particularly true on existing platforms which may already have had system upgrades and / or other capabilities competing for installation space. The right balance needs to be struck so that the mission and survivability can be delivered within the constraints.

# 3   SYSTEMS ENGINEERING

This chapter develops a research approach to deal with the problems identified at the end of Chapter 2. It starts by conducting a literature search of the systems engineering domain to provide the holistic approach required and to investigate suitable methods to address the problems. Systems engineering principles and lessons learnt from relevant defence projects have also been researched and identified.

The chapter researches relevant systems engineering theory including: definitions, principles and background information. The theory ranges from generic, high-level through to more specific defence acquisition applications. The discussion identifies opportunities to apply selected aspects of the theory to the problem. Promising methods are then selected for development Chapter 4.

## 3.1     Why is systems engineering important?

Systems engineering provides the ability to manage the complexity of advancing technology (Stevens et al 1998). Defence projects are also increasing in complexity as technology develops, particularly with regard to network enabled capability and as the requirement for interoperability expands. Many major defence projects suffer from technical issues relating to systems integration. Improving systems engineering is a high priority for industry and the MOD, to ensure that the Armed Forces receive the equipment they need (Ministry of Defence 2005a). Managing capability throughout the life of a system is also aided by systems engineering, which provides the ability to integrate new technology into legacy platforms.

The MOD's 'Smart Acquisition' process was based on systems engineering processes and was fundamentally sound. Past problems with defence projects have generally been associated with sub-standard application of the process (Sparks 2006). Wymore (1993) attributes many methodological errors as being frequently repeated in the absence of a proper problem statement. This can lead to huge cost and schedule overruns and performance shortfalls attributed to the acquisition large-scale complex systems. It is important that systems engineering processes are understood and conducted in the right way, because successful implementation is everything.

## 3.2     Definitions and background

### 3.2.1     *System*

There are many definitions of a 'system.' Hitchins (2005) provides a high-level example: "A system is an open set of complementary, interacting parts with properties, capabilities and behaviours emerging both from the parts and from their interactions."

The International Council on Systems Engineering (INCOSE) provide the following more specific definition:

"An integrated set of elements, subsystems, or assemblies that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements" (INCOSE 2010).

The term 'system-of-systems' is frequently used within the systems domain. Section 3.5 usefully sets out the definition within the system engineering levels classification. Some regard the 'system-of-systems' term as unnecessary 'jargon;' however, for completeness the INCOSE (2010) definition is as follows:

"System of systems applies to a system-of-interest whose system elements are themselves systems; typically these entail large scale inter-disciplinary problems with multiple, heterogeneous, distributed systems."

### 3.2.2   *Systems engineering*

Systems engineering is defined as "the art and the science of creating systems," (Hitchins 2005) and is a "pursuit of reason" (Westerman 2000). The Defence Industrial Strategy contains a more specific definition: "Systems engineering is the general term for the methods used to provide optimally engineered, operationally effective, complex systems. Systems engineering balances capability, risk, complexity, cost and technological choices to provide a solution which best meets the customer's needs" (Ministry of Defence 2005a).

The ancient Egyptians demonstrated many of the features of systems engineering when building the pyramids around 4500 years ago (Hitchins 2005). There is some debate as to who invented the actual term. Apparently the term "systems engineering" was coined by Bell Telephone Laboratories in the 1940s and the concepts can be traced back further within Bell Labs to the early 1900s (Fagen 1978 cited in Buede 2000). The Gemini and Apollo programmes developed by NASA in the 1950s and 1960s were a showcase for the new philosophy of systems engineering.

Many of the systems engineering principles have been developed experimentally without a formal or theoretical background (Sheard and Mostashari 2009). Consequently, systems engineering is still not a recognised engineering discipline, although it is evolving into one (Kasser 2007). Many definitions for systems engineering have been cited since the adoption of systems engineering as a 'profession' in the 1950s (see Buede (2000) and Kasser (2007) for comprehensive listings).

Systems engineering is a creative activity with both a technical and managerial dimension (Stevens et al 1998). Successful systems design is about "building the right thing and building the thing right." The project and the product must be designed, involving project management, procurement and the interaction of people, processes and technology (Elliott and Deasley 2007).

The term 'systems thinking' is often used, perhaps to appear more abstract or unconstrained. In reality, systems thinking is part of 'systems engineering;' and can therefore, be encapsulated within the 'systems engineering' definition. 'Systems engineering' perhaps has a greater purpose and sense of delivery than 'systems thinking'. Elliott and Deasley (2007)

point out that systems thinking[19] is particularly helpful to span across traditional engineering disciplines that may not share the same assumptions.

### *3.2.3*   *Systems engineer*

Wymore (1993) states that systems engineers are "problem staters," because systems engineering starts by stating problems comprehensively without referring to any particular methods or solutions. Westerman (2000) concludes that systems engineers need to be honest, have a background in at least one technical discipline, a broad understanding of others and the ability to think. The Defence Engineering Group describe the requirement for a T shaped knowledge base, with expertise in depth of at least one of the relevant technologies and disciplines affecting the system and an adequate broad understanding of all the others (Ministry of Defence 2005c). Sheard (1996) identified 12 systems engineering roles that are either connected with the 'system life-cycle' or 'programme management'. Often a single individual cannot possess all of the capabilities ideally required to be a systems engineer, so mixed teams of generalists and specialists are used (Hall 1962 cited in Kasser 2007). This breadth comes with experience and so it needs to be recognised that good systems engineers take time to 'grow' and must be given a wide range of opportunities to develop the right skill set.

### *3.2.4*   *Systems principles*

The first systems principle states that: "The properties, capabilities and behaviours of a system derive from its parts, from interactions between those parts, and from interactions with other systems" (Hitchins 2005). There is also an associated corollary: "Altering the properties, capabilities, or behaviour of any of the parts, or any of the interactions, affects other parts, the whole system, and interacting systems" (Hitchins 2005).

### *3.2.5*   *Classification of systems*

It is helpful to classify systems and the following classifications have been taken from Blanchard and Fabrycky (1998).

*Natural and human-made systems*

Natural systems can be defined as those that were created through natural processes. Human-made systems are created by human intervention and exist within the natural world. The relationships between natural and human-made systems have recently become particularly pertinent through mankind's adverse impact upon the environment. Human-made helicopter and threat systems operate within the natural environment that comprises many natural

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[19] Sparks (2006) provides a comprehensive critique on systems engineering and its application to defence acquisition.

systems such as the weather, terrain and flora and fauna. A helicopter must be able to operate alongside these natural systems and can use them to its advantage; for example, using trees and the weather for camouflage and concealment.

*Physical and conceptual systems*

Physical systems can be defined as those that exist in a physical form. Conceptual systems exist as symbols that define the attributes of components; for example, ideas and concepts. The acquisition cycle deals with conceptual systems initially and then physical systems as the acquisition progresses to the demonstration and manufacture phases. User and system requirement documents are examples of conceptual systems. Conceptual system simulations can be used to model proposed physical systems, for example man in the loop (MITL) simulation.

*Static and dynamic systems*

A static system can be defined as having a structure, but is without activity. A dynamic system, such as a helicopter, has structure and activity. System operation can often contain an element of randomness and can therefore be described as probabilistic. Helicopter operations and the behaviour of 'pop-up' threats often have random elements associated with them.

*Closed and open systems*

A closed system does not interact to any great degree with its environment. An open system interacts with its environment, allowing information, matter and energy to pass through its boundaries. Helicopter systems can be considered to be open because they emit energy to their surroundings; for example, in generating motion, electromagnetic and acoustic emissions. Entropy is sometimes used to describe the organisation of a system. A system has high entropy if it is disorganised and this entropy reduces as it becomes more organised.

## 3.3 Hitchins' systems engineering philosophy

### 3.3.1 *The three components*

Hitchins (2005) states that there are three components to his systems engineering philosophy:

*Holistic*

Any system should be conceived, designed and developed as a whole and not "cobbled together" from available or separately developed parts. "Systems theorists have pointed out that we can better understand an entire system by examining it from a general, holistic perspective that does not give as much attention to the function of the parts" (Saaty 2001).

*Organismic*

The whole system should be viewed as an open system and as analogous to an organism. The various sub-system parts are interactive and mutually independent. The constraints on the system requires compromise and complementary behaviour of the parts and their interactions. This view is required in order to create optimal solutions that satisfy limiting conditions, such as: performance, value for money, cost effectiveness and weight.

*Synthetic*

Systems are constructed from components that are in themselves systems, interconnected so that the whole provides emergent properties, behaviours and capabilities. "Synthesis is the opposite of reduction" (Ackoff 1981 cited in Hitchins 2005). Reduction looks into a system, breaking things down. Synthesis looks out of a system, building things up.

### 3.3.2    *Systems Engineering Problem-solving Paradigm*

There are many potential solutions to a problem and the systems engineering philosophy uses the Systems Engineering Problem-solving Paradigm (SEPP) to deal with this. One of the advantages of this process is that good features from unselected options can be included within the chosen solution. The SEPP is outlined in Figure 3-1.
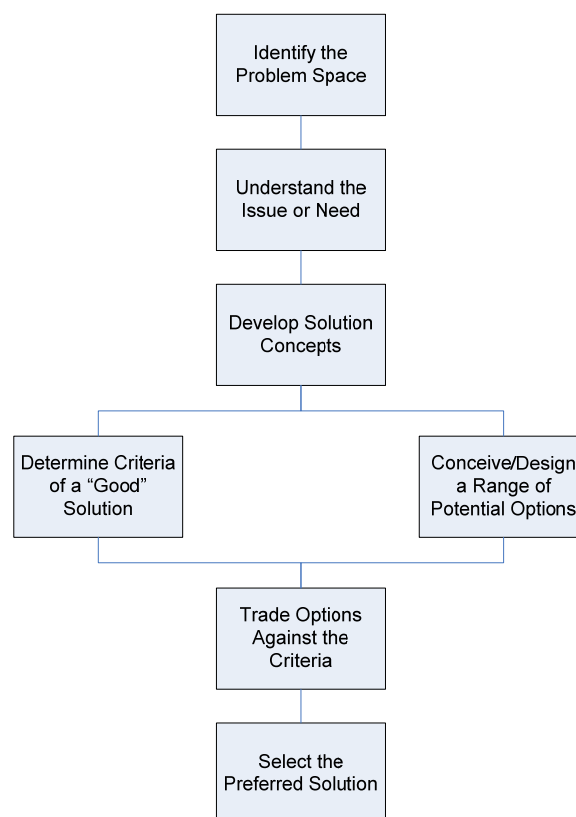


**Figure 3-1 – Systems Engineering Problem-solving Paradigm (SEPP) process (Hitchins 2005).**

### *3.3.3 System philosophy methods*

Hitchins (2005) outlines a number of methods that would be used to implement his systems engineering philosophy. The methods are outlined below and examples have been applied to helicopter survivability. These methods are similar to the principles for integrated system design outlined by The Royal Academy of Engineering (Elliott and Deasley 2007), see Section 3.4.

*Highest level of abstraction*

When approaching a new problem one should try to maintain a high level of abstraction for as long as possible. This will avoid premature assumptions and missed opportunities. For example, consider an attack helicopter not an Apache; a heavy lift helicopter not a Chinook; a survivable helicopter not just a DAS.

*Disciplined anarchy*

The systems engineer needs to generate many options and as many criteria as possible and then question implicit assumptions, in order to maintain the high level of abstraction. Brainstorming the helicopter survivability system with a broad range of stakeholders and experts is an example of how this can be achieved.

*Breadth before depth*

One should analyse the whole problem space before focusing on parts of the potential solution. The first level of elaboration including the interactions, external interactions and environments should be described before partitioning or elaborating any sub-system. Initially concentrating on the helicopter operating environment, should enable the interactions to be established at a broad level.

*One level at a time*

It is recommended to complete each level of elaboration before "drilling down" into progressively more technical detail. This prevents an imbalance, with some systems receiving most consideration and some being neglected. This could be achieved by developing top-level influence diagrams in the first instance.

*Functional before physical*

Deriving a purposeful system necessitates the generation of functions that can then be grouped into sub-systems for physical creation. Consideration of the pillars of survivability and use of influence diagrams are consistent with the functional approach.

## 3.4    Integrated system design principles

The Royal Academy of Engineering (RAEng) outline six integrated system design principles that have been derived by experienced engineers based upon extensive experience (Elliot and Deasley 2007). The six principles are consistent with the MOD's acquisition system[20] and build on the systems engineering philosophy introduced in Sections 3.3 and 3.3.3. The six principles are:

- Debate, define, revise and pursue the purpose.

- Think holistically.

- Follow a systematic procedure.

- Be creative.

- Take account of the people.

- Manage the project and the relationships.

The first principle involves defining the requirements and carrying out trade-off studies between demands, considering the parameters of cost, performance and timescale and the risk of each. The second principle involves considering the system as a whole, defining the system boundaries and includes the product, process and people throughout the entire lifecycle. This approach is consistent with Hitchins (2005) 'highest level of abstraction' and 'breadth before depth'. The third principle is well defined by the systems engineering Vee-diagram (explained in Section 3.7.3). The Vee-diagram provides a systematic process of iteration to construct and integrate the components within the system.

The fourth principle involves defining the capability, creating the top-level design and facilitating each stage of the system lifecycle. Importantly, "Designers create the emergent properties, not just broker trade-offs" (Elliot and Deasley 2007). The fifth principle recognises that people are part of the system when it is built and when it is operated and the system designer must take this into account. Ergonomics and human factors integration, physically and psychologically are an important part of system design. The system may include training and recruitment to ensure that sufficient competent people are available during the development and operating phases. The sixth principle stems from the large number of people required to implement a system during its lifecycle. Many organisations will be involved, formally and informally and so communication is critically important. Project management is essential to ensure that the project and the system are properly designed. The system architecture will normally be translated into a work breakdown

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[20] The acquisition system was set up by the Defence Acquisition Change Programme as a result of the Enabling Acquisition Change study of 2006. It builds on Smart Procurement (Ministry of Defence 2008b).

structure, keeping interfaces as simple as possible. Partnerships between customers and suppliers encourage co-operation and greater openness allowing problems to be resolved early. This is especially valuable for complex projects and requires both a competent customer and supplier.

## 3.5    System engineering levels

It is useful to recognise that there are different 'levels' at which systems engineering is conducted. Hitchins (2005) sets out a five-level system structure to classify these levels. The Royal Academy of Engineering define three system classification levels according to system complexity (Elliot and Deasley 2007):

- Level 1: A sub-system, e.g. an aircraft antenna.

- Level 2: A system, e.g. an aircraft.

- Level 3: A system of systems, e.g. military command and control.

These levels are consistent with Hitchins definitions because the first three levels are equivalent. Hitchins' levels 4 and 5 expand upon the 'system of systems' definition above. The system engineering level definitions and their relevance to helicopter survivability has been summarised in Table 3-1.

**Table 3-1 – Systems engineering levels (Hitchins 2005, Elliot and Deasley 2007).**

| RA Eng Level | Hitchins Level | System Engineering Level | Example systems | Example outputs |
|---|---|---|---|---|
| 3 | 5 | Socio-economic systems engineering | Legal, political, social, economic. | Optimum solution of socio-economic paradigms for the successful future of a nation, e.g. MOD and other government departments. |
| | 4 | Industry system engineering | National wealth creation, the nation's engine. | Optimisation of the industrial system, e.g. "UK plc" and UK Defence Contractors. |
| | 3 | Business system engineering | Industrial wealth creation. Many businesses make an industry. | Optimum volume in the supply channel, e.g. a helicopter manufacturer and their suppliers. |
| 2 | 2 | Project system engineering | Corporate wealth creation. | Optimum holistic system solution, e.g. the design and manufacture of a helicopter. |
| 1 | 1 | Product/sub-system engineering | Artefacts: to some the only "real" systems engineering. Many products (can) make a system. | A tangible product that meets its purpose, within its operating constraints, e.g. the design and manufacture of a threat warning system or a DAS. |

## 3.6    Classic systems engineering model

The design and manufacture of a helicopter falls into a level 2 system category. The conceptual approach to systems engineering at this level is the "classic" approach that has been in use since the 1950s, as illustrated in Figure 3-2 (Hitchins 2005). This approach starts with the problem, then researching to find the "need," as opposed to the "want" that may not solve the problem. In terms of survivability, the problem is threats, and the need might be "to survive in the man-made hostile environment, as defined by the relevant mission and operating environment definitions." The "want" might be "a DAS." Solution-design options are created, along with the design criteria against which they will be judged in order to find

the "good" solution. This process is the systems engineering problem solving paradigm (SEPP) in operation.
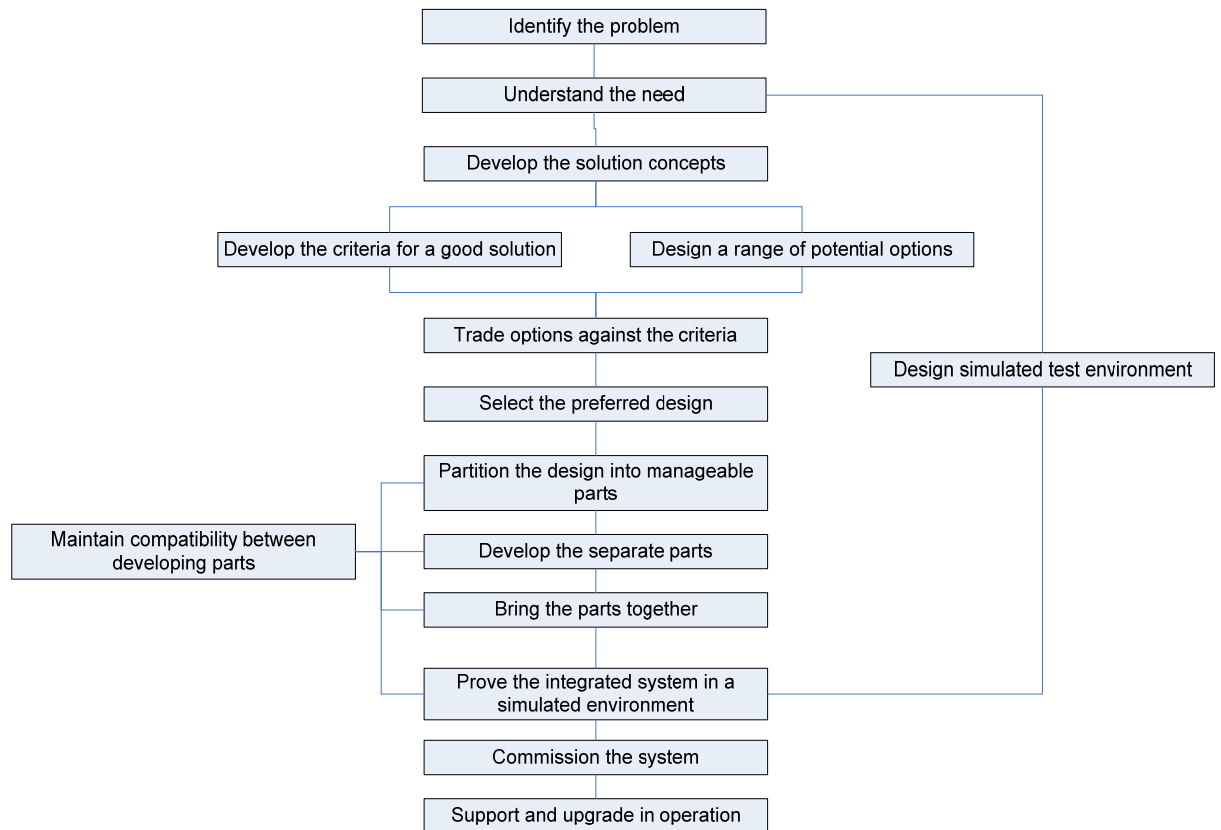


**Figure 3-2 – Classic level 2 systems engineering conceptual process model (Hitchins 2005).**

The design is then partitioned into manageable parts, e.g. functional sub-systems. This partitioning requires that interfaces are created between the partitions, "so that the process becomes one of elaboration rather than decomposition" (Hitchins 2005). The parts are developed or acquired and are then progressively tested and combined within a simulated test environment representing the environment that the system will operate within. The system can then be commissioned and then supported and upgraded in service.

The process should result in a holistic system solution that is optimal. The use of SEPP is intended to identify the optimal solution from a range of options. There are, however, a number of potential problems; for example, the range of potential options may not span the optimal solution. In this case, SEPP would find the "best of the bunch," which may fall short of optimal (Hitchins 2005).

The SEPP is consistent with and complementary to the defence CADMID cycle and Vee-diagram. The first two steps in the SEPP: to 'identify the problem' and to 'understand the need' are developed by definition of the user requirement document (URD) and system requirement document (SRD) respectively. Verification and validation tests are identified

within the SRD and then detailed in the separate Integrated Test, Evaluation and Acceptance (ITEA) documentation, which covers the SEPP 'design simulated test environment' step. The requirement decomposition and testing processes are well illustrated by the Vee-diagram (Figure 3-5) and have corresponding steps within the SEPP.

## 3.7 Systems engineering process models

Systems engineering process models provide a structured approach to carry out the steps defined in the systems engineering philosophy and integrated system design principles detailed in Sections 3.3 and 3.4. There are a number of such models including: the Waterfall, Spiral and Vee models. These models find their original roots in the software domain and have all since been adopted by the wider systems engineering community.

### 3.7.1 Waterfall

The Waterfall model (Figure 3-3) was defined by Royce (1970) to identify a sequential phased development process for software (Forsberg and Mooz 2006). Requirements are defined before design and design before coding. The downwards arrows show the flow-down of requirements and solutions. The upward arrows show the 'backward adjustment' of the baseline as issues are found that may influence the baseline (Forsberg and Mooz 2004). The model can also be used for hardware and system development (Forsberg and Mooz 2006).
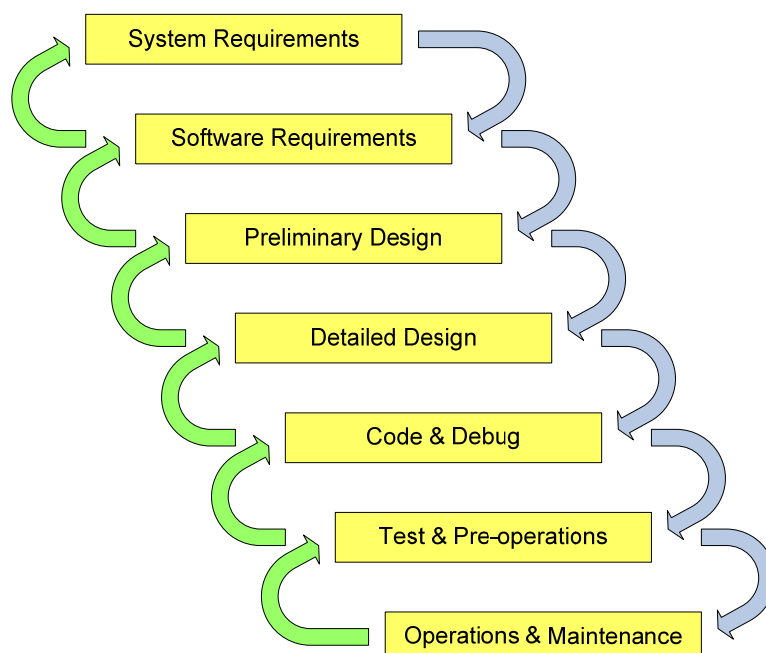


**Figure 3-3 - Waterfall method / model (Royce 1970 cited in Forsberg and Mooz 2004).**

### 3.7.2 Spiral

The Spiral model was defined by Boehm (1988) to address risk in software development before transition to a waterfall approach. 'Prototypes' are developed to identify risks and define appropriate action (Forsberg and Mooz 1991). The model can also be used for hardware and system development (Forsberg and Mooz 2006).
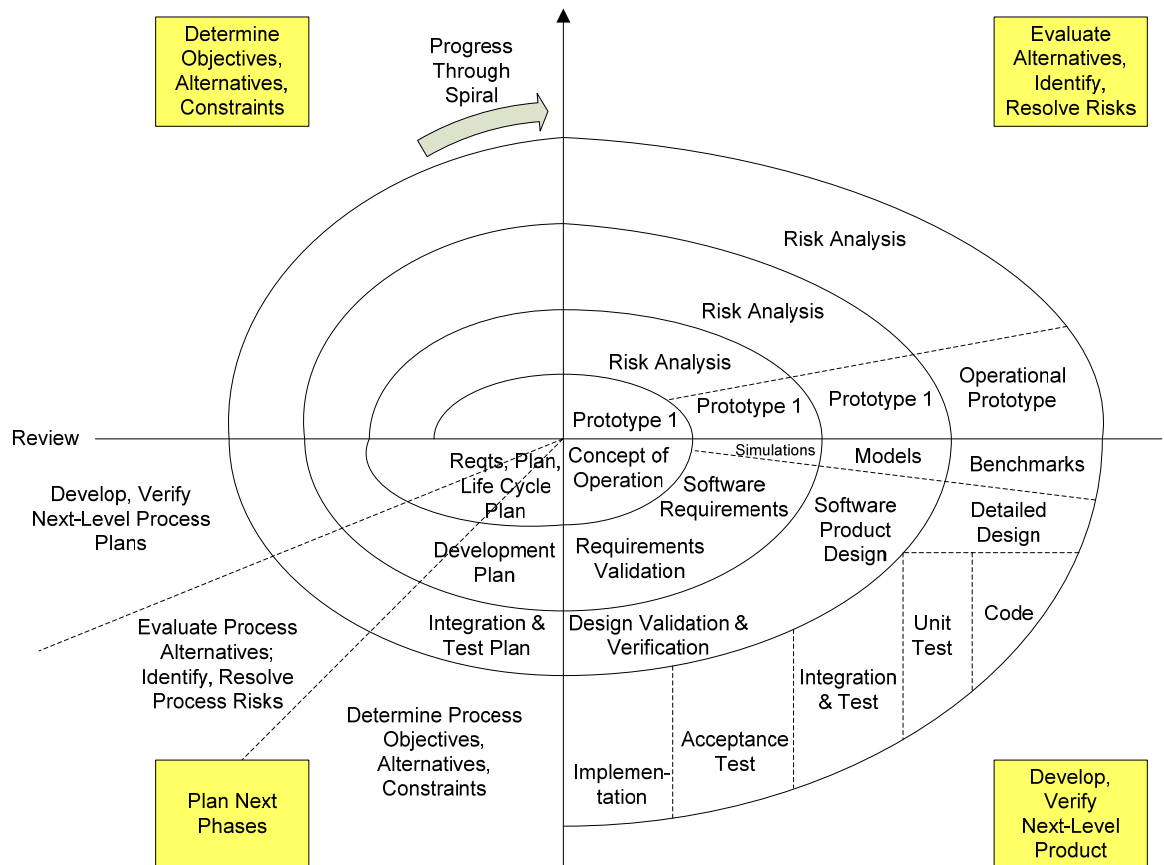


**Figure 3-4 - Spiral model of the software process (Boehm 1988 cited in Forsberg and Mooz 1991)**

### 3.7.3 Vee-diagram

The Vee-diagram was developed by Rook (1986) cited in Kasser (2007) as a software project management tool. The diagram was introduced to the systems engineering domain by Forsberg and Mooz (1991), who also define a third dimension, whereby a systems analysis and design process is conducted at each step of the process. The Vee-diagram describes "the technical aspect of the project cycle" (Blanchard and Fabrycky 1998) and is useful because it sets out the major steps in an accessible manner. The model is a clear representation of the systems engineering process and has been adopted by the acquisition community and is

referenced within the Acquisition Operating Framework. A version of this model set against system readiness levels (SRLs)[21] and the CADMID cycle is illustrated in Figure 3-5.
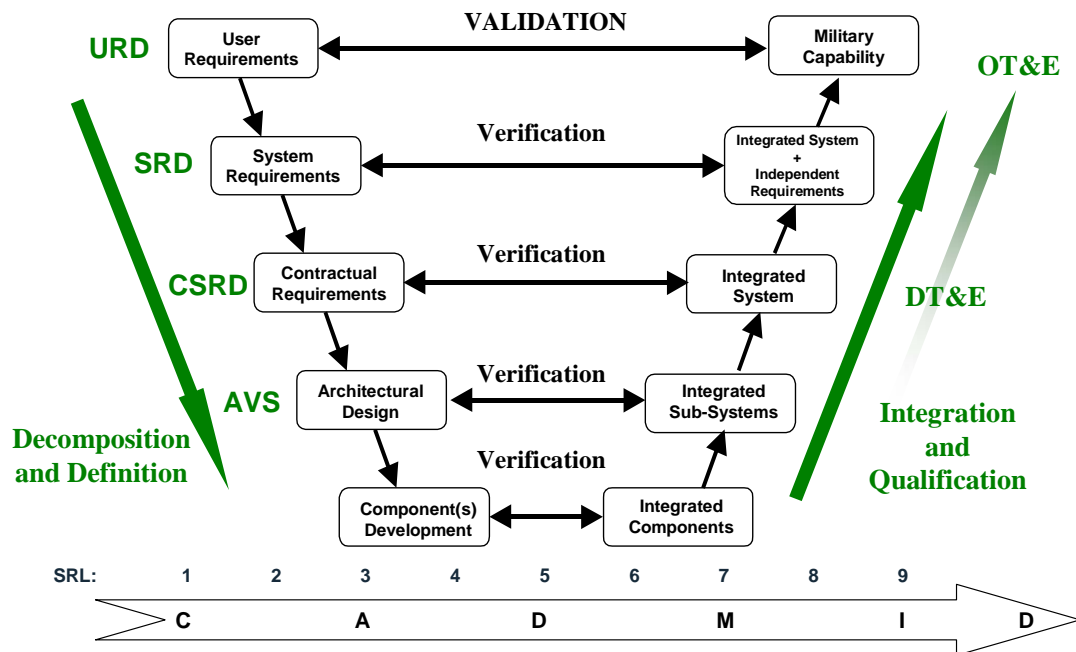


**ABBREVIATIONS:** URD User Requirement Document, SRD System Requirement Document, CSRD Contracted System Requirement Document, AVS Air Vehicle Specification, DT&E Developmental Test & Evaluation, OT&E Operational Test & Evaluation, SRL System Readiness Level

**Figure 3-5 - Systems engineering Vee-diagram.**

The systems engineering Vee-diagram depicts the design and integration process. The left-hand side forms the requirement decomposition and design definition process. The right-hand side represents the integration and qualification activities. The process is started at the top left with the user requirement, which is then decomposed to form the system requirement. In practice, the project team and contractor will produce contractual requirements against the system requirements. The architectural design (or air vehicle specification, AVS) will then be developed. Components will then be designed from the AVS. Progress along the system lifecycle (or CADMID) and SRLs can be tracked horizontally with time. Vertical iterations are essential to ensure success (Guindon 1990 cited in Buede 2000) and the procedure is guidance, not a 'straight jacket' (Elliot and Deasley 2007). Stakeholder interaction is also essential and is assumed throughout the process. The vertical movement between design stages is challenging within defence procurement because of the boundary between the customer (MOD) and the supplier (industry).

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[21] SRLs are explained in section 3.9.1.

Forsberg and Mooz (2006) have developed the concept further with a 'dual vee' that represents an 'architecture vee' and an 'entity vee' as a third dimension. In practice, this means that the Vee-diagram process is conducted at each architecture level and the architecture also follows its own Vee-diagram process.

*Requirements decomposition*

"A requirement is an unambiguous statement of the capability that the system must deliver. It is expressed in operational terms (what the system will do) rather than solutions (how the system will do it). The statement of a requirement must also define how it is to be tested – if it can't be tested or measured, it isn't a requirement" (Elliot and Deasley 2007). Many computer-based systems have been delivered late and over budget because of problems with the systems requirements (Kotonya and Sommerville 1998).

Definition of user requirements is the first step in system design. The user requirements identify what the user wants in operational terms. Systems engineers must interact with users to develop a coherent set of agreed requirements that is then issued as the user requirements document (URD) (Stevens et al 1998).

System requirements identify what the system will do, not how it should be done. Systems requirements are a functional definition of the system and must be traceable to the user requirements and the design (Stevens et al 1998). System requirements are often managed within a software package such as IBM$^®$ Rational$^®$ DOORS$^®$ that provides a structured functional decomposition and can present various views including a tree diagram as well as helping to manage the change control process.

*Test and evaluation*

Testing determines the level of conformance to requirements, i.e. does the system do what it is supposed to do at a functional level? Evaluation determines the capability, i.e. what can the system actually do? (Kasser 2007).

The Ministry of Defence (2008c) define test and evaluation (T&E) as: "The demonstration, measurement and analysis of the performance of a system, and the assessment of the results". T&E provides confidence that the requirements have been met, that the system is safe to use and that it is 'fit for purpose' across all DLODs. Conducting T&E can also enable system design improvements, development of TTPs and the collection of data on system deployment. The ITEA is the MOD's process for conducting T&E. ITEA plans are 'living documents' that are developed to pass initial and main gate points (Ministry of Defence 2008c).

Figure 3-5 shows that integration involves building up the system from lower-level components into higher-level integrated components that are then integrated into sub-systems that are then integrated to form the overall system. Qualification testing is conducted to check each stage of integration. This verification testing can also be referred to as developmental test and evaluation (DT&E) and can be summarised as: "Have we built the system right?" or "does it meet the spec?"

The final stage of qualification is validation, where the military capability is tested against the user requirement. This step is also referred to as operational testing and evaluation (OT&E) and can be summarised as: "Have we built the right system?" Put another way, can the system be used to accomplish the mission and be supportable and maintainable? (Kasser 2007).

Survivability is difficult to validate because, arguably, full validation will only take place when the military capability operates within the 'real' hostile environment. Limited validation can be conducted prior to deployment, for example simulation testing using actual hardware in the loop or live fire testing of sub-systems or even the full platform. Modelling and simulation can be used in conjunction with flight testing to enable the best possible assessment. Once the validation has been successfully completed then acceptance can take place. The Capability Sponsor[22] is the acceptance authority within MOD.

It is important that the integration testing evidence is built up during the gradual progression from DT&E to OT&E. It is not possible to test every detail of the system at OT&E and it is not possible to test the whole system in a realistic environment at DT&E. Every step of testing builds confidence in the system by teasing out and resolving issues.

Successful implementation of the T&E process is not always achieved because defence systems are often large and complicated and the defence acquisition process is also complex. The importance of T&E is sometimes underestimated and consequently under resourced. Testing is an essential activity that ensures that the right capability is provided to the front line. It also provides the user with an understanding of performance and confidence in that capability. T&E is much more than just demonstrating that the contract has been delivered.

## 3.8    A systems engineering framework

Kasser (2007) identifies the need for a framework to understand systems engineering. Kasser and Massie (2001) proposed a solution that combined Hitchin's (2000) systems engineering levels with generic phases of the systems engineering life cycle. Kasser (2007) develops this idea further by adding a third dimension from Shenhar and Bonen's (1997) taxonomy of

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[22] Formerly the Equipment Capability Customer (ECC).

systems based on technical uncertainty (risk). The resulting framework in Figure 3-6 has been adapted by the author to include the CADMID cycle and to illustrate the third dimension.
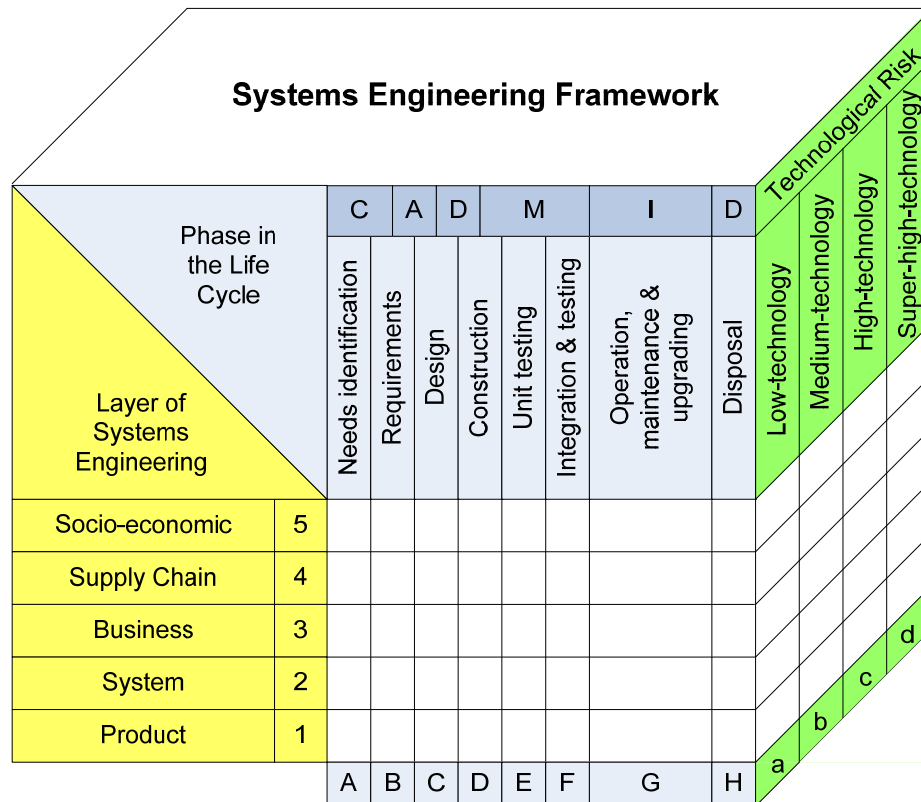


**Figure 3-6 - The Hitchins-Kasser-Massie Framework, adapted from Kasser (2007).**

The third dimension is defined as follows from Kasser (2007):

Type a – Low-technology projects, which rely on existing and well-established technologies to which all industry players have equal access.

Type b – Medium-technology projects, which rest mainly on existing technologies; however, such systems incorporate a new technology or a new feature of limited scale.

Type c – High-technology projects, which are defined as projects in which most of the technologies used are new, but existent – having been developed prior to the project's initiation.

Type d – Super-high-technology projects, which are based primarily on new, not entirely existent, technologies.

The framework is a useful concept to help understanding of different types of systems and different activities depending upon location within the matrix. There is also a realisation that systems engineering should not be conducted in the same way for all types of system.

In practice, the system engineer will typically mitigate technical risk associated with high-technology projects through a risk reduction programme such as a technical demonstrator programme (TDP). For example, this could enable a 'type d' project to progress to a 'type c' and the technology then being available for integration on to platforms.

## 3.9    System maturity

### 3.9.1    *System readiness levels*

System readiness levels (SRLs) are used within the defence community to define system maturity. The Acquisition Operating Framework (Ministry of Defence 2009c) outlines nine SRLs that define system maturity assessed across a range of system disciplines. SRLs can be set against the system engineering Vee-diagram (see Figure 3-5). The system disciplines are defined as follows:

- Systems engineering drivers.

- Training.

- Safety and environment.

- Reliability and maintainability.

- Human factors integration.

- Software.

- Information systems.

- Airworthiness.

- Project specific areas.

### 3.9.2    *Technology readiness levels*

NASA developed technology readiness levels (TRLs) during the 1980s and McKinsey recommended that the MOD adopt their use in 2001. TRLs define the technical maturity of a project by identifying the technology and system integration risks. The TRL scale is illustrated in Figure 3-7 and uses specific criteria to define the technology maturity.

Theoretically, the MOD's research programme or industry's own private venture funding develops technology from TRL 1 (basic principles observed) to TRL 4 (validation in a laboratory environment). A technology demonstrator programme (TDP) will sometimes be used to develop a technology from TRL 4 to TRL 7 (technology system prototype demonstration in an operational environment). This reduces technical risk before integration of the actual system on to a platform.

Successfully completing the T&E process for the actual system will result in TRL 8. Acceptable qualification through successful mission operations will result in TRL 9. For survivability systems this means a consistent track record of successfully protecting the platform against real threats in a hostile environment.

Unfortunately TRLs are sometimes poorly applied. They are usually aligned with technology, or at best sub-systems and rarely take account of integration. For example, TRL 6 or 7 'components' may still only provide a TRL 2 system.
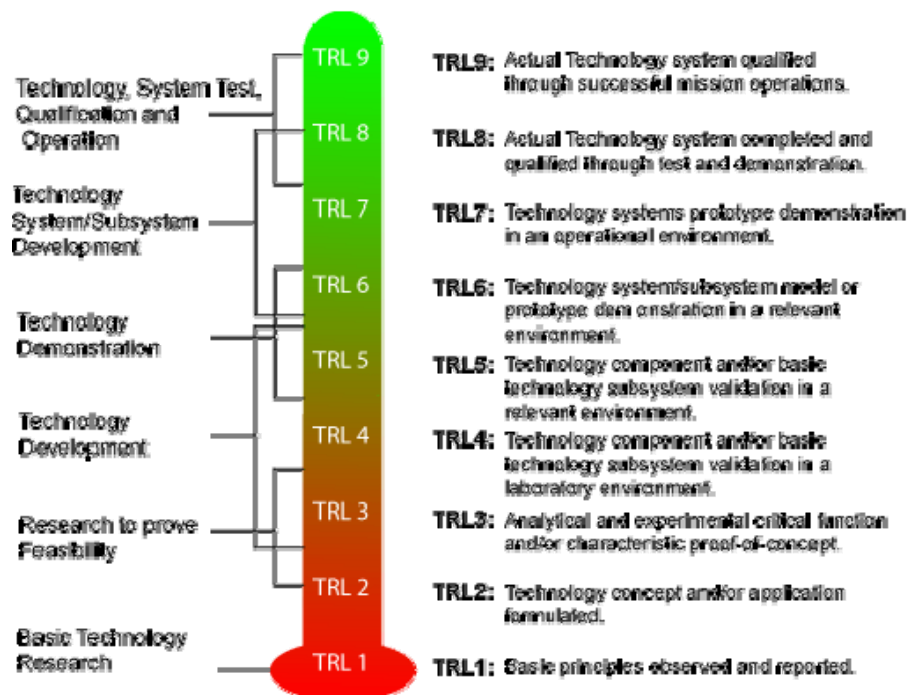


**Figure 3-7 - Technology readiness levels (Ministry of Defence 2009c).**

## 3.10 System modelling and simulation

A model consists of logical relationships that represent the assumptions made about the system of interest. Models can be used to predict quantitatively the emergent properties of a system. They can be used to represent systems that already exist and those that are conceptual. Investigations using system models result in reduced development time and cost compared with direct manipulation of the system itself (Blanchard and Fabrycky 1998). It is important to remember that: "A model is any incomplete representation of reality, an abstraction" (Buede 2000), and so, input data must be relevant to the problem and results should be considered within the context of both the model and the input data before being used. Additionally, models must be verified and validated to ensure that they are fit for purpose.

Westerman (2000) identifies two categories of people required to provide input data: system analysts and technical experts. Westerman (2000) also states that system analysts should be people who "know a reasonable amount about all technical areas and who can keep in mind the purpose of it all." System analysts must engage with technical experts to provide the depth of knowledge required within the context of the system. The right mix of people is important to consider the necessary breadth and depth of the problem. A critical requirement is a thorough understanding of the limitations of the techniques being used.

"A simulation is a dynamic model that allows people to be involved" (Elliot and Deasley 2007), for example a flight simulator. A simulation typically uses a computer to numerically exercise the inputs of a model, or models to analyse the effect upon the output. Simulations are typically used to numerically evaluate complex real-world systems that cannot be calculated analytically (Law and Kelton 2000).

Models can be classified by the following types:

- Physical.

- Analogue.

- Schematic.

- Mathematical.

A *physical model* is a geometric equivalent, for example an aircraft model used in a wind tunnel. This is usually sub-scale and may have some limited functionality. *Analogue models* focus on similar relationships, for example an electric circuit diagram can be used to represent mechanical, hydraulic or even economic systems (Blanchard and Fabrycky 1998). *Schematic models* reduce a problem using charts or diagrams. Examples of such models are process flow charts and organisation charts. Schematic models help to facilitate a solution, but they are not in themselves the solution (Blanchard and Fabrycky 1998). The House Of Quality (HOQ) used in Quality Function Deployment (QFD) and the hierarchies developed as part of the Analytical Hierarchy Process (AHP) can be described as schematic models. *Mathematical models* use mathematical relationships and expressions to describe the systems that they represent. They provide a high level of abstraction and precision in their use. Many mathematical models use probability to incorporate uncertainty and randomness. Measures of effectiveness can be optimised by understanding which variables to control and how they influence other components of the system.

## 3.11 Systems engineering methodologies

This section explores the methods used in systems engineering and their possible application within the survivability domain.

### 3.11.1   Design trade-off

Deciding between alternative design concepts is difficult because there are often multiple conflicting criteria against which a possible solution must be assessed. There is known and unknown information and uncertainty associated with the decision space. The solution and assessment spaces must remain open because other candidate solutions may be identified and the selection criteria may not be complete or appropriately weighted (Cook et al 2002).

As part of the design process it is usual to produce a number of possible solutions. These solutions are reviewed and a method is used to select the best option. These design trade-off studies use multiple criteria against which the possible solutions are assessed. This process is commonly referred to as multiple criteria decision analysis (MCDA). Trade-off methods can be grouped into two main types: subjective and quantitative.

*Subjective methods*

Subjective methods involve forming verbal arguments that compare the characteristics of the possible solutions. Selection criteria are chosen and then each solution is discussed. The resulting conclusions are used to determine the most suitable option. Subjective methods have the advantage that they can include knowledge that goes beyond the requirements themselves. Intuition and feelings can also be incorporated. Sometimes subjective methods can provide the only meaningful and 'honest' approach and are entirely acceptable to the customer (Westerman 2000). The main disadvantage is that subjective methods are not quantitative and so the decision can be more likely to attract criticism (Cook et al 2002).

*Quantitative methods*

Quantitative trade-off methods involve generating an objective function that incorporates the selection criteria taking into account their relative importance and the effectiveness of the options against the criteria. Quantitative methods have the advantage that they are perceived to provide a stronger justification to the decision and that the reasoning is explicit. The disadvantages are that forming the weighting functions is difficult and in itself subjective. The decision space is more closed so that "correct" but naïve decisions can be made (Cook et al 2002). There are a number of quantitative decision analysis methods that can be used to support the design trade-off process.

### 3.11.2   Multi-attribute value analysis

"Multi-attribute value analysis is a quantitative method for aggregating a stakeholder's preferences over conflicting objectives to find the alternative with the highest value when all objectives are considered" (Buede 2000). There are a number of steps to the multi-attribute value analysis (MVA) process (Cook et al 2002):

- Define the assessment criteria.

- Define value scales for each criterion.

- Establish the relative value of each criterion.

- Calculate the objective function for each option.

*Defining the assessment criteria*

The assessment criteria should be defined directly from the requirements.

*Defining value scales for each criterion*

An objective (most desirable) value scale and threshold (minimum acceptable) value scale is derived for each criterion. A value function can be used to define the relative value of performance between the threshold and the objective values.

*Establishing the relative value of each criterion*

The weights, $w_i$ must be determined so that the value function over the vector, $v(x)$ of n criteria can be written as a weighted additive function of value functions of each individual criterion. The weights are often normalised to sum to 1 and the value functions normalised to range from 0 to 1.

$$v(x) = \sum_{i=1}^{n} w_i v_i(x_i)$$

*Calculate the objective functions, v(x)*

The objective function for each option is calculated and the results evaluated. The preferred option is normally the one with the highest value or best 'value for money' if cost data is available at that point in the analysis and is taken into account.

### 3.11.3 Deriving value functions

*Value curves*

Value curves are functions that span from the minimum acceptable value to the most desired value. A potential design solution will score dependent upon its performance against the value function. There are families of value curves available, but often stakeholders are able to draw suitable curves based upon their experience (Cook et al 2002).

*Direct techniques*

Direct techniques involve allocating points among the objectives. Stakeholders rank the objectives in order of importance and then various mathematical transformations can be used that translate rank to weight (Cook et al 2002).

*Indirect techniques*

There are a number of methods that can support MVA. These approaches have similar aims but a different mathematical basis. Examples are:

- Quality Function Deployment (QFD).

- Saaty's Analytical Hierarchy Process (AHP).

### 3.11.4  Quality Function Deployment

*Introduction*

Yoji Akao invented "Hinshitsu Kino Tenkai" or Quality Function Deployment (QFD) in Japan in the late 1960s, where it was used to support the product design process for large ships. Practitioners further developed QFD to support service development and the planning process. Today QFD can be used to support any activity where a team systematically prioritises responses to a given set of objectives. The objectives can be referred to as "whats," and the responses are referred to as the "hows." QFD is then used to evaluate "How" a team can best achieve the "Whats." QFD has been successfully implemented by many large organisations including: Xerox, the Ford Motor Company, Procter and Gamble and 3M (Cohen 1995).

QFD has application to systems engineering by supporting the functional decomposition process typically used for flowing customer requirements through to design. It can be used to examine the relative effectiveness of solutions against the user requirement through a systematic and auditable process. QFD can offer many other benefits that include improved communication and customer focus within an organisation.

*Method*

The method is generally applied through the use of a matrix or 'House Of Quality' (HOQ) as illustrated in Figure 3-8. Starting from the left side of the diagram the customer needs or "whats" are identified with their priorities. At the top the technical design characteristics (the "hows") are identified. The "roof" of the HOQ is used to identify relationships between the technical design characteristics, both positive and negative. The relationship matrix is used to score how well the technical design characteristics satisfy the customer needs. The bottom part of the HOQ is used to compare the "value" of the technical design characteristics. The right side is used for planning purposes, but is not used for analysis here. A series of HOQs can be used in a "street" to provide decomposition of requirements, for example: from customer requirements, to design requirements, to production requirements through to manufacturing requirements, as shown in Figure 3-9.
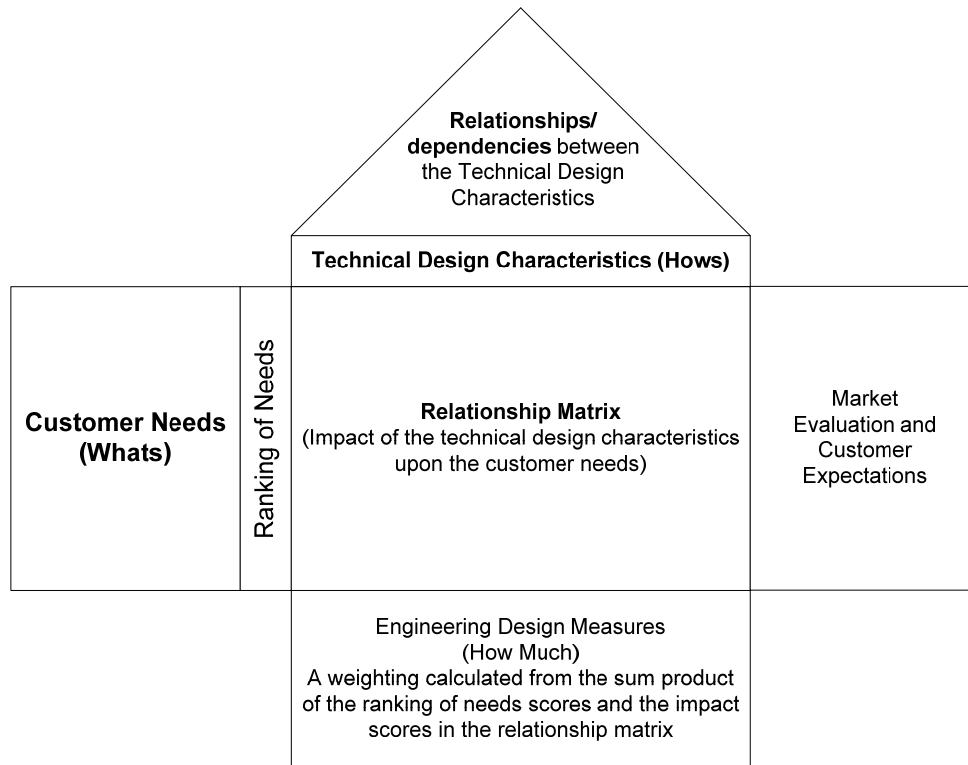
**Figure 3-8 - House of Quality modified from Cohen (2005).**
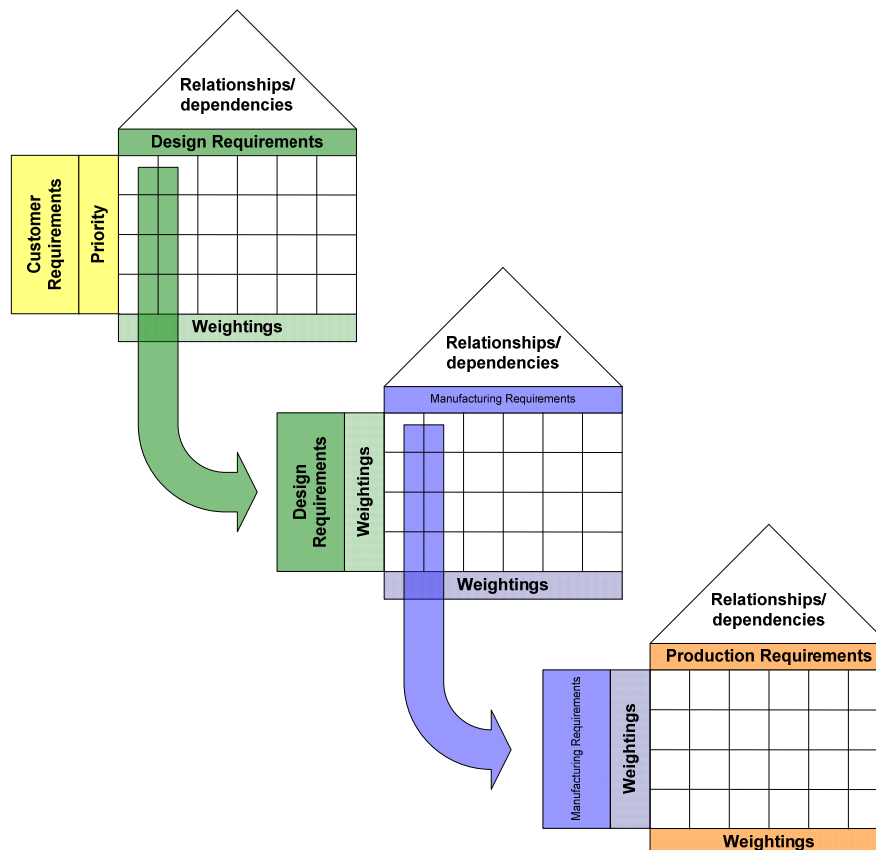


**Figure 3-9 - Functional decomposition using a "street" of HOQs.**

*Application*

The potential application of QFD to survivability was identified by Wells in 2002 through the development of the 'Partridge' model. This concept was then further developed within the helicopter domain by Wells, Haige, Goldsmith, McGuire and the author.

NASA used QFD successfully to prioritise which ozone depleting chemicals they should phase out of use in order to comply with federal legislation. Interestingly, they referred to the method as being semi-quantitative. They used a weighting system for the relationships as follows: weak (1), medium (3) and strong (9). The roof was scored using both positive and negative values as follows: strong negative (-9), negative (-3), positive (3) and strong positive (9) (Cruit et al 1993).

QFD has also been used by Kim (2001) to model the deployment of 'strategy to task' for the Korean military. Military missions to tasks were cascaded down to major procurement project options and then the effectiveness of these capabilities was plotted against cost to identify an optimum set of projects. Kim (2001) used both a 1, 2, 3 and a 1, 3, 9 scoring system and checked the sensitivities between the two.

Smith (2004) has demonstrated an application of QFD suitable for downselecting armoured fighting vehicle survivability options for a more detailed analysis. Smith (2004) found the following advantages with the method:

- Useful for identifying 'good' technologies.

- Good at suggesting suites of technologies.

- Flexible.

- Transparent, i.e. not a 'black box'.

### 3.11.5  *Analytical Hierarchy Process*

*Introduction*

The Analytical Hierarchy Process (AHP) was developed by Thomas Saaty in the early 1970s (Saaty 2001). The purpose of the method is to measure quantities by eliciting subjective judgements of relative magnitude. The process structures the following elements into a hierarchy: criteria, stakeholders, outcomes; and elicits judgements to develop priorities. These judgements can then be used to predict possible outcomes. The result of this can be used to rank alternatives, carry out a balance of investment appraisal and allocate resources. Inconsistency of judgement is also captured and this is used to assess how well the user understands the relationships among factors. The AHP has been applied and developed by individuals, corporations and governments since the early 1970s. Examples include: energy

rationing, the conflict in Northern Ireland, terrorism, benchmarking and resource allocation at IBM, NASA applications and the stock market (Saaty 2001).

*Method*

The AHP consists of three components: hierarchical decomposition, pair-wise comparisons and synthesis of overall weightings. The purpose of hierarchical decomposition is to assist system analysis by breaking the system down into components. Decomposition works (Grotte et al 1990) when:

- Better knowledge exists about the components and their relationships than that of the system as a whole.

- There is a method for combining the knowledge of the parts that preserves this superiority.

In the AHP, decomposition takes the form of a hierarchy. The top node represents the overall goal. The next level down in the hierarchy represents the attributes contributing to the goal. Lower levels further break out the sub attributes. The alternatives within the decision space are nested under the lowest level attributes.

The pair-wise comparison component involves collecting pair-wise comparisons from the attributes descended from a common node one level above in the hierarchy. The judgements relate to the priority of the attributes. The meaning of 'priority' depends upon the question being asked, and could be interpreted as, for example: importance, priority, weight or likelihood of occurrence. The numerical score of any attribute X as it compares with Y must be the reciprocal of how Y compares with X. For example, if one attribute is three times as important as another, then the second attribute must be scored as being a third as important as the first.

The final component of the method involves scoring the alternative's performance score against the lowest attribute. The lowest attribute weighting is then multiplied by the performance score for each alternative. The overall priority for each alternative is calculated by summing the priorities for each criterion from which it has been assessed.

Saaty uses an eigenvector prioritisation method to make the comparative judgements. A positive reciprocal matrix is set up. When the judgements in a positive reciprocal matrix are consistent, then all but one of the corresponding eigenvalues will equal zero. The eigenvector of the nonzero eigenvalue will be equal to the priority vector of the judgement data. This method also copes with inconsistent judgements (Grotte et al 1990).

Saaty also developed two consistency measures: the consistency index (CI) and the consistency ratio (CR). The CI is a function of the maximum eigenvalue of the judgement

matrix and is at its minimum of zero when the matrix is consistent. The CR is the ratio of the CI of the judgement matrix and the average of the CIs of randomly generated matrices of the same size. Saaty states that a CR should be no larger than 0.10 (Grotte et al 1990).

*Application*

Some research has reported that AHP is a credible method based upon the fact that it is well supported by modern tools (Knight 2001). This is not a robust enough basis in itself, but does provide some indication of its perceived value. Forman and Selly (2002) provide a positive review of the AHP, stating that it is simpler, more realistic and more powerful than other decision theories.

AHP has had considerable application within US defence analysis. Grotte et al (1990) raise questions as to the validity of the AHP methodology, with implications ranging from ignoring all but the ordinal results to disregarding the method completely. The Australian Defence Science and Technology Organisation (DSTO) has published a comprehensive AHP review and concluded that: "Overall, even without the ordinal scale problem, there are enough questionable features in the AHP to severely doubt the validity of the output priorities. With this in mind, the method should be applied with great caution" (Warren 2004). It should be noted that other multi-criteria decision analysis techniques suffer from similar problems. Buede (2000) also has reservations about the AHP method.

### 3.11.6   *Probabilistic methods*

Probabilistic methods of systems engineering modelling include fault-tree and event-tree analysis. These techniques are often used by process industries (including nuclear, oil and gas and chemical) and their insurers to quantify risk. Research into the application of these techniques to survivability was suggested and conducted by the author and also researched by Goldsmith and Sun (2005) at the Systems Engineering and Innovation Centre (SEIC), Loughborough University. This approach was found to provide a system's view that generated 'means of improvement' across many lines of development and also provided links between survivability failure events and top level consequences.

A methodology for combat-induced failure modes and effects analysis (CIFMEA) was derived by the US in 1974. This method focused on aircraft vulnerability and examined the consequence of the aircraft being hit by using "fault-trees." The research concluded that the collection and recording of such data were an essential input to vulnerability and survivability analysis (Tauras 1974).

### 3.11.7  *System dynamics*

The system dynamics discipline was founded by Forrester (1961) who defined the subject as: "…the investigation of the information-feedback of systems and the use of models for the design of improved organizational form and guiding policy."

*Influence diagrams*

Influence diagrams are used in the analysis of system dynamics. They are used to describe and understand systems and also as a starting point to build quantitative models (Coyle 1996).

Example influence diagrams are included in Coyle (1996) and Waring (1996). Standard diagrammatic conventions and guidelines for drawing influence diagrams are comprehensively defined by Coyle (1996). Some of the standard conventions are provided below:

- Solid lines define physical flows.

- Dashed lines define information or control action flows.

- A large 'D' represents a significant time delay.

- A box identifies an external driving force.

- A + sign indicates as the variable at the tail of the arrow changes, the variable at the head of the arrow changes in the same direction.

- A – sign has the opposite effect.

*Causal loop diagrams*

Causal loop models can be used to illustrate non-linear, feedback cause and effect views. They are actually broad level influence diagrams that do not show the finer details that can be illustrated in an influence diagram (Coyle 1996). Causal loop models are good at illustrating the behaviour of non-linear dynamic systems and may help in understanding issues effecting survivability. At a high level this approach could be used to understand interactions across all the lines of development.

### 3.11.8  $N^2$ *charts*

An $N^2$ chart is a square matrix that captures system functions and the relationships or interfaces between them. The leading diagonal of the matrix is populated with the system functions. Outputs for a function are shown in the row relating to that function and inputs are entered into the relevant column. An $N^2$ chart can be surrounded by another layer to incorporate other systems that interact with the system of interest (INCOSE 2010).

The N$^2$ chart representation is similar to the roof of the house of quality in QFD and may be useful for modelling the system of interest surrounded by external systems. The N$^2$ chart concept is illustrated in Figure 3-10.

System functions placed on leading diagonal

E.g. This box represents an output from system C that provides an input into system A

Inputs

Outputs
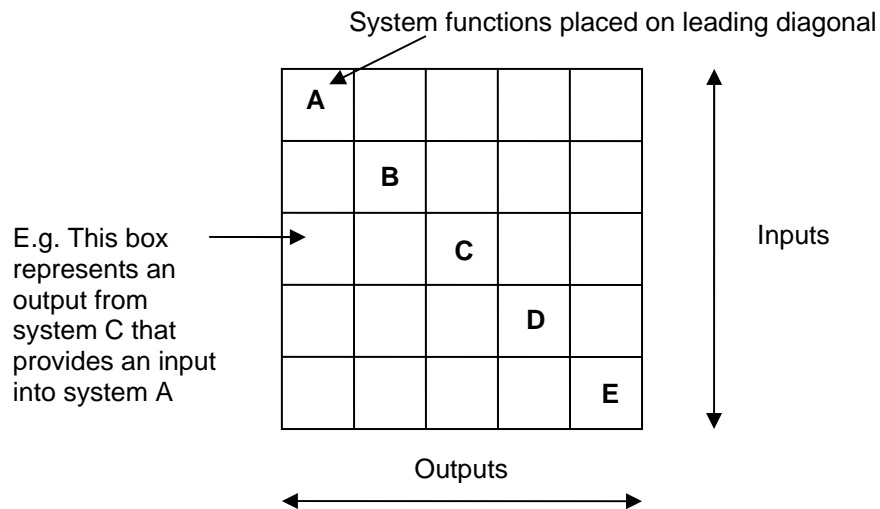
**Figure 3-10 - N$^2$ Chart**

### 3.11.9  *Soft Systems Methodology*

Soft systems thinking is used to tackle complex problems (often involving humans) where there are many issues to consider, many of which may be unclear. Soft systems problem situations might also be considered to be a 'mess'. Soft systems methods provide a vague way of structuring the problem and issues (Waring 1996).

Checkland (1981) developed a seven-step approach called the Soft Systems Methodology (SSM) that divides the situation up into the 'real world' and 'the world of abstract systemic thinking.' The method involves outlining the problem and then developing a 'rich picture' of the problem situation. Notional functional system components are then developed and then conceptual models. The differences between the actual situation and the 'notional' representation are compared and feasible desired changes are identified. These changes are discussed with responsible staff who then take actions to improve the original problem (Waring 1996).

## 3.12  Defence related systems engineering challenges

### 3.12.1  *Example lessons learnt*

A number of lessons have been learnt from previous and current helicopter programmes. Access to data from US contractors were a problem on both the UK Apache and for the Chinook Mk3. These problems were to some extent contractual, in that insufficient provision for required data had been made in the original contracts. The timescales required by urgent

operational requirements (UORs) are challenging for the systems engineering process, particularly testing and evaluation and training.

*UK Apache*

The UK Apache programme experienced a number of systems engineering challenges because of the complexity of HIDAS, commercial sensitivities and access to data from the US (National Audit Office 2002). This resulted in the helicopter being delayed into service.

*Chinook Mk3*

The MOD ordered eight Chinook Mk3 helicopters in 1995. Although Boeing had met its contractual obligations, unfortunately the avionics software could not be shown to meet UK standards required for an airworthiness certificate. The MOD did not specify access to the Mk3 cockpit software source code in the original contract. When requested, Boeing and its sub-contractors would not provide the source code in order to protect their intellectual property rights. The code could well have taken two years to analyse and may not have been comprehensible in any case. The reversion programme to revert the aircraft to Mk2/2a standard is currently ongoing and intends to get the platform into service during 2010, around eight years late and at a total cost in excess of £422 million (National Audit Office 2008).

*DAS urgent operational requirements*

UORs to provide the required level of DAS capability were implemented for Operation TELIC. "The shortfall in defensive aids suites further limited platform flexibility and dictated the size of the helicopter force that could be sent to the Gulf in 2003. For example, such was the haste to deploy refitted Lynx Mk7s on Operation TELIC, that two aircraft flew direct from modification at the Defence Aviation Repair Agency, Fleetlands, to embarking ships. 3 Regiment, Army Air Corps were, therefore, unable to familiarise themselves with the new defensive aids suite until they arrived in the Gulf, not having had the opportunity to practise with suitably equipped helicopters during their previous year's training. Moreover, the need for trials (and for sufficient time to train) on new equipment does not fit naturally within the timescales dictated by Urgent Operational Requirements" (National Audit Office 2004). This example highlights the pressures on getting the right capability into theatre and the impact on the other DLODs.

### *3.12.2 Open systems*

*Introduction*

Open systems and open system architectures have been identified by MOD (2006) as a 'priority technology' within the Defence Technology Strategy. Open systems architectures will enable the UK to be the system design authority, supporting the flexible development and upgrade of survivability systems through life to deal with changing threats (Ministry of Defence 2006).

The term 'open systems' emerged during the 1970s mainly to describe computer systems based upon the UNIX® operating system. UNIX® systems were unusual at that time because they used standard programming interfaces and peripherals encouraging the development of UNIX® hardware and software by third parties. UNIX® is in widespread use worldwide and has developed an open set of standards managed by 'The Open Group' (The Open Group 2003).

*Definitions*

Kiczuk and Roark (1995) define an open system architecture to be "one whose interfaces are defined with open system standards." Open systems standards are: "clearly and completely defined interfaces, which support interoperability, portability and scalability." (Kiczuk and Roark 1995). The Open Systems Joint Task Force (OSJTF) has the following definition: "A system that employs modular design, uses widely supported and consensus based standards for its key interfaces, and has been subjected to successful validation and verification tests to ensure the openness of its key interfaces" (Open Systems Joint Task Force 2007).

Open systems are at their best 'plug and play.' Microsoft® (2010) provide the following definition: "plug and play provides automatic configuration of PC hardware and devices. Each plug and play device must be uniquely identified, state the services it provides and resources it requires, identify the driver that supports it, and allow software to configure it" (Microsoft 2010). In practice, 'plug and play' means that when a hardware device is first plugged into a PC, the PC will locate a software 'driver' already available on the machine or download a suitable 'driver' from the internet. This 'driver' provides the proprietary software interface. Even in a commercial off the shelf (COTS) mass market, 'plug and play' is not totally 'open' at all levels.

*Advantages*

Open systems architectures and standards have the advantage of increasing affordability through life. Military programmes are no longer the major producer of technology, so leveraging from commercial markets by using commercial off the shelf (COTS) where

appropriate can reduce costs significantly. COTS cannot solve all military avionics needs; hence, the need for military off the shelf (MOTS) in some applications. Open systems architectures need to allow flexibility to incorporate new technology, especially as technology becomes obsolescent at a much faster pace than interfaces and software languages. Successful implementation of open systems leads to the following benefits (Kiczuk and Roark 1995):

- Increased affordability.

- Interoperability.

- Portability.

- Rapid integration of new technology.

- Improved incremental acquisition.

- Reduced integration risk.

- Reduced development cycle time.

- Flexible reconfiguration.

- Greater choice of suppliers in the marketplace leading to greater competition.

- Greater ability to gain leverage from the COTS market.

- Improved collaborative working by industry, universities and MOD.

- Increased commonality and reuse of components (OSJTF 2003).

*Disadvantages*

The main disadvantage regarding 'open systems' is that the concept is not well defined, resulting in misunderstanding and confusion. Within the context of integrated survivability, Kiczuk and Roark's (1995) definition above would require that interfaces are defined and available to those industry partners that need them.

*Characteristics*

From reviewing the published literature, open systems and open systems architectures are characterised by:

- Modularity.

- Interoperability.

- Open software standards.

- Standard interfaces.

- Standard agreed architectures.

- Readily availability interface specifications and standards.

- Standards with widespread stakeholder endorsement.

*Proprietary systems*

Consistent with the open systems philosophy, the Defence Technology Strategy (Ministry of Defence 2006) discourages the use of proprietary networks and interfaces within equipments. Historically, bespoke proprietary software has also been a problem. As early as 1975, the US DoD ran a competition to create a new standardised programming language to reduce the burden of supporting the existing 2000 programming languages used for their mission-critical systems (Moir and Seabridge 2006). There have also been further initiatives in the US including the OSJTF set up in 1994 and the "Open Systems Development Initiative" (OSDI). The OSJTF has developed open systems policy guidance that has been incorporated within the US acquisition policy. The OSJTF guidance states that a modular open system approach (MOSA) should be adopted wherever possible (OSJTF 2003). Work by the OSDI found that standardisation was of greater benefit than optimisation of interfaces (Paul 1998).

*Organisational behaviour*

Turning open systems into a reality requires a number of organisational behaviours:

- Industry communicating and agreeing standards.

- MOD leading, developing and owning system architectures (Ministry of Defence 2008b).

- An industry and MOD endorsed catalogue of standards.

- Successful validation and verification tests to ensure the openness of key system interfaces (Open Systems Joint Task Force 2007).

### 3.12.3   *Sovereignty*

The Defence Industrial Strategy (DIS) sets out the importance of 'appropriate UK sovereignty' to ensure operational independence, and hence, national security. Sovereignty of key capabilities can also be used to provide strategic influence in military, political or industrial terms. Furthermore, sovereignty reduces the risk of dependence on an overseas monopoly and makes the UK an attractive partner for collaboration (Ministry of Defence 2005a).

Sovereignty means UK access to, not necessarily UK owned, so a company could be owned or established by a foreign owned company. Examples of UK based companies providing 'sovereign capabilities' include Agusta Westland and SELEX Galileo, which are part of the Italian Finnmecanica group. Similarly Thales UK is a French owned company. Sovereignty provides assurance of security of supply and access to key onshore survivability capabilities such as (Ministry of Defence 2005a and Ministry of Defence 2006):

- Systems engineering expertise to integrate new technology, particularly to solve urgent operational requirements (UORs) in a timely manner.

- UK based test and evaluation (T&E) facilities and the ability to direct, understand, analyse and verify T&E results.

- Integration of DAS.

- UK electronic warfare capability.

- Access to open architectures and interfaces to maintain UK control and to promote technology insertion and integration.

- Deep understanding of threats, (i.e. the starting point for the survivability problem).

- Cost effectiveness assessment.

### 3.12.4  *Common Defensive Aids Suite programme*

The Common Defensive Aids Suite (CDAS) strategy sets out a coherent, cross-platform approach to acquisition of aircraft survivability. The strategy addresses the requirement for sovereign DAS open architectures to enable easier upgrade to address changes in the threat or role (SELEX Galileo 2010).

The CDAS Technology Demonstrator Programme (TDP) led by SELEX Galileo, will develop and demonstrate a flexible open architecture with standardised interfaces and a common approach to programming. This architecture will support existing in-service equipment, as well as new capabilities, including missile warning systems, hostile fire indicators and DIRCM (SELEX Galileo 2010). The open architecture approach should exploit some of the advantages discussed in Sections 3.12.2 and 3.12.3.

## 3.13  Discussion

### 3.13.1  *Systems engineering is important*

Successful systems engineering is seen to be hugely important for defence (Ministry of Defence 2005a), because military projects are generally large and complex. There are many examples of projects that have gone over time and over budget owing to systems integration

issues. MOD has many of the right systems engineering processes in place with Smart Acquisition; however, there have been problems with the application of those processes on some projects. It is also important to recognise that successful systems engineering requires a team of people with a breadth of skills and experience.

### 3.13.2 Systems engineering is a large subject

A considerable amount of background information exists on 'systems engineering,' ranging from the theoretical abstract to more specific application. There are also many definitions of the discipline and approaches to its application owing to the breadth of the subject and because the discipline is still evolving. Consequently, 'systems engineering' means different things to different people. It is useful to have an appreciation of the wider definitions, but the work must focus on the specific defence definition going forward:

"Systems engineering is the general term for the methods used to provide optimally engineered, operationally effective, complex systems. Systems engineering balances capability, risk, complexity, cost and technological choices to provide a solution that best meets the customer's needs" (Ministry of Defence 2005a). Successfully selecting, understanding and applying relevant theory to the 'integrated helicopter survivability' problem is where the main challenge of this work lies.

### 3.13.3 Critical systems engineering aspects

The systems engineering review has identified many theoretical areas that are relevant to the project. Critical aspects and their contributions to dealing with the problems set out at the end of Chapter 2 are discussed below.

#### System boundary

Consideration of the problem at the system level helps to draw the system boundary. The integrated survivability problem can be considered at any of the three system levels depending upon the purpose of the analysis. Analysis at level three (system of systems) is useful for a high-level strategic view. Level two (system) is more focussed towards a specific platform system solution. The focus for this project is primarily at the platform-level (level two), although consideration will also need to be made to the external systems that support the system of interest. Level one sub-systems will be component parts of the platform-level system; however, they will not in themselves be analysed in detail. A system influence diagram will be a useful tool to show the system boundaries.

#### Scope

The review of systems engineering has helped to scope the project elements within the systems engineering process. The project primarily focuses on the concept and assessment

regions of the CADMID systems engineering lifecycle. The work should support the requirements definition process and early concept design phases. The wider survivability assessment process should support the whole system lifecycle. The project scope is illustrated within the systems engineering framework in Figure 3-11. The level of technological uncertainty (risk) depends broadly on the type of system. For example, integration of a new DAS system comprising mainly existing technologies on to a platform might be classed as 'high-technology' (level c). Development of a new DAS architecture (for example the CDAS TDP) before exploitation on to a platform might be considered as 'super-high technology' (level d). Hence, there is a TDP to de-risk the CDAS architecture technology and develop it to TRL 7. The CDAS architecture would then fall within the level 'high-technology' (level c) when exploited on a platform in the future. The system engineering processes that the project seeks to influence are highlighted in Figure 3-12.
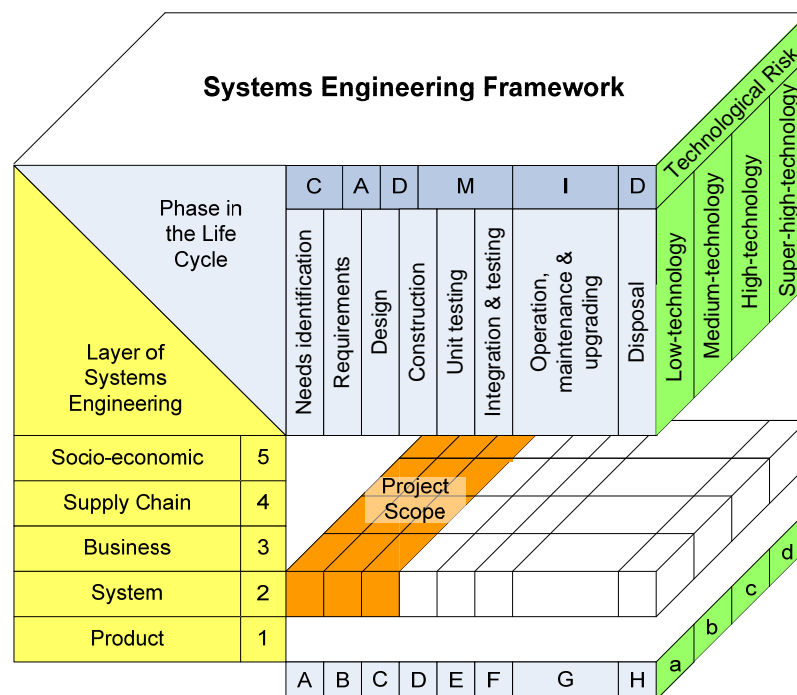


**Figure 3-11 - Primary project scope (highlighted in orange) set within the systems engineering framework, (adapted from Kasser 2007).**

*Outputs*

The work needs to define an integrated survivability assessment process, system influence diagrams and an integrated survivability model to support survivability measurement, assessment and trade-offs. The survivability assessment process will need to generate the necessary input data for the survivability model.

*Properties and interactions*

Survivability is one emergent quality of a system. Availability, maintainability and mission effectiveness are other important emergent qualities. Good systems engineering requires consideration of these qualities across all the DLODs: equipment, training, personnel, information, concepts and doctrine, organisation, infrastructure and logistics. At the platform level, survivability must be considered alongside the other important system qualities, so that sensible trade-off decisions can be made.

The theory identifies the importance of interactions. If one part of the system is changed, it will affect the other parts. For example, fitting survivability equipment increases mission capability and protects lives, but adds weight which reduces mission payload / range. The project, therefore, needs to deal with these interactions. Influence diagrams and the 'roof' of the 'house of quality' in QFD are possible tools to investigate this impact on a system.

*Systems engineering principles*

The RAEng integrated system design principles encapsulate much of the theory and are consistent with Hitchins' systems engineering philosophy (Hitchins 2005). The first principle of defining requirements, conducting trade-off analysis and considering the constraints is the core problem that the project is addressing from a survivability perspective. The second principle of holistic thinking will be addressed through the use of influence diagrams and consideration of the system lifecycle and DLODs. The third principle to follow a systematic procedure is addressed through use of the Vee-diagram (Figure 3-5), the application of the SEPP to the project (Figure 3-11) and through development of a survivability assessment process. The fourth principle of being creative involves defining the capability. The required capability is to be able to conduct the mission within a hostile environment. The project needs to find a process for doing this. Influence diagrams again provide a possible method to develop and illustrate concepts. The fifth principle of taking account of the people will be covered by consideration of the DLODs. The sixth principle of managing the project could be assisted by the communication benefits when the process and methods to be developed by this project are used. The project output also aims to help with the intelligent customer status, i.e. knowing what is required and how to test it.

*Systems engineering Vee-diagram*

The systems engineering Vee-diagram contains the same basic elements that make up the earlier waterfall and spiral models. The spiral model clearly depicts the concept of taking smaller iterative development steps or 'spirals' to reduce risk. A series of Vee-diagrams could be used to represent the approach illustrated by the spiral model. The Vee-diagram model provides guidance and should be used creatively and flexibly to suit the project. The

Vee-diagram clearly depicts the systems engineering process and has been widely adopted by the systems engineering community. For these reasons the project proposes to use this model going forward.

*System maturity*

The systems engineering review has identified SRL and TRL definitions and how they relate to the systems engineering process. It must be recognised that at early stages within the system lifecycle, system concepts will be immature and associated data may have high levels of uncertainty. Any system trade-off process will need to take this into consideration. Any systems engineering process also needs to take into account that as a system matures associated performance data will improve in confidence and have reduced levels of uncertainty. These considerations need to be incorporated within the requirements decomposition and T&E processes outlined within the systems engineering Vee-diagram.

*Requirements definition*

The project should provide a process to improve survivability requirements definition and a tool to help inform trade-offs at the early concept phase.

*Lessons learnt*

The systems engineering process needs to be able to cope with UORs, or UORs need to be better 'tuned' from a systems engineering perspective. The UK Apache and Chinook Mk3 programmes highlight that management of the system (i.e. the contract) is as important as the technical aspects of systems engineering. Access to required information to enable the T&E activities is crucial and must be built into the contract.

*Open systems and sovereignty*

Open systems and UK sovereignty of core system components, such as architectures, will enable the UK to be system design authority and are important to facilitate upgrade of survivability systems through the life of a platform to deal with changing threats. However the 'open systems' concept is not well defined, hence the CDAS TDP will be developing this definition for air-platform survivability.

The flexibility to upgrade technology quickly to defeat future threats is the key requirement. This is because all helicopter platforms typically have long service lives of around thirty years. Open systems and open system architectures with sovereignty on key elements, therefore, form part of the solution space.

### 3.13.4    *Systems engineering methodologies selected for further investigation*

A number of the systems engineering methods identified in this chapter have been selected to analyse the integrated helicopter survivability problem. The selection rationale has been summarised in Table 3-2. The selected methods will be developed further in Chapter 4.

**Table 3-2 – Selection rationale for systems engineering methods.**

| Method class | Rationale | Selected? |
|---|---|---|
| MVA – values curves | The thinking is not mature enough at this stage to develop suitable value functions. | No |
| MVA - direct | QFD provides a structured approach that is consistent with this concept. | No |
| MVA – indirect, QFD | Successful widespread use, semi-quantitative. | Yes |
| MVA – indirect, AHP | Successful widespread use, semi-quantitative. | Yes |
| Probabilistic | Has the potential to offer a quantitative approach that is consistent with the survivability measure of effectiveness, probability of survival. | Yes |
| System dynamics – influence diagram | Good at handling the 'wider' and 'softer' issues. | Yes |
| Causal loop | Concept can be incorporated within an influence diagram. | Not specifically |
| $N^2$ chart | Concept can be covered within the QFD 'roof'. | Not specifically |

Influence diagrams have been selected to develop high-level system of system 'holistic' (level three) models to be consistent with the systems theory and systems design principles of 'breadth before depth'. Influence diagrams will also be effective at describing and understanding systems and capturing interactions.

Three methods will be developed to create platform system (level two) models with the aim of supporting the survivability assessment process:

- Quality Function Deployment (QFD).

- The Analytical Hierarchy Process (AHP).

- Probabilistic fault-tree method.

These methods have been chosen because they offer: the ability to assess a wide range of criteria, a quantitative approach, the ability to include 'hard' and 'soft' data and have some pedigree in terms of their previous applications. Some of the other systems techniques can also be considered within these core methods, for example soft systems approaches can be considered when developing hierarchies and structures and elements of the $N^2$ chart approach can be incorporated within the QFD 'roof'. QFD and AHP are actually 'semi-quantitative' methods because they use derived numeric input data rather than 'hard,' scientific data directly.

The generic systems engineering process identified by Hitchins (2005) has been adapted in Figure 3-12 to show how the key elements developed by the project will contribute to the systems engineering process.
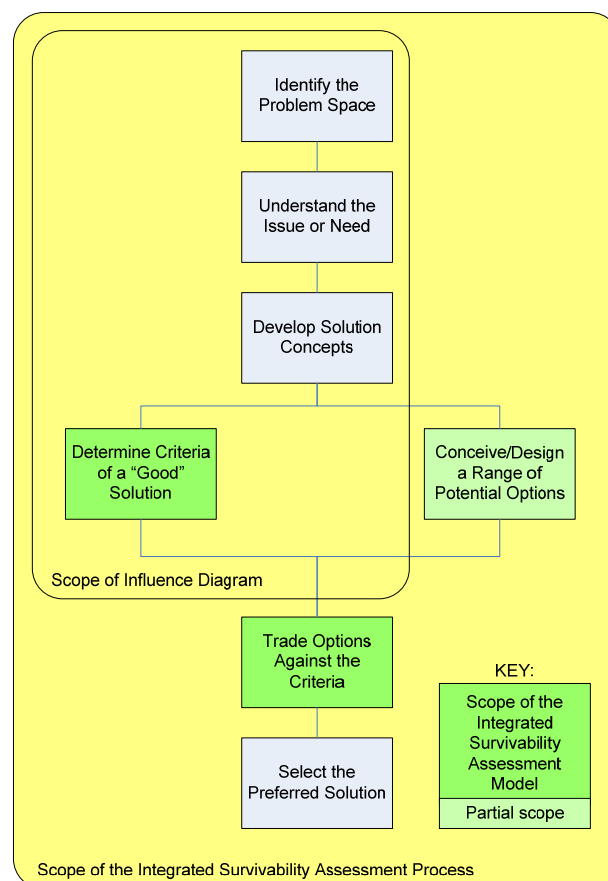


**Figure 3-12 - SEPP with the scope of the project outputs identified.**

A specific integrated survivability tool is required to support the following SEPP processes: developing the criteria for a good solution and trading options against the criteria to support the selection of the preferred design. The integrated survivability process will include the steps to understand the problem and so derive suitable input data to feed the integrated

survivability tool. The supporting tool-set will include a wide variety of existing models, simulations and other tools, each optimised for their particular role in the process.

## 3.14 Summary

This chapter has conducted a literature search to identify systems engineering aspects and methods that are relevant to the problem set out in Chapter 2. These areas have then been used to develop a research approach that has been summarised below. This research approach will be implemented and the resulting research outputs presented in Chapter 4.

### 3.14.1 Critical systems engineering aspects

The following systems engineering aspects and lessons have been identified:

- A 'holistic' high level view should first be taken that considers the 'ilities' and DLODs early so that informed trade-off decisions can be made and a complete system view can be formed.

- A systematic procedure will need to be followed that requires the development of a survivability assessment process that can support the acquisition process and widely endorsed systems engineering Vee-diagram concept.

- Experience has shown that management of the contract is an important activity that could be better supported by systems engineering methods that identify DLOD interactions early, for example: T&E, tactics and training.

- System flexibility is important to enable platforms to be upgraded quickly to deal with future scenarios, roles and threats that may not have been anticipated when a helicopter platform was originally procured.

- The three dimensional systems engineering framework is a useful concept to frame the systems engineering domain and to understand where this research fits within it.

### 3.14.2 Methods

The following methods (Table 3-3) were selected after an initial assessment of their potential strengths in dealing with the problem areas set out in Chapter 2 and their potential to address the systems engineering aspects identified in this chapter.

**Table 3-3 – Summary method assessment**

| Method | Holistic approach | Interactions | Quantitative | Uncertainty | Requirement Definition |
|---|---|---|---|---|---|
| Buede's concept diagram | √√ | √√ | | | √ |
| Influence diagram | √√√ | √√√ | √[23] | | √ |
| QFD | √√ | √√ | √√ | √ | √√ |
| AHP | √ | √ | √√ | √ | √ |
| Probabilistic | √ | √ | √√√ | √√ | √ |

Potential utility:

√√√ = High

√√  = Medium

√   = Low

### 3.14.3 Research approach

The output from this chapter has enabled the following research approach to be developed:

- Develop a survivability assessment process that supports the military helicopter life cycle and situates the requirement for integrated survivability assessment methods.

- Develop methods to identify holistic issues including DLODs and interactions by experimenting with Buede's concept diagram, influence diagrams and QFD.

- Develop methods to provide a quantitative assessment of survivability using QFD, AHP and probabilistic methods.

- Develop methods to provide suitable input data to integrated survivability models, for example, the rate of encountering threats.

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[23] Influence diagrams can be developed into quantitative models, however for this application they are defined at a higher level to capture the wider issues including DLODs.

- Discuss how the methods could be used at the different stages of a military helicopter's lifecycle.

- Discuss any wider issues arising from the results.

# 4 INTEGRATED SURVIVABILITY MODELLING

This chapter implements the research approach developed at the end of Chapter 3. The resulting research outputs are presented and discussed. It firstly considers survivability policy and defines a survivability assessment process that links the requirement for integrated survivability modelling into the acquisition process. The chapter then applies the methods selected from the systems engineering chapter (Chapter 3) to the integrated helicopter survivability problem set out in Chapter 2.

Initially, high-level system-of-system 'holistic' (level 3) models, including context and influence diagrams are developed to identify DLOD interactions. The chapter then develops platform-level system (level 2) models with the aim of providing a quantitative assessment method. In Chapter 3, three systems engineering methods were selected to be evaluated for this application: Quality Function Deployment (QFD); the Analytical Hierarchy Process (AHP) and the probabilistic fault-tree method. The performance of these platform-level system models has been evaluated. The probabilistic fault-tree method was applied to a helicopter acquisition programme as a case study and lessons learnt have been identified.

Methods to provide derivation of input data have been developed to feed the platform-level system models, both to evaluate the probability of encountering threats and the performance of the survivability attributes. A demonstration showing how survivability attribute input data can be derived from a lower-level physics-based model to provide input to a higher-level systems model has also been provided. The survivability modelling environment has also been defined to help to identify lower-level models that provide input data to integrated system level survivability models. The implications of the work to the acquisition of integrated helicopter survivability have been discussed along with how the methods could be used at the different stages of a military helicopter's lifecycle.

## 4.1 Survivability policy and processes

The purpose of this section is to understand the strategic requirements for the survivability assessment process and supporting methods to support the helicopter acquisition lifecycle. Survivability acquisition policy and processes are introduced, including the mandated US survivability process and the process that the author has helped to develop for UK helicopter platforms. These survivability processes are required to implement policy laid down by US government directives and UK high-level strategic papers.

### 4.1.1 Policy

The US procurement directives (DoD5000) state that a "program manager should establish and maintain a survivability program throughout the system life cycle to attain overall program objectives" (DoD 2005). The guidelines also state that mission-critical systems, including crew, should be survivable to the predicted threat levels in their projected operating environment as detailed in the System Threat Assessment Report (STAR). Design and testing is used to ensure that the platform and crew can withstand the man-made hostile environment "without the crew suffering acute chronic illness, disability, or death" (DoD 2005). The US also has a statutory requirement to assess personnel survivability for covered systems occupied by their personnel (10 USC 2366). In addition to the procurement guidelines, the US has a legal mandate for survivability for which the Secretary of State for Defense is responsible:

"The Secretary of Defense shall provide that a covered system may not proceed beyond low-rate initial production until realistic survivability testing of the system is completed…" (Legal Information Institute 2004). The Secretary of Defense also has to provide a report at the conclusion of survivability or lethality testing to the Congressional defence committee. This report must include the testing results and must provide the secretary's overall assessment of the testing.

The UK does not have a specific, mandated legal requirement for survivability testing, although any equipment should be 'fit for purpose'. The Acquisition Management System (AMS) (now Acquisition Operating Framework (AOF)) set out a survivability requirement under the Integrated Test Evaluation and Acceptance (ITEA) process: "Has an acceptable loss rate against current approved threats" (DPA 2004). This raises the contentious question: "what is an acceptable loss rate?" The author recommended that the most pragmatic way forward was to take a risk assessment approach and reduce survivability risks to as low as reasonably practicable (ALARP) (Law and Wells 2006). The author, as part of the Dstl team,

has worked with DTIC (Defence Technology and Innovation Centre)[24] and the Capability Sponsor[25] Air and Littoral Manoeuvre (ALM) to define a survivability policy and process for UK helicopters (Law and Wells 2006).

### 4.1.2 *Helicopter survivability assessment process*

Given that it is now policy is to reduce survivability risk to ALARP, a process was required to measure and test levels of survivability so that ALARP could be demonstrated. This survivability assessment process would provide a standardised risk assessment approach that could be used at appropriate points in the acquisition cycle. This would enable survivability assessments and risk reduction activities to be conducted in a structured, consistent and auditable manner.

In response to this requirement, the survivability assessment process was developed by Law et al. (2006). The process positions modelling and simulation in a consistent way and ensures that the input and output data are prepared in an appropriate and repeatable manner. Some analysis and interpretation may be needed to provide models with the required input data, so it is important to provide an auditable and standardised process for doing this task. Figure 4-1 illustrates the process. The author has developed the survivability assessment process further and linked it into the systems engineering Vee-diagram in Figure 4-2. The author has then developed supporting methods in the subsequent sections within this chapter.
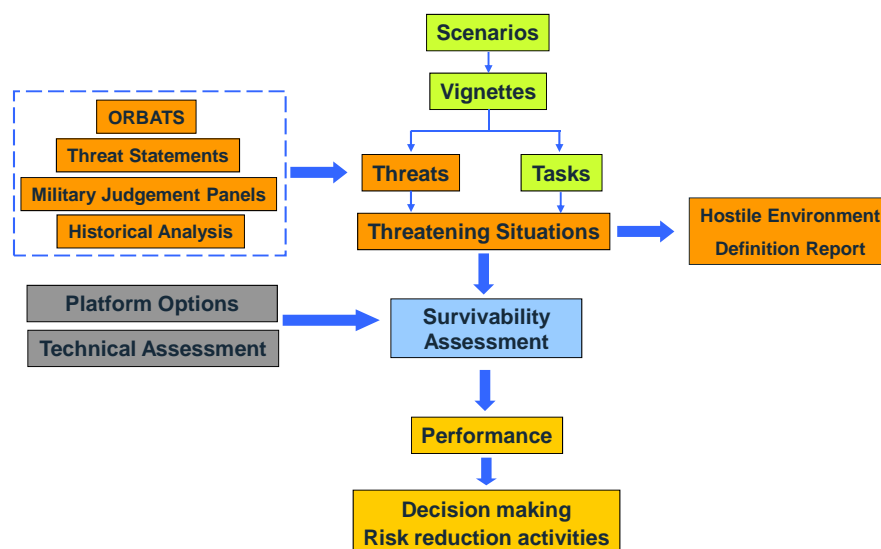


**Figure 4-1 - Survivability assessment process (Law and Wells 2006).**

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[24] Previously known as the Research Acquisition Organisation (RAO) and is now the Programme Office within Dstl.

[25] Previously known as the Equipment Capability Customer (ECC) and previous to that the Directorate of Equipment Capability (DEC).

The green boxes represent the mission definition from broad scenarios through to specific helicopter tasks. The orange boxes represent the threat definition that is derived from written sources such as orders of battle (ORBATS) and threat statements that look into the future. Analysis is also conducted by military judgement panels taking into account all available information, including historical records. The output of this process is a hostile environment definition report that provides the context (or standard testing environment) and a threat weighting input to the survivability assessment (blue box). The grey boxes represent the systems of interest, for example a platform type with different configurations of survivability equipment. The light orange boxes represent the model output in the form of a performance metric that can be used to assist decision making. The process can be found in Appendix D in more detail.

Figure 4-2 illustrates how the survivability assessment process could support the systems engineering process and acquisition lifecycle. The threatening situations define the threat environment that the user needs to operate the platform within, so providing important input to the URD. Early concepts can be run through the survivability assessment to inform the initial down select. The assessment can also assist with the requirement definition process, by prioritising system functions. As more data become available, the survivability assessment can be re-run to inform trade-offs and help develop solutions. The process can also be applied to platforms in service that are undergoing upgrade or capability sustainment programmes.
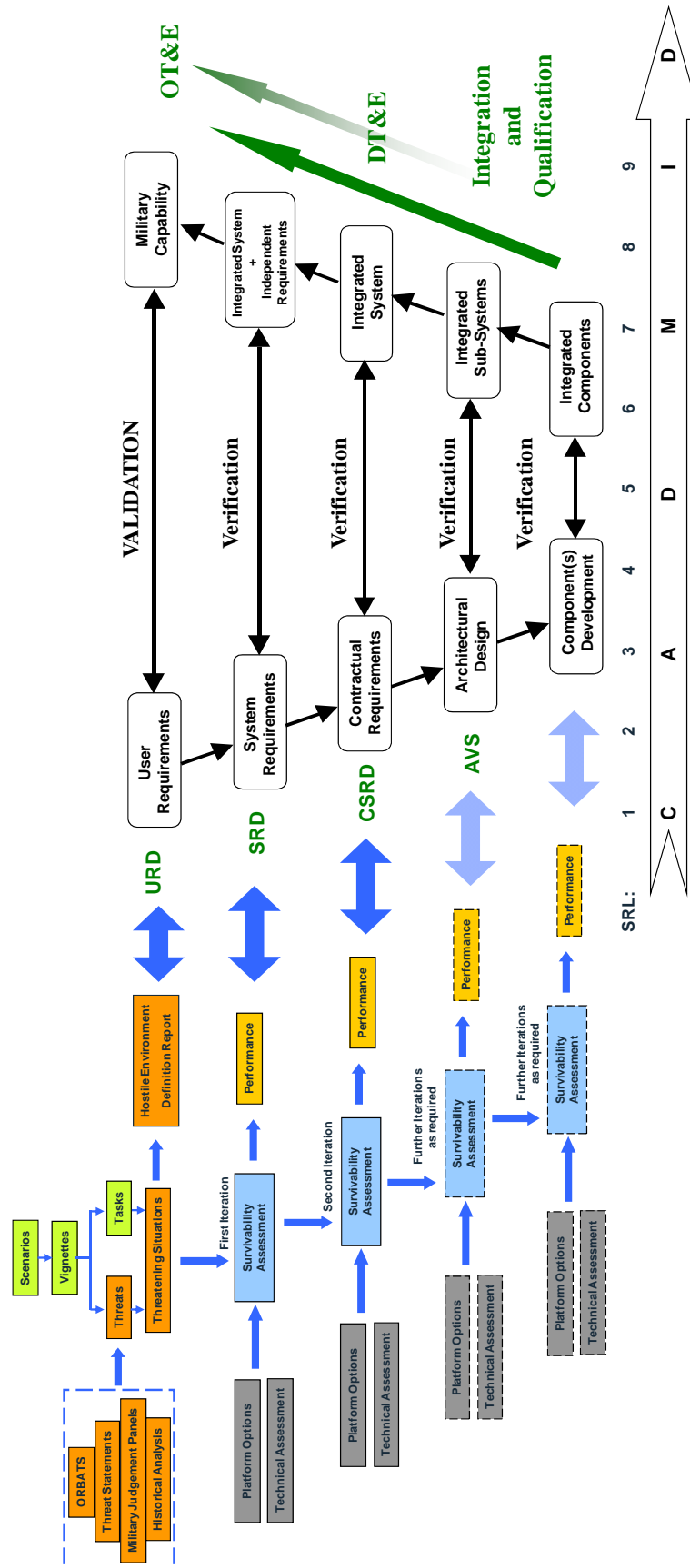
**Figure 4-2 - Survivability assessment process supporting the systems engineering process**

## 4.2    System of systems level modelling

'System of systems' level modelling has been considered to capture holistic survivability issues across all defence lines of development. These high-level (level 3) models are required to be consistent with the systems theory and systems design principles of 'breadth before depth'. A system concept diagram and influence diagrams have been used.

## 4.3    System concept diagram

### *4.3.1    Method*

Buede's (2000) simple concept diagram for representing a system, its external systems and context was applied initially to capture the wider systems issues, see Figure 4-3. This diagram includes systems and context relating to mission effectiveness and survivability; however, the associated explanation below concentrates on the survivability issues. The centre of the diagram illustrates the main system under consideration: the helicopter system. The square box bounds the external systems that are influenced by the system and interact via the system interfaces. These external systems can be existing legacy systems. The context is captured outside of the square box and comprises entities that have an impact upon the system, but are not influenced by the system itself.

Some systems cross between context and external systems, for example 'concepts and doctrine'. Concepts and doctrine have an impact upon how the system is used through previously-defined concepts of operation and employment. The system will also influence the development of concepts and doctrine, especially if it is providing a 'new' capability.
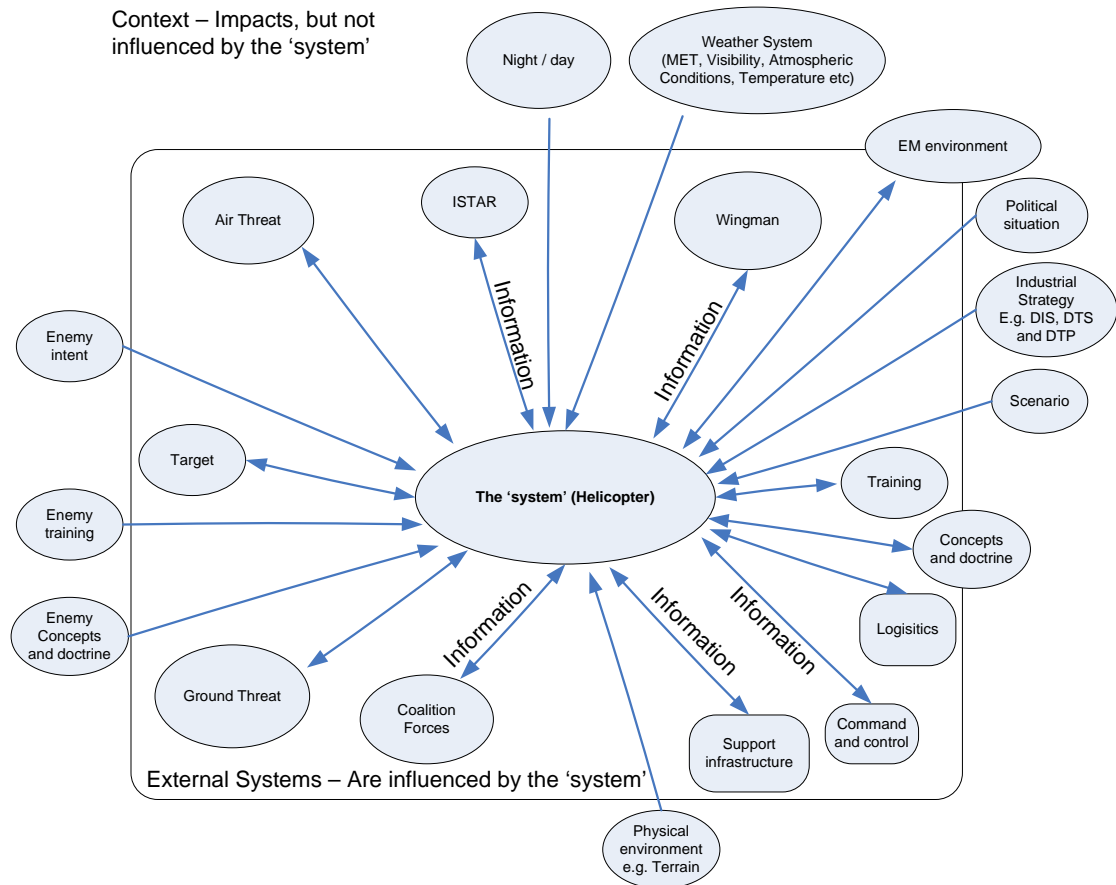
**Figure 4-3 – Depiction of a helicopter system, its external systems and context.**

### 4.3.2  *The helicopter system*

The helicopter system incorporates those sub-systems physically located within the aircraft and associated aircraft-specific support systems. These sub-systems include: the crew, airframe, rotors, avionics, flight controls, mission systems, communication systems, engines, fuel systems, electrical systems, transmissions and protection systems. Aircraft-specific support systems might include unique maintenance tools and flight simulator training aids. The design and use of these systems contributes to both mission effectiveness and survivability.

### 4.3.3  *External systems*

The external systems influence many of the survivability system requirements and are explained below in further detail.

*Command, control, communication and information*

Command, control, communication and information ($C^3I$) systems support survivability at the force and platform levels by providing wider situational awareness and the means to control forces effectively. The ability to provide the right information at the right time

without overloading users helps forces to 'not be there'. These systems are likely to improve as NEC develops and becomes more mature. The survivability of $C^3I$ systems is fundamental to platform survivability.

*ISTAR*

External ISTAR systems, for example, a satellite, a reconnaissance aircraft or uninhabited aerial vehicle (UAV) can enhance situational awareness.

*Own forces*

Own force 'joint' operations involving air, land and maritime forces require interoperability, particularly with communication and data systems. The system may often be used in conjunction with a 'wing-man' to provide co-operative support or as part of a larger package of aircraft or force.

*Electromagnetic environment*

Electromagnetic (EM) environment spans external systems and context; however, the system will have an influence on it, for example, during radio communications. Interference within the EM environment could be caused unintentionally by allies or intentionally in the case of jamming by enemy forces.

*Training*

Training provides crews with skills so that they can operate effectively within the hostile environment, using appropriate TTPs. Systems are required to support crew training and include flight simulators, which can be used to simulate threat engagements. Training system requirements will be influenced by the system; for example, updates to flight simulators and TTPs may be required for a new platform or survivability system upgrade. Training is also required for front line DAS maintainers, users and programmers.

*Logistics*

Platform protection systems, such as DAS, require expendable flare and chaff stores to be in the right place at the right time. Quantity and type of countermeasure will be influenced by the system design. Survivability systems need to be reliable and maintainable in order to keep the logistics burden manageable. Specialist contractor repair facilities may be required to deal with units that are beyond first line repair. Sufficient line replaceable units will be required within the logistics chain to replace unserviceable units, so enabling aircraft to continue to operate.

*Support infrastructure*

Survivability related support infrastructure includes: threat analysis facilities, DAS programming facilities, databases, survivability T&E facilities and DAS test equipment.

*Coalition forces*

Interoperability with coalition forces is important, especially interoperability of communication systems. Compatible identify friend or foe (IFF) systems (such as 'Blue Force Tracker') and TTPs are also important to improve situational awareness and prevent fratricide.

*Enemy threats*

Enemy threats and the associated risk to the system are the primary influence on the system design and the focus of the survivability problem. The threat environment is potentially vast and should be comprehensively identified by the threatening situations definition. Enemy concepts and doctrine and training influence threat effectiveness. Enemy intent influences the likelihood of a threatening situation. Suppression of enemy air defence (SEAD) may be used to reduce threat effectiveness.

*The target*

The target set will influence the detection and signature requirements of the system. For example, the target may be an RF system, in which case, the radar return from the helicopter will influence the detection capability of the threat. A key system design parameter is: 'can the helicopter 'see' the target before the target sees them?' This could be a design driver, dependent upon the platform role; for example, reconnaissance or covert operations would place significant emphasis on signature.

### 4.3.4   *Context*

Entities that have an impact upon the system, but are not influenced by the system are explained in further detail below.

*Physical environment*

The physical environment includes the terrain and atmospheric conditions (for example air temperature, air pressure and visibility). The weather cannot be influenced directly by a military system[26]; however, if it can be accurately forecast then it can be used to provide an element of surprise, for example operating within low visibility conditions such as a fog or storm to mask your whereabouts to the enemy. Terrain can also be used by a helicopter to

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[26] This is not strictly true. For example, on occasion during World War 2, mist and fog were 'burnt off' by burning fuel alongside runways at night to guide aircraft on final approach.

'hide' within clutter or to break line of sight when flying at low-level. Terrain can also constrain helicopter operations, for example in mountainous terrain where the altitude may exceed the helicopter's performance capability. Threats can also use terrain to their advantage to hide in and set ambushes.

*EM environment*

The EM environment will be influenced by other military and civilian activity, as well as natural effects. The EM environment could potentially interact with systems on the aircraft causing, for example, interference to communications. Aircraft systems need to be able to operate within the natural background.

*Political environment*

The political environment may influence how a military campaign is conducted and this will in turn influence how the helicopter system is used. For example, a high-level of political pressure to minimise casualties may lead to an increased level of effort to improve survivability of helicopter systems. Helicopter sorties may also increase to reduce casualties on the ground by reducing the reliance on riskier forms of transport, for example via road. Provision of helicopters also influences CASEVAC capability to improve the chances of survival of wounded personnel.

*Scenario*

The scenario has a significant impact upon the system, for example, it could be a peacekeeping or warfighting scenario with a corresponding difference in the threat and rules of engagement.

*Industrial strategy*

The UK Defence Industrial Strategy and its implementation has an influence on the design of current and future systems. For example, the intention to maintain UK sovereignty of key technologies and to use 'open architectures' to more readily exploit new technology will affect the future upgrade of existing helicopters and the design of entirely 'new' helicopter systems.

### 4.3.5   *Discussion*

This approach helps to structure the problem and provides a framework to consider influences on the system of interest; however, it is a simple representation. The elements and their interactions need to be considered in further detail. The 'influence diagram' in the next section aims to develop these ideas further.

## 4.4 System influence diagram

### 4.4.1 *Method*

The survivability influence diagram was developed to consider survivability as part of the overall capability, i.e. delivery of the mission. This is not just a platform and equipment issue. The key in Figure 4-4 illustrates the different elements of the diagram, including variables, external forces and their influences on the helicopter. The influence diagram is shown in Figure 4-5.

The context is a battlefield helicopter in a warfighting low-technology threat environment. The main system of interest is the helicopter, bounded by the large dotted ellipse. The key mission capabilities and specific areas of interest are denoted by the filled ellipses. Performance is about getting there with the required payload. Situational awareness is about getting to the right place at the right time with the right information. Survivability is about getting there and back intact as explained in the definitions provide previously (Section 1.4.1). Other mission capabilities captures everything else and includes mission specific enablers, for example: CASEVAC, MEDEVAC, cargo / load handling equipment (e.g. winch, cargo nets & strops).
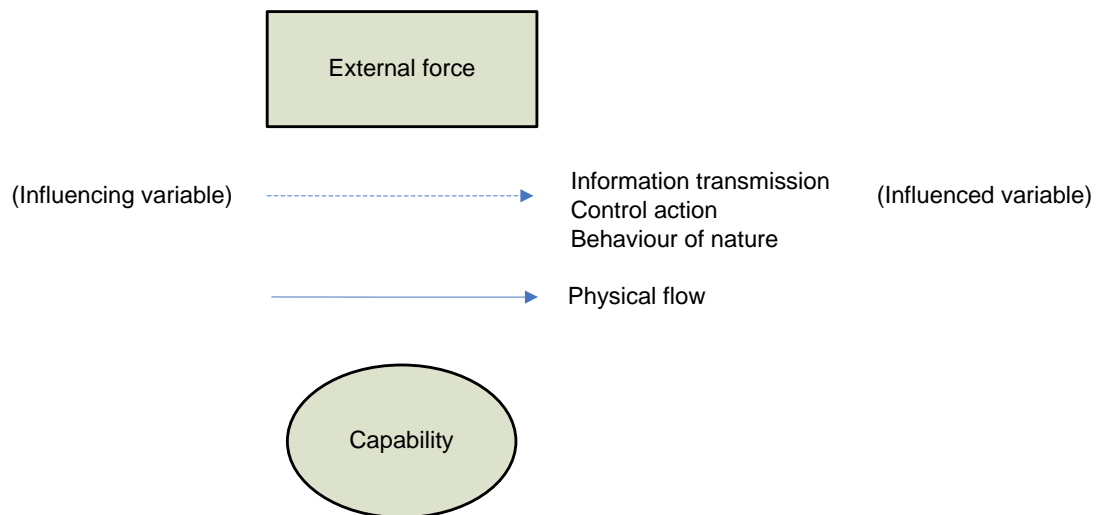


**Figure 4-4 – Influence diagram key**

### 4.4.2 *Results*

The diagram shows that survivability has many influences with other capability areas; manoeuvre is just one example. Additional manoeuvre ability is influenced by increased performance through available excess power, advanced rotors providing greater lift and reduced mass enabled by technologies such as advanced lightweight materials. Mass can also be reduced by not fitting certain technologies. Whether capabilities can be 'traded' or not depends upon the context (i.e. scenario and role). Core capabilities cannot be 'traded-out'

otherwise the mission would be impossible or present too high a risk to the survivability. Realistically, these are a theatre specific fit because of the integration constraints on the airframe, i.e. you would not change these from mission to mission. Certain capabilities (e.g. modular armour) can be 'traded-out' on a mission by mission basis to keep mass as low as possible and so increase mission capability by increasing payload / range. Flexibility is important to allow platforms to be optimised or 're-roled' quickly. This requirement may be enabled by a 'fitted for, not with' philosophy.

The key external influence on survivability is the threat. The diagram illustrates the cycle of survivability methods reducing threat performance and then newer more capable threats possibly reducing survivability.

Key interactions include the effect of aircraft performance on survivability. Excess power enables manoeuvre and the ability to conduct tactical take-off and landing, reducing exposure to the threat. Weapons used offensively (in the case of Apache) or defensively (in the case of a support helicopter) provide an effect, as well as contributing to survivability by suppressing or incapacitating a threat. IR signature suppression technology reduces signature, so increasing countermeasure effectiveness and reducing threat engagement opportunities.

Some external influences, such as 'EM environment' have not been considered because the effects are too complex for the diagram. However, a specific influence diagram on this subject could be produced.

Figure 4 – 5 - Survivability influence diagram for a battlefield helicopter in a warfighting low-technology threat environment.

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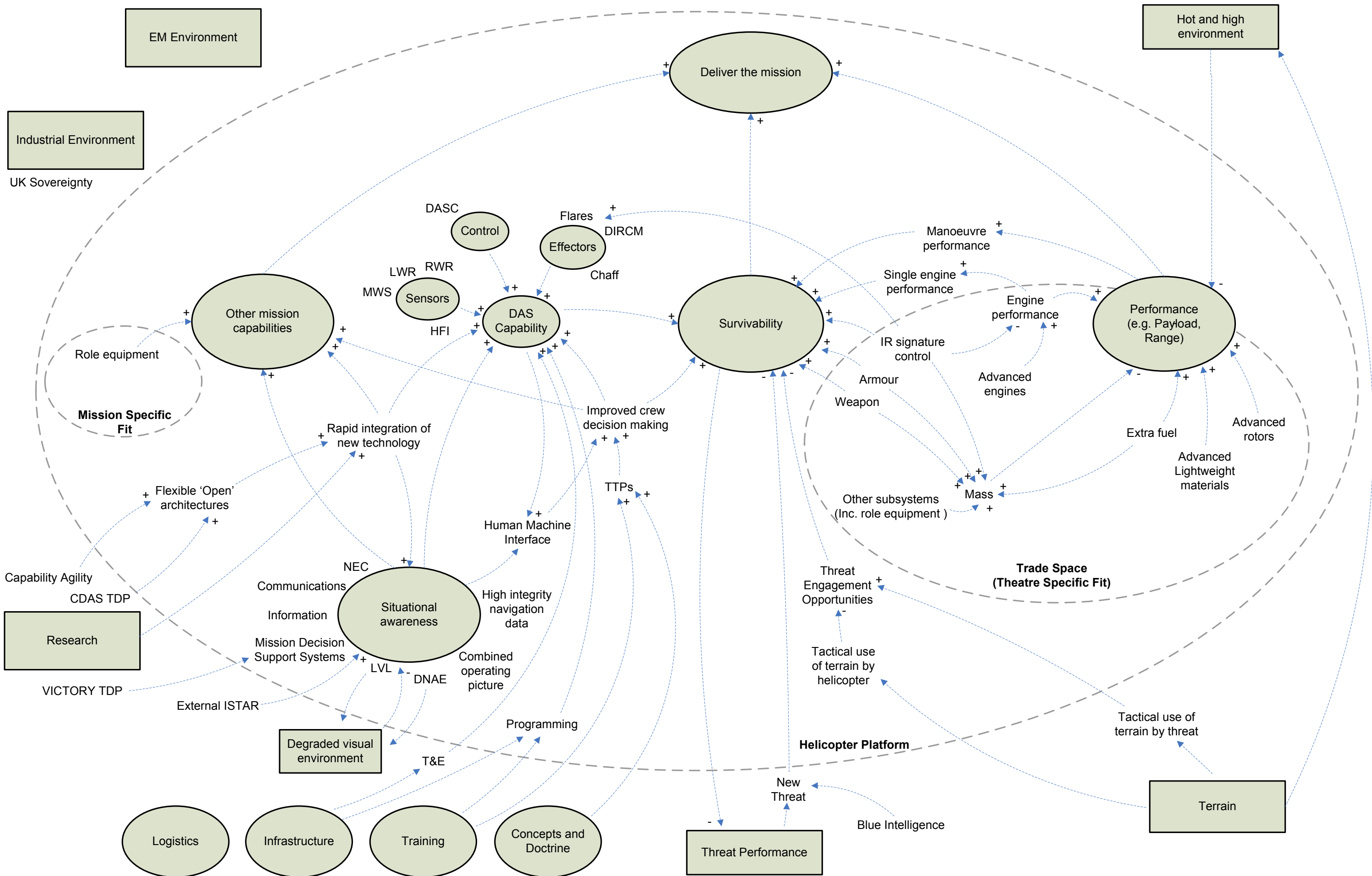
### *4.4.3 Discussion*

Developing the influence diagram has shown that survivability has many interactions with other attributes making up the overall capability. Survivability cannot, therefore, be considered holistically in isolation, because many capabilities contribute both to survivability and mission effectiveness. At a minimum, certain cross-cutting capabilities need to be considered within a holistic survivability analysis in addition to the core survivability attributes:

- Manoeuvre.

- TTPs.

- Situational Awareness.

- Weapons.

The interactions should also be explored further in the subsequent modelling. The level at which the influence diagram considers the problem is also important, whether at a strategic, tactical or technical viewpoint. Influence diagrams allow the flexibility to cover various levels of detail within one diagram. This approach is represented by a diagonal ellipse in Coyle's 'cone' of influence diagrams (Coyle 1996).

The level 3 influence diagram provides the utility to start to understand the whole problem space and check for completeness. This 'big picture view' shows the interrelationship and complexity of capabilities as the other DLODs (not just the equipment) are considered. The focus has been on platform level survivability, although all levels, including 'force-level' could be considered using the influence diagram approach.

## 4.5 System-level modelling

System-level modelling (level 2) concentrates on the helicopter platform. The systems engineering framework in Figure 4-6 has been used to illustrate two examples of survivability sub-systems within this level. The orange bar illustrates that existing DAS equipment can be considered high-technology, as it is 'cutting edge' to stay ahead of the threat. Integrating such technology on to an existing aircraft could be considered to be 'high-technology' and carries a corresponding level of technical risk. On a 'new' platform the integration can be conducted throughout the CADMID cycle. For an upgrade or UOR it will occur within the 'in service' part of CADMID cycle for the platform. The DAS system itself would have its own CADMID cycle. The red bar illustrates the development of a new DAS system. This would be pushing the boundaries of technology and so would fit within the 'super high-technology' area. A development programme (e.g. TDP) could be used to reduce the technical risk and increase the TRL.

A platform-level survivability hierarchy has been developed in Figure 4-7 to illustrate the grouping of survivability attributes below the 'pillars' of survivability. Each attribute has been mapped to a number of example technologies and tactics that contribute to that particular attribute. These attributes have been explained previously in Section 2.3. Heikell (2005) concluded that a balanced 'top-down' approach should be taken to electronic warfare self-protection, with hierarchical sectoring and consideration of horizontal interactions. The platform survivability hierarchy is consistent with this approach and applies the concept more widely across survivability as a whole.
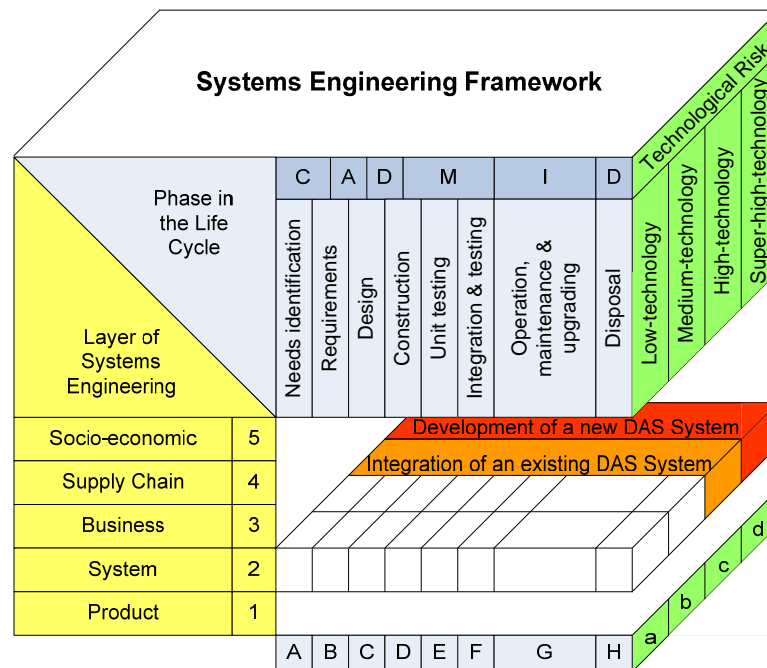
**Figure 4-6 – Examples of level 2 DAS systems engineering.**
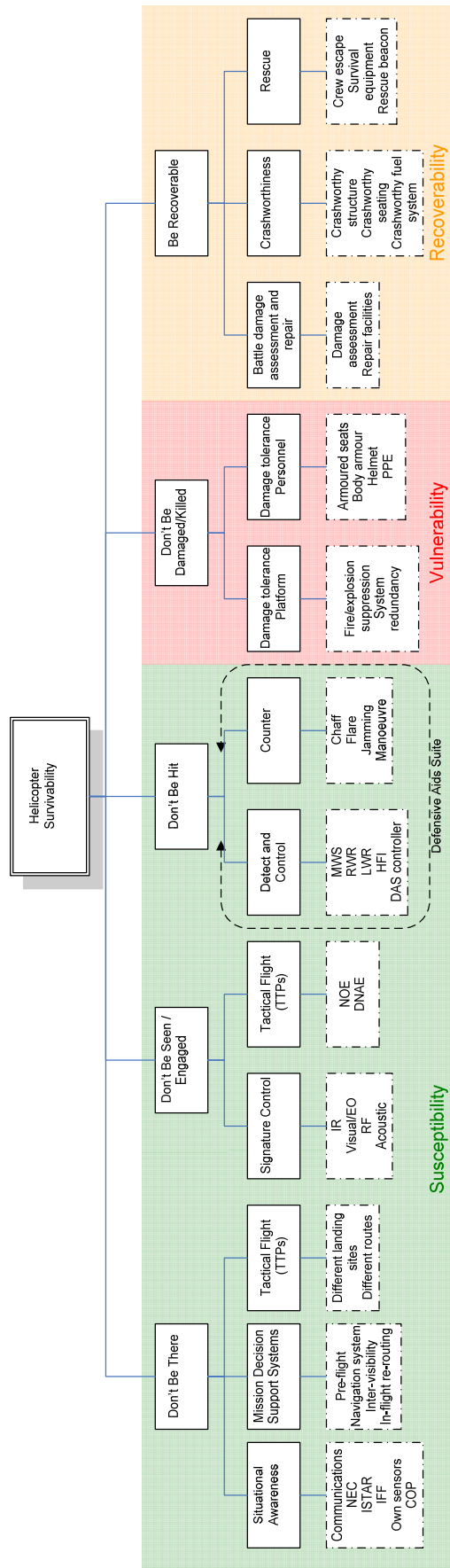
**Figure 4-7 – Platform level survivability hierarchy.**

## 4.6    Quality Function Deployment

### 4.6.1    Method

The Wells and Haige (2003) 'Partridge' model was further developed by the author who refined ideas and input data during reviews with colleagues and subject matter experts. The method takes the customer requirement for a survivable helicopter and functionally decomposes it from scenarios to threats and then threats to survivability attributes. Platform options were then assessed against the survivability attributes taking into account cost. A 'street' of HOQs were developed as illustrated in Figure 4-8. When scoring the matrices a simple high (9), medium (3), low (1) or zero (0) scoring system was used. The scoring system effectively provides a 'value function' that deliberately biases a 'high' score in order to draw out strong relationships. This scoring system was consistent with that used by other QFD practitioners, including NASA (Cruit et al. 1993). A high (3), medium (2), low (1) or zero (0) scoring system was also used as part of a sensitivity analysis. To illustrate the method, the author populated the matrices based upon his experience of workshops with colleagues and subject matter experts. The input data were checked during review and are considered to be broadly representative and consistent with the generic example scenarios.

*Scenarios*

Four generic scenarios have been used to test the analysis methods using open sources:

Peace keeping is characterised by a low threat (low intent and low capability) intensity and 'tighter' rules of engagement. The peace keeping scenario could be a peace enforcement scenario that gradually reduces in threat before military forces eventually withdraw altogether.

Peace enforcement is characterised by a medium threat (medium intent and medium capability) intensity and less constraining rules of engagement.

The warfighting (low technology) scenario is characterised by conventional or asymmetric warfare against a threat employing predominantly 'low technology' weapons, such as small arms, AAA, RPG, IEDs and early generation MANPADS. The threat has a high level of intent and given the opportunity will engage. The threat also has a medium level of capability, is well trained and high in morale.

The warfighting (high technology) scenario is characterised by conventional warfare against a threat employing predominantly 'high technology' weapons such as an IADS, including MANPADS and RF SAMS. The threat environment has a high level of intent and will engage a helicopter given the opportunity. The threat spectrum also has a high level of capability and operators are well trained and high in morale.

**Figure 4-8 – QFD applied to helicopter survivability.**
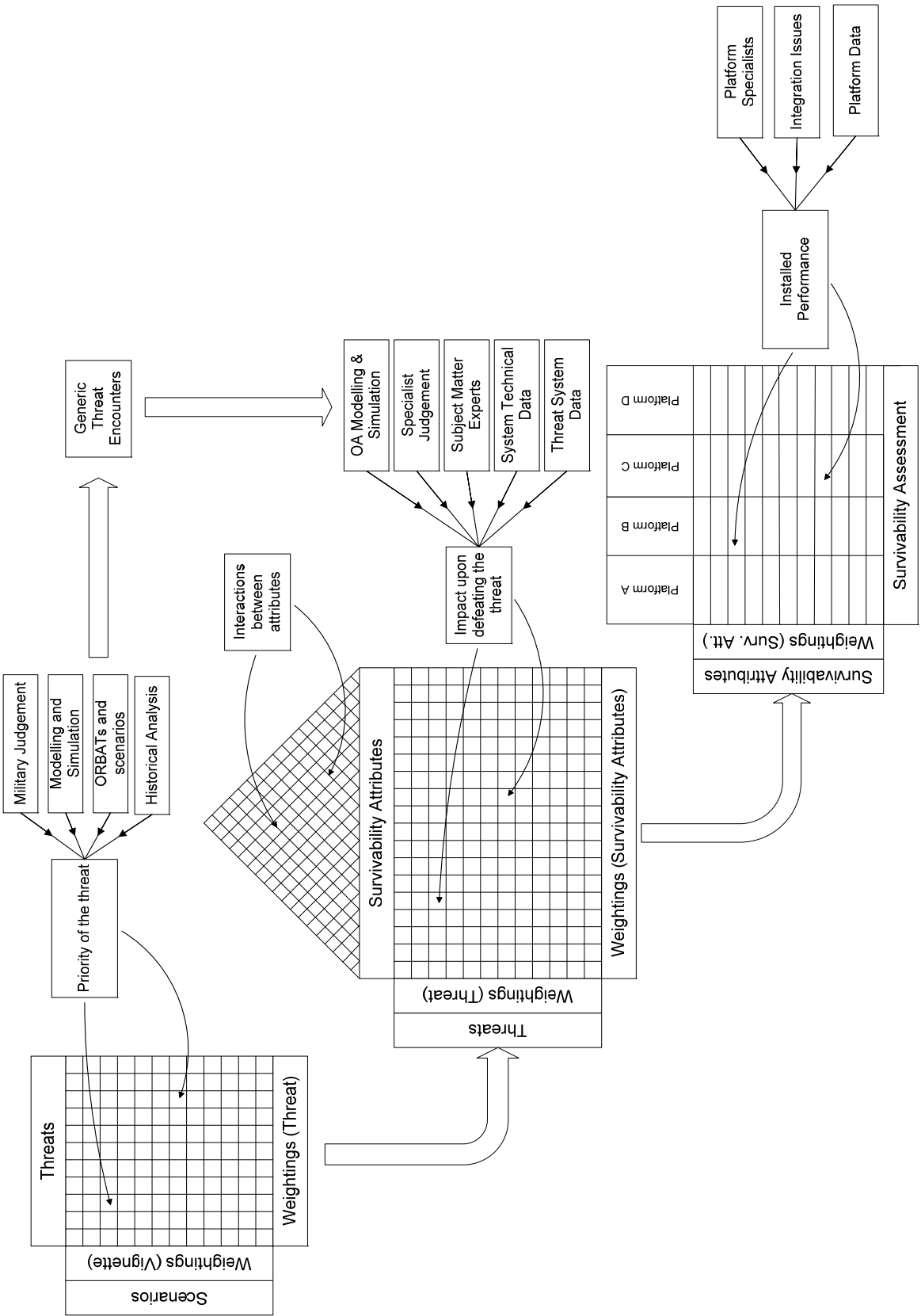
ABBREVIATIONS: OA Operational Analysis, ORBAT Order of Battle

*Example calculations*

The first matrix scenario weightings are evaluated and then input into column 2. The threat weighting, Tw is calculated from the sum product of the scenario weighting and the threat category score. For example, referring to Table 4-1:

Tw $_{(small\ arms)}$ = (9 x 1) + (9 x 3) + (9 x 9) + (1 x 9) = 126

The threat weightings for all threat categories are then normalised to one. This is calculated by summing all of the threat weightings, $\sum$Tw and then dividing each Tw by $\sum$Tw.

$\sum$Tw = 126 + 54 + 48 + 12 + 45 + 18 = 303

Tw $_{(small\ arms\ normalised)}$ = Tw $_{(small\ arms)}$ / $\sum$Tw

Tw $_{(small\ arms\ normalised)}$ = 126 / 303

Tw $_{(small\ arms\ normalised)}$ = 0.42

The normalised Tw weightings are then carried through to column two in the second matrix (Table 4-2). The above process is then repeated for each matrix. The attribute weightings in the second matrix are carried through to column two in the third matrix and then the survivability performance weightings in the third matrix (Table 4-4) are calculated.

## 4.6.2   *Results*

*The first matrix – scenario-to-threats*

The first 'scenario-to-threats' matrix is shown in Table 4-1. The scenario weightings were evaluated based upon the likelihood of the platform conducting each scenario. The threat matrix was evaluated based upon the likelihood of encountering a threat in that particular scenario (not the likelihood of being hit). The generic scenario descriptions were used to evaluate the threat.

In this particular example, small arms had the highest weighting (0.41), followed by the other low-tech threats, with the higher technology threats (MANPADS and RF SAMs) being evaluated as having a relatively low threat weighting. These results are illustrated in Figure 4-9. Intuitively, the result seems to bias the small arms and low-technology threat, because it does not take into account the likelihood or consequence of being hit by each threat.

Whilst a small arms engagement is more likely because of threat proliferation, the likelihood of being hit and the level of damage is less than other threats, for example a MANPADS. MANPADS are guided, so increasing the likelihood of being hit compared with unguided systems. The consequence of a hit is also greater, because they also contain a warhead capable of destroying a helicopter (see Section 2.2.5).

**Table 4-1 –Normalised threat weighting by scenario.**

| Scenario | Scenario Weighting | Threat | | | | | | Sum |
|---|---|---|---|---|---|---|---|---|
| | | Small Arms | AAA | RPG | ATGW | MANPADS | RF SAM | |
| Peacekeeping | 9 | 1 | 1 | 1 | 0 | 0 | 0 | |
| Peace enforcement | 9 | 3 | 1 | 1 | 0 | 1 | 0 | |
| Warfighting (low tech) | 9 | 9 | 3 | 3 | 1 | 3 | 1 | |
| Warfighting (high tech) | 1 | 9 | 9 | 3 | 3 | 9 | 9 | |
| | Threat Weighting, Tw | 126 | 54 | 48 | 12 | 45 | 18 | 303 |
| | Tw (normalised) | 0.42 | 0.18 | 0.16 | 0.04 | 0.15 | 0.06 | 1 |
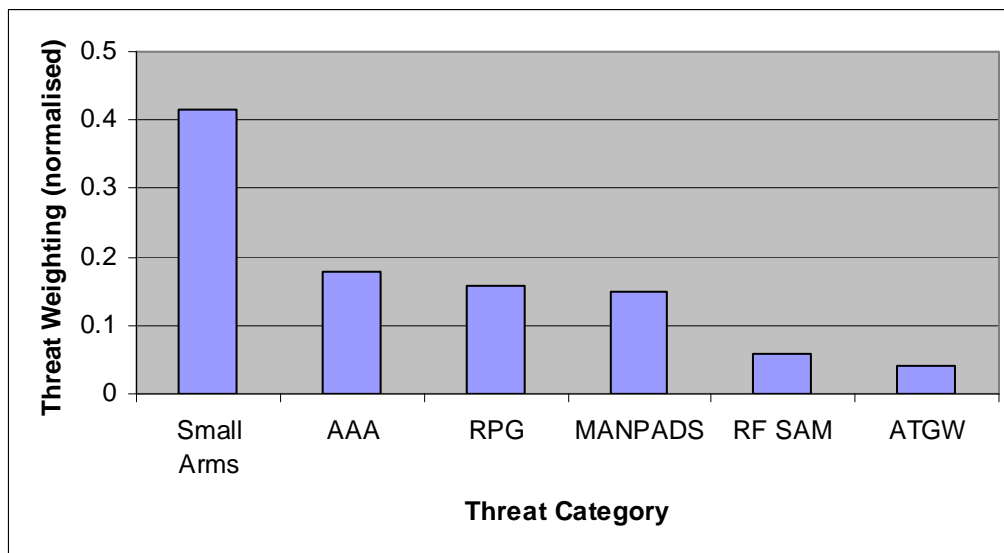


**Figure 4-9 - Normalised threat weighting by threat category.**

*Second matrix – threats-to-attributes*

The second 'threats to survivability attributes' matrix is shown in Table 4-2. The matrix was evaluated based upon the contribution that each survivability attribute made to defeating the threat.

In this example, the attributes with the greatest 'value' were ballistic tolerance and explosion suppression (0.15 each), then detect threats (0.13) and then DNAE and signature control scoring 0.09 each, see Figure 4-10. This result shows the impact on survivability attribute weightings when the threat weightings are biased towards the low-tech unguided threat. Unsurprisingly the result favours the attributes providing solutions to the low-tech threat.

**Table 4-2 – Normalised survivability attribute weighting by threat.**

| Threats | Threat Weighting | Survivability Attributes | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Don't be there | | Don't be seen | | | Don't be hit | | | | Don't be killed | | |
| | | Situational Awareness | MDSS | Signature Control | DNAE | NOE | Detect Threats | Expendable CMs | Counter fire | Manoeuvre | Ballistic Tolerance | Fire/ explosion suppression | Crash-worthiness |
| Small Arms | 0.42 | 1 | 1 | 1 | 3 | 1 | 3 | 0 | 3 | 3 | 9 | 9 | 1 |
| AAA | 0.18 | 3 | 3 | 1 | 3 | 1 | 3 | 1 | 1 | 3 | 3 | 3 | 1 |
| RPG | 0.16 | 1 | 1 | 1 | 3 | 1 | 1 | 0 | 3 | 3 | 1 | 1 | 1 |
| ATGW | 0.04 | 1 | 1 | 1 | 3 | 1 | 3 | 1 | 0 | 3 | 1 | 1 | 1 |
| MANPADS | 0.15 | 1 | 1 | 9 | 3 | 3 | 9 | 9 | 0 | 0 | 1 | 1 | 1 |
| RF SAM | 0.06 | 3 | 3 | 9 | 1 | 3 | 9 | 9 | 0 | 3 | 1 | 1 | 1 |
| Attribute Weighting, Aw | | 1.48 | 1.48 | 2.66 | 2.88 | 1.42 | 3.93 | 2.09 | 1.90 | 2.55 | 4.68 | 4.68 | 1.00 |
| Aw (normalised) | | 0.05 | 0.05 | 0.09 | 0.09 | 0.05 | 0.13 | 0.07 | 0.06 | 0.08 | 0.15 | 0.15 | 0.03 |
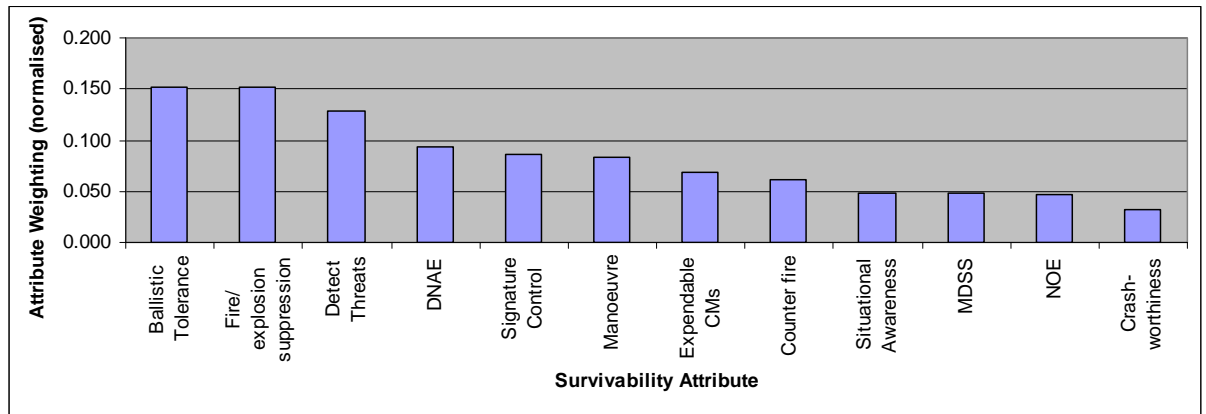
**Figure 4-10 - Normalised survivability attribute weightings.**

*Third matrix – attributes-to-platform options*

The third 'survivability attributes to platform options' matrix was formulated based upon the installed performance of the survivability attributes on 'theoretical' platforms for illustration of the method. The equipment fit for each of the 'theoretical' platforms is outlined in Table 4-3. The survivability attributes-to-platform options matrix is shown in Table 4-4. Dummy cost data were included to illustrate the method.

The corresponding graphical output of the platform results is shown in Figure 4-11. Survivability fits or upgrades can be compared with a baseline aircraft using the survivability weighting. Comparing the influence of the impact of the constraints (e.g. cost, mass, space and technical risk) can be made by plotting them versus the survivability weighting or dividing the survivability weighting by the constraint. The survivability weighting / cost metric has been included as an example. This metric was included to provide an initial indication of survivability cost effectiveness, however, it could not be used to make acquisition decisions without further analysis because it is actually 'meaningless'.

*Equipment fit assumptions*

Equipment fit assumptions were used to evaluate sub-system performance against each of the survivability attributes. The baseline aircraft has limited survivability sub-systems fitted as standard, it does not have a DAS or any signature control system. The aircraft is a baseline platform, so its mass is relatively low, resulting in improved manoeuvrability over the basic aircraft. Some ballistic tolerance, fire / explosion suppression and crashworthiness have been 'built in' as part of the integrated design process.

The basic aircraft has a basic DAS fit, early generation IR suppressor and armoured seats for the pilots. The intermediate aircraft has a more sophisticated DAS fit, second generation IR suppressor and armoured seats for the pilots. Crashworthiness was assessed to be similar across all platform options, because it is not an attribute that can be easily retro-fitted. It

needs to be incorporated into the structure at an early design stage. The advanced aircraft has the most advanced survivability systems in each area with technologies similar to those developed under the Comanche programme.

**Table 4-3 - Equipment fit summary table**

| Attribute | Sub-System | Baseline | Basic | Intermediate | Advanced |
|---|---|---|---|---|---|
| Situational Awareness | Communications and HMI | LOS insecure voice | LOS insecure voice | BLOS insecure voice and data | BLOS secure voice and data<br><br>COP |
| MDSS | Mission decision support systems | Paper map, GPS | Paper map, GPS | Moving map | Moving map with integrated real-time re-routing |
| Signature Control | IR Signature Control | Nil | 1st generation suppressor | 2nd generation suppressor | Advanced suppressor |
|  | RF Signature Control | Nil | Nil | Limited retro fit | Integrated into the design |
| DNAE | NVG | Yes | Yes | Advanced | Advanced, image fusion |
|  | FLIR | No | No | Yes | Advanced, image fusion |
| NOE | NOE | Radar altimeter | Radar altimeter | Radar altimeter | Obstacle avoidance system |
| Detect Threats | RWR | No | Basic | Advanced | Next generation |
|  | MWS | No | Basic | Advanced | Next generation |
| Expendable CMs | Expendable CMs | No | Basic | Improved | Advanced |
| Counter fire | Weapon system | No | No | Machine gun | Machine gun |
| Manoeuvre | Engines | Standard | Standard | High performance | High performance |
|  | Rotors | Standard | Standard | High performance | High performance |
| Ballistic Tolerance | Ballistic Tolerance | No | Armoured pilot seats | Armoured pilot seats | Strategic armour fit (pilot, crew, critical systems) |
| Fire / explosion suppression | Fire / explosion suppression | Engine fire extinguisher system | Engine fire extinguisher system | Self sealing fuel tanks, fire suppression system | Advanced fuel tanks & fire suppression system |
| Crashworthiness | Structure, seating and fuel system | Crashworthy structure, seats and fuel system | Crashworthy structure, seats and fuel system | Crashworthy structure, seats and fuel system | Crashworthy structure, seats and fuel system |

**Table 4-4 – Matrix linking survivability attributes to platform options.**

| | | A | B | C | D |
|---|---|---|---|---|---|
| | Attribute Weighting (normalised) | **Baseline** | **Basic** | **Intermediate** | **Advanced** |
| **Situational Awareness** | 0.05 | 1 | 1 | 3 | 9 |
| **MDSS** | 0.05 | 1 | 1 | 3 | 9 |
| **Signature Control** | 0.09 | 0 | 1 | 3 | 9 |
| **DNAE** | 0.09 | 0 | 1 | 3 | 9 |
| **NOE** | 0.05 | 1 | 3 | 9 | 9 |
| **Detect Threats** | 0.13 | 0 | 1 | 3 | 9 |
| **Expendable CMs** | 0.07 | 0 | 3 | 3 | 9 |
| **Counter fire** | 0.06 | 0 | 0 | 3 | 3 |
| **Manoeuvre** | 0.08 | 3 | 1 | 3 | 3 |
| **Ballistic Tolerance** | 0.15 | 1 | 3 | 3 | 9 |
| **Fire/ explosion suppression** | 0.15 | 1 | 1 | 3 | 9 |
| **Crash-worthiness** | 0.03 | 3 | 3 | 9 | 9 |
| | Survivability Weighting, Sw | 0.79 | 1.54 | 3.47 | 8.13 |
| | **Sw (normalised)** | **0.06** | **0.11** | **0.25** | **0.58** |
| | Cost (£100k) | 5 | 8 | 12 | 25 |
| | Sw / cost (£100k) | 0.011 | 0.014 | 0.021 | 0.023 |
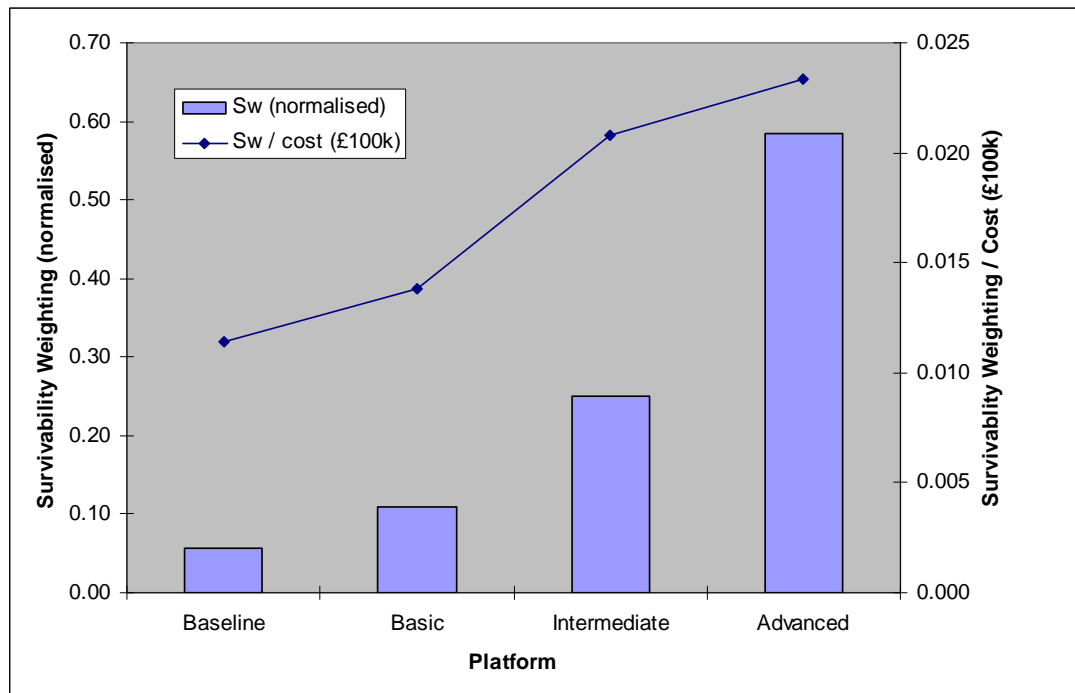


**Figure 4-11 - Normalised survivability weighting and cost effectiveness by platform.**

*The roof of the HOQ*

The 'roof' of the HOQ detailing the interactions and dependencies is shown in Table 4-5. For ease of manipulation in Microsoft® Excel®, the roof was converted to a square matrix with half of the matrix populated along the leading diagonal. The matrix was evaluated based upon how strong the interaction was between the attributes. The scoring system used to evaluate the interaction was identical to that used to evaluate the attributes: high (9), medium (3), low (1) or zero (0). Many interactions were captured, for example, situational awareness had interactions with all the other susceptibility related attributes and particularly with the ability to carry out mission planning, detect threats and provide an effective response (e.g. counter fire and manoeuvre). Situational awareness of where the threat is in relation to the platform would be essential in order to return fire and manoeuvre.

The 'roof' was found to be excellent for identifying the strength of an interaction and illustrating how many interdependencies there are. This provides an idea of the impact of making a change to the system and the impact it can then have on the 'whole,' consistent with the corollary to the first systems principle (Section 3.2.4). The 'strength of interaction' identified in the 'roof' is not capable of modelling the precise relationship between attributes; however, it provides a good starting point for more detailed analysis or physics-level modelling. The roof also offers a method of satisfying Heikell's (2005) recommendation to identify horizontal interactions.

**Table 4-5 – Matrix showing the survivability attribute relationships and dependencies.**

| | Situational Awareness | MDSS | Signature Control | DNAE | NOE | Detect Threats | Expendable CMs | Counter fire | Manoeuvre | Ballistic Tolerance | Fire/ explosion suppression | Crash-worthiness |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Situational Awareness** | | 9 | 3 | 3 | 3 | 9 | 1 | 9 | 9 | 0 | 0 | 0 |
| **MDSS** | | | 9 | 9 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Signature Control** | | | | 3 | 9 | 1 | 9 | 1 | 9 | 0 | 0 | 0 |
| **DNAE** | | | | | 9 | 3 | 3 | 3 | 3 | 0 | 0 | 0 |
| **NOE** | | | | | | 3 | 9 | 3 | 3 | 1 | 1 | 0 |
| **Detect Threats** | | | | | | | 9 | 1 | 3 | 0 | 0 | 0 |
| **Expendable CMs** | | | | | | | | 0 | 9 | 0 | 0 | 0 |
| **Counter fire** | | | | | | | | | 9 | 3 | 3 | 0 |
| **Manoeuvre** | | | | | | | | | | 1 | 0 | 0 |
| **Ballistic Tolerance** | | | | | | | | | | | 9 | 3 |
| **Fire/ explosion suppression** | | | | | | | | | | | | 9 |
| **Crash-worthiness** | | | | | | | | | | | | |

*Explanation of the 'roof' evaluation*

A complete evaluation of the interactions and dependencies making up the 'roof' are included within Appendix E. Some selected examples are provided here:

- Situational awareness (SA) and mission decision support systems (MDSS) have a high inter-relationship, because SA provides the information that enables mission decisions to be made. For example, communication of data to the platform could allow the Recognised Air Picture (RAP) to be updated in real time, allowing the mission plan to be optimised in flight. 'Pop-up' threats detected by a third-party asset and communicated to the platform could be avoided by real time re-routing, by calculating the route of least risk. MDSS are supported by NEC.

- MDSS and signature control have a high interaction, because knowledge of the platform signature allows 'safe routing' to be conducted. The mission can be pre-

planned and then potentially re-planned in flight to reduce the signature as much as possible by using terrain and optimum flight profiles.

- Signature control and expendable countermeasures have a high interaction, because signature and countermeasures have to be designed as a system. Reducing signature can help to make expendable countermeasures more effective, by making the countermeasure an even more desirable target compared with the platform signature.

- DNAE and NOE have a high interaction, because DNAE is an enabler to flying NOE. For example, clearly defined visual cues in low light and at night would be essential in order to fly safely at low level.

- 'Detect threats' and expendable countermeasures have a high interaction, because for the expendables to work, they require the threat to be detected correctly in the first place.

- Expendable countermeasures and manoeuvre have a high interaction, because deploying countermeasures will normally be associated with a manoeuvre in order to increase countermeasure effectiveness. The TTPs combine these attributes to maximise chances of survival.

*Hybrid risk and QFD method*

The initial application of the QFD matrix works well with some skewing of results, because of sub-optimal threat categorisation and evaluation. The hybrid risk and QFD method was developed by the author to improve the threat evaluation by incorporating a risk assessment approach. This approach is also consistent with the recommendation to apply risk assessment and ALARP to the survivability problem, see Section 4.1.1.

The method involved constructing a threat matrix with a likelihood of occurrence and consequence columns for each threat category. 'Likelihood of occurrence' was defined as how likely it was that the threat would engage the aircraft. 'Consequence' was defined as how likely it was that the threat would hit and kill the aircraft, given an engagement. The threat priority was then a product of the two scores consistent with how 'risk' is calculated. This matrix was then evaluated by the author using generic data to assess whether the new method offered improvements compared with the original method, see Table 4-6.

**Table 4-6 - Normalised threat 'risk' weighting by threat category.**

| Scenario | Scenario Weighting | Small Arms | | | AAA | | | RPG | | | ATGW | | | MANPADS | | | RF SAM | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | L | C | R | L | C | R | L | C | R | L | C | R | L | C | R | L | C | R |
| Peacekeeping | 9 | 1 | 1 | 1 | 1 | 3 | 3 | 1 | 3 | 3 | 0 | 3 | 0 | 0 | 9 | 0 | 0 | 9 | 0 |
| Peace enforcement | 9 | 3 | 1 | 3 | 1 | 3 | 3 | 1 | 3 | 3 | 0 | 3 | 0 | 1 | 9 | 9 | 0 | 9 | 0 |
| Warfighting (low tech) | 9 | 9 | 1 | 9 | 3 | 3 | 9 | 3 | 3 | 9 | 1 | 3 | 3 | 3 | 9 | 27 | 1 | 9 | 9 |
| Warfighting (high tech) | 1 | 9 | 1 | 9 | 9 | 3 | 27 | 3 | 3 | 9 | 3 | 3 | 9 | 9 | 9 | 81 | 9 | 9 | 81 |
| Threat Weighting, Tw | | 126 | | 126 | 54 | | 162 | 48 | | 144 | 12 | | 36 | 45 | | 405 | 18 | | 162 |
| Tw (normalised) | | 0.42 | | 0.12 | 0.18 | | 0.16 | 0.16 | | 0.14 | 0.04 | | 0.03 | 0.15 | | 0.39 | 0.06 | | 0.16 |

ABBREVIATIONS: L Likelihood of encounter, C Consequence of encounter, R Risk

The hybrid threat 'risk' weighting in Figure 4-12 shows a significant difference in threat priority compared with the original QFD method set out in Section 4.6.2. This is because of the inclusion of the consequence of engagement scoring column to determine the threat 'risk'. Small arms is much less significant than in the original method, because the consequence is relatively low, owing to the probability of a hit and damage being lower than the other threats. MANPADS is much more significant than in the original method, because the consequence of an engagement is high, owing to the probability of a hit and damage being much higher than the low-technology threats.

The low-technology threat (small arms, AAA and RPG combined) is seen to be as high a risk as MANPADS, whereas the original method showed MANPADS to be less than half the priority of small arms. The risk method, therefore, gives a different set of priorities that it is argued here is more realistic than the original QFD method. Figure 4-12
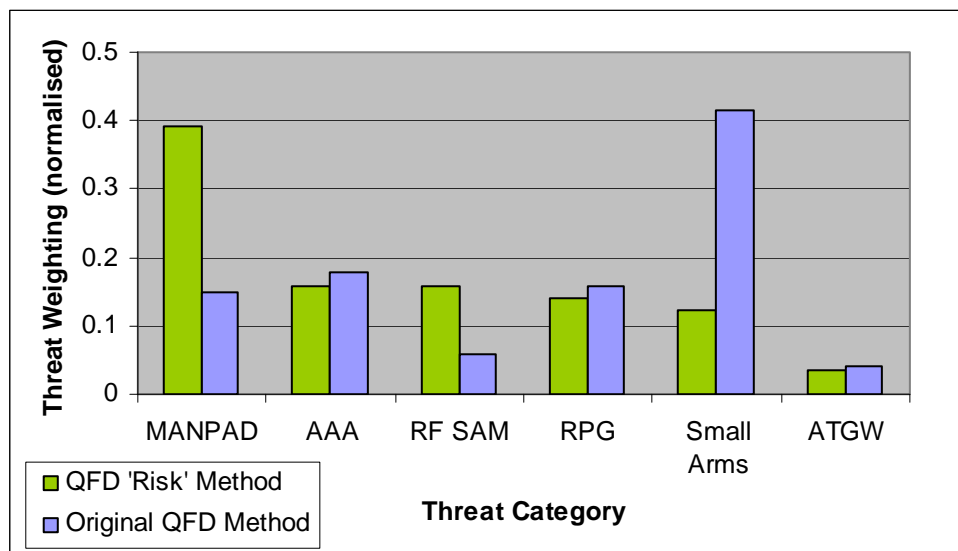


**Figure 4-12 – Comparison of QFD normalised threat weighting by threat category.**

The change to the threat weighting has resulted in a change in the survivability attribute weightings as shown in Figure 4-13. Ballistic tolerance and fire and explosion suppression are much less significant than in the original method, because the low-technology threat has been reduced to a more realistic level and these attributes provide a high level of protection against the low-technology threat. Detect threats, signature control and expendable countermeasures are more significant than in the original method, because the guided threat (MANPADS and RF SAM) weightings have increased and these attributes protect predominantly against these threats.

The results show that the hybrid 'risk' method offers improvements over the original method, because it provides a more balanced answer that is less prone to inadvertent biasing.

The method forces the user to consider likelihood and consequence separately, so providing a more consistent and repeatable process.
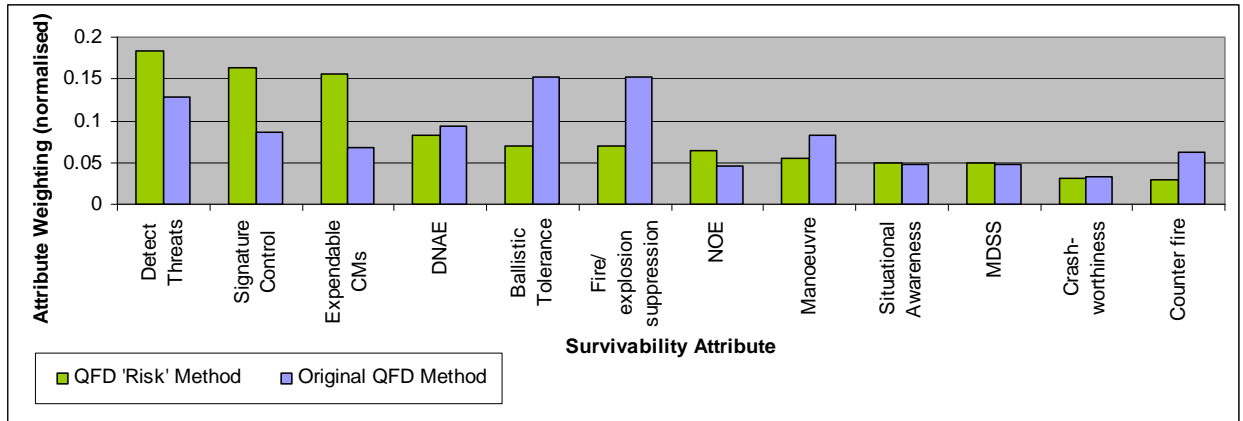


**Figure 4-13 – Comparison of QFD normalised survivability attribute weightings.**

Figure 4-14 shows a comparison of platform performance for the two methods. The two methods show negligible differences except for the baseline platform. The baseline platform has some limited capability against the low-technology threat, hence its performance is higher in the original method, where the low-technology threat has a higher weighting than the 'risk' method. The performance of the basic, intermediate and advanced platforms is not significantly different between the two methods. This is because, for the 'risk' method, the attribute weightings providing benefit against the low-technology threat are lower, but then the attribute weightings providing benefit against the guided threats are higher. This leads to a similar, if not identical overall result.
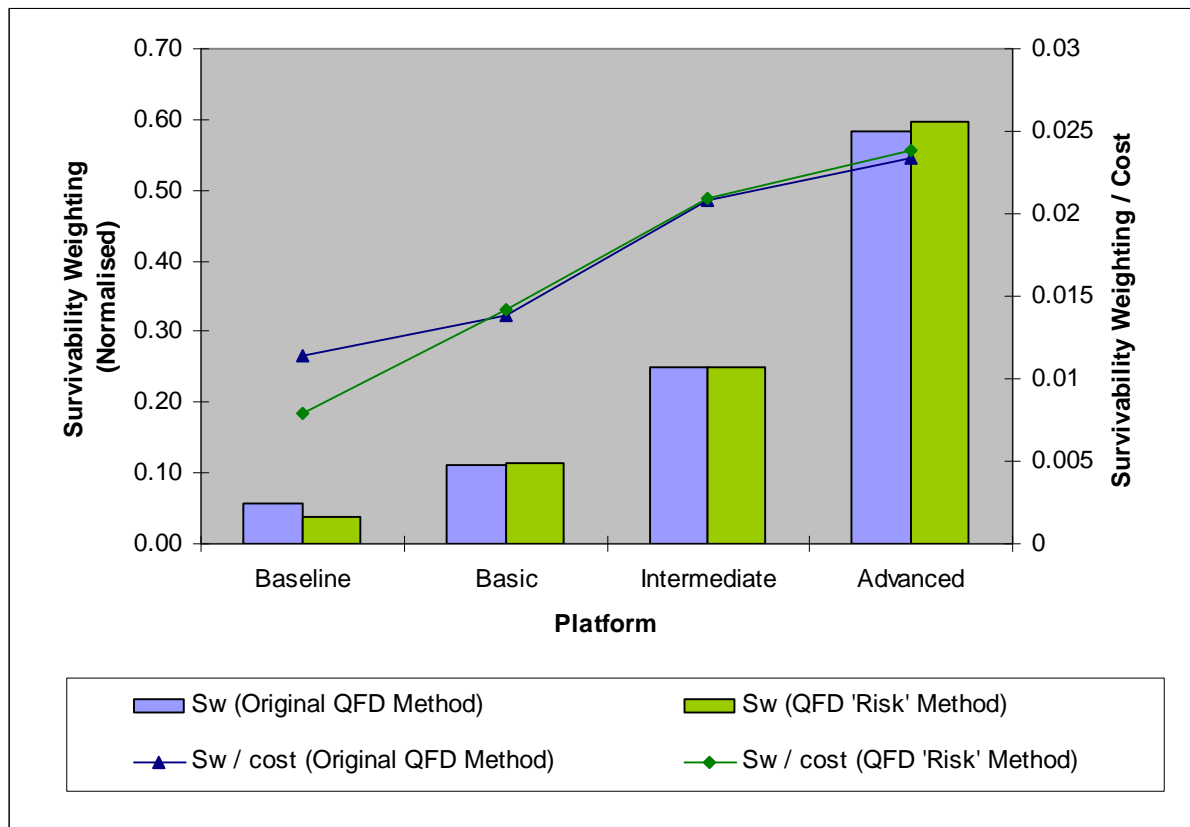
**Figure 4-14 – Normalised survivability weighting and cost effectiveness by platform.**

*Sensitivity analysis*

The two scoring schemes (0, 1, 2, 3 and 0, 1, 3, 9) were compared. Figure 4-15 compares the survivability weighting output from the two QFD methods for each of the two scoring schemes. Neither scheme changes the relative result when platforms are assessed against one another. Unsurprisingly the 0, 1, 3, 9 scheme brings out differences in better solutions more strongly than the 0, 1, 2, 3 scheme. This is clearly illustrated by the 'advanced' platform result.

The 0, 1, 3, 9 scheme is used in the literature (Cruit et al. 1993) and is judged to be 'fit for purpose' for this project. Where QFD analysis is being used to inform decisions, it is recommended that the two scoring schemes are applied when checking results. This is important when the survivability weighting is used in further analysis; for example, assessing the impact of constraints such as cost and mass.
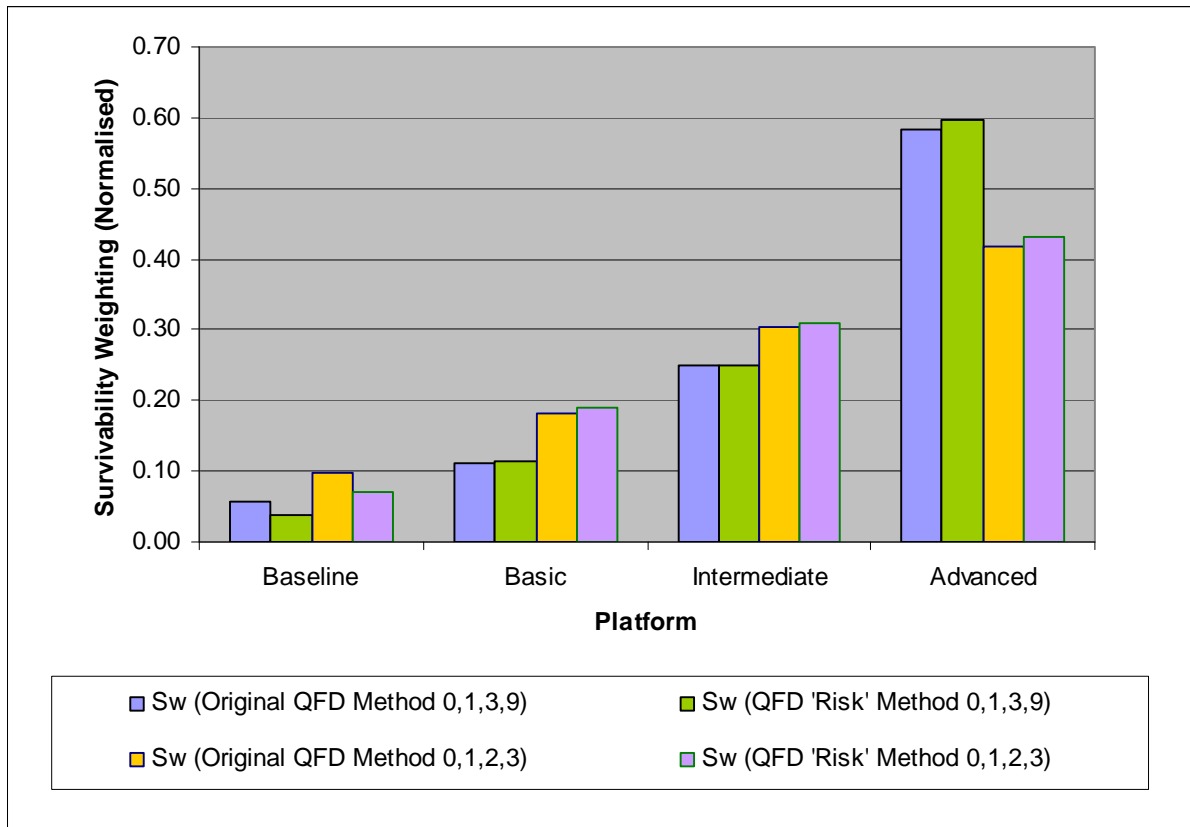
**Figure 4-15 - Sensitivity analysis of the two scoring schemes.**

### 4.6.3    Discussion

The following advantages, disadvantages and observations were made regarding the QFD methods.

*Advantages:*

- There is a good audit trail from scenarios through to survivability attributes.

- It provided a transparent process and analysis technique, i.e. it was not a 'black box'.

- Straightforward to use and understand.

- Supports an holistic approach, because the whole problem can be seen easily.

- It provides a relative score that can be used to rank the importance of survivability attributes.

- It provides a structured approach for asking the right questions and highlights important issues (including unknowns) that can be captured and analysed later in more detail.

- It provides a focus for communication that can be used to bring together different functional disciplines and stakeholders within and outside an organisation.

- It supports the capture and analysis of subjective arguments.

- The hybrid risk and QFD approach does offer some improvement over the initial QFD method. The technique is now less likely to be biased on the basis of threat proliferation alone.

*Disadvantages:*

- The matrices can be difficult to evaluate, because of the subjective arguments.

- Large matrices can result and these are resource-intensive to populate.

- There is a potential for inadvertently biasing the answer depending upon how categories are sub-divided.

- The method does not provide a 'hard' quantifiable output, e.g. a probability of survival output.

- Incorporating the platform role within the matrices is difficult, especially when a platform type may be used for a number of different roles.

*General*

The QFD method has promise at the early design stage and can help with requirement elicitation. The assumptions, questions, issues and unknowns that the method raises are as important, if not more important, than the numerical assessment itself. Because of the method's semi-quantitative nature, it would not be appropriate to use it to carry out 'hard' analysis of requirements later in the design process, as higher confidence input data becomes available.

The QFD method also has a limited potential to carry out analysis across the whole capability, such that mission effectiveness and survivability can be assessed together. Sensible grouping of up to 20 attributes and 20 user requirements should be manageable. The assessment would obviously be very 'top level' and the input data would be aggregated; however, this could be appropriate at an early design stage to support down-selection of potential solutions. Initially an influence diagram could be used to identify important attributes and interactions that could then be evaluated further using the QFD method.

The hybrid risk and QFD approach does offer some improvement over the initial QFD method. The technique is now less likely to be biased on the basis of threat proliferation alone. Care must still be taken with threat subdivision to ensure that the threat weighting and subsequent outputs are not inadvertently biased.

Further improvement could be made to the method by incorporating the platform's role or task within the first matrix (scenario-to-threats). This concept is illustrated in Table 4-7.

**Table 4-7 - Improved first matrix (scenario & role-to-threats)**

| Scenario | Role | Scenario Weighting | Threat | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Small Arms | AAA | RPG | ATGW | MANPADS | RF SAM |
| Peacekeeping | Attack | | | | | | | |
| | Find | | | | | | | |
| | Lift | | | | | | | |
| Peace enforcement | Attack | | | | | | | |
| | Find | | | | | | | |
| | Lift | | | | | | | |
| Warfighting (low tech) | Attack | | | | | | | |
| | Find | | | | | | | |
| | Lift | | | | | | | |
| Warfighting (high tech) | Attack | | | | | | | |
| | Find | | | | | | | |
| | Lift | | | | | | | |
| | | Threat Weighting, Tw | | | | | | |
| | | **Tw (normalised)** | | | | | | |

QFD is a useful tool to bring the design process together in a structured way and to focus communication. Diverse areas of the platform can be considered together potentially reducing 'stovepiping' within organisations such as the MOD, industry and other stakeholders. The QFD approach is consistent with the systems design principles outlined by the Royal Academy of Engineering (Elliot and Deasley 2007), particularly the principles of requirement definition, holistic thinking and following a systematic procedure.

## *Conclusion*

QFD is appropriate for early concept analysis and can be used across capabilities. It also has potential as a top-level capability or survivability management tool. QFD could be used to further explore important attributes and interactions that have been identified by an overall influence diagram that defines the problem space.

## 4.7 Analytical Hierarchy Process

### 4.7.1 Method

The AHP requires that a hierarchy is constructed with the top node representing the overall goal. The next level down in the hierarchy represents the attributes contributing to the goal and the lower levels further break out the sub attributes. Pairwise comparisons are made between attributes descended from a common node one level above in the hierarchy. Alternatives are scored with respect to the lowest attribute. The lowest attribute weighting is then multiplied by the performance score for each alternative. The overall priority for each alternative is calculated by summing the priorities for each criterion from which it has been assessed. See Section 3.11.5 for further background on the AHP.

An AHP survivability hierarchy was developed to be consistent with the QFD approach to enable comparison of the two methods, see Figure 4-16. The goal at the top of the hierarchy is 'helicopter survivability'. The second level in the hierarchy sets out the broad range of scenarios that helicopters are expected to operate within, i.e. to achieve helicopter survivability we need to survive when operating in each expected scenario. The third level breaks out the threat categories, i.e. to survive each scenario we need to survive any engagement with each type of threat within each scenario. The fourth level provides the survivability attributes, i.e. how important is each attribute in defeating each threat category. The fifth level contains the alternative platform configurations under consideration, i.e. how important / effective is each alternative at implementing each attribute.

At each level the elements are ranked in importance of achieving the element above. For example, in order to survive (level one), how important is 'peace keeping' compared with 'peace-enforcement?' and how important is 'peace enforcement' compared with 'warfighting in a low technology threat environment?' and so on. Once the AHP is complete, then the hierarchy can be populated with weightings for each element and the different platforms can be assessed.

It was established that a high number of judgements would be required to populate the hierarchy set out in Figure 4-16. To keep the assessment manageable the hierarchy was populated for one scenario only (survive warfighting in a low technology threat environment) and some survivability attributes were combined, as shown in Figure 4-17. The survivability attributes were reduced in number from 12 to 9 by combining MDSS, DNAE and NOE into 'tactical flight' and combining fire / explosion suppression and crashworthiness together.

Figure 4-18 shows part of the survivability hierarchy to illustrate the method further and the large size of the overall hierarchy. The pairwise comparisons were evaluated using the AHP scale shown in Table 4-8.

**Table 4-8 - AHP scale.**

| Attribute | Relative importance | AHP Scale |
|---|---|---|
| A | Extreme | 9 |
| | Very strong | 7 |
| | Strong | 5 |
| | Moderate | 3 |
| | Equal | 1 |
| | Moderate | 1/3 |
| | Strong | 1/5 |
| | Very strong | 1/7 |
| B | Extreme | 1/9 |

*Example calculations*

Table 4-9 shows an example threat matrix. The cells above the leading diagonal are populated by evaluating each pairwise comparison. The reciprocals then placed below the leading diagonal (shaded cells). This square matrix is then evaluated to find the eigenvalue and corresponding principal eigenvectors.

**Table 4-9 - Example threat matrix.**

| | Small arms | AAA | RPG | ATGW | MANPADS |
|---|---|---|---|---|---|
| Small arms | 1 | 1 | 2 | 5 | 1/7 |
| AAA | 1 | 1 | 3 | 7 | 1/7 |
| RPG | 1/2 | 1/3 | 1 | 5 | 1/7 |
| ATGW | 1/5 | 1/7 | 1/5 | 1 | 1/9 |
| MANPADS | 7 | 7 | 7 | 9 | 1 |

The eigenvalue and eigenvectors can be calculated using a numerical computation application such as Scilab™ or MATLAB®.

The largest eigenvalue: 5.405

Corresponding eigenvectors: -0.1887, -0.2278, -0.1208, -0.0453, -0.9465

The principal eigenvector values are then normalised so that the elements sum to unity. The normalisation constant is the sum of the elements:

(-0.1887) + (-0.2278) + (-0.1208) + (-0.0453) + (-0.9465) = -1.529

The threat priorities are then:

Small arms priority = -0.1887 / -1.529 = 0.1234

AAA priority = -0.2278 / -1.529 = 0.1490

RPG priority = -0.1208 / -1.529 = 0.0790

ATWG priority = -0.0453 / -1.529 = 0.0296

MANPADS priority = -0.9465 / -1.529 = 0.6190

This process for evaluating priorities and weightings is repeated for each matrix.

Applications to manage the whole assessment process including the hierarchy, matrices, calculations and processing of results are available, for example Expert Choice™. See Ishizaka and Labib (2009) for an example of the AHP using Expert Choice™.
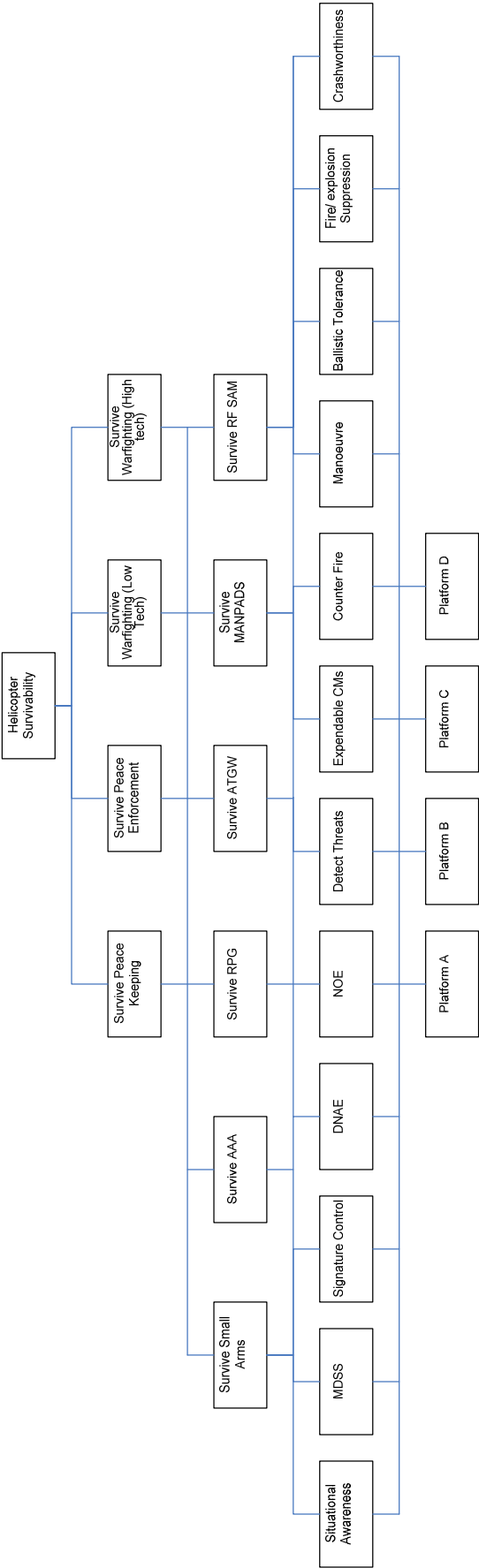
**Figure 4-16 – A survivability hierarchy consistent with the QFD example.**
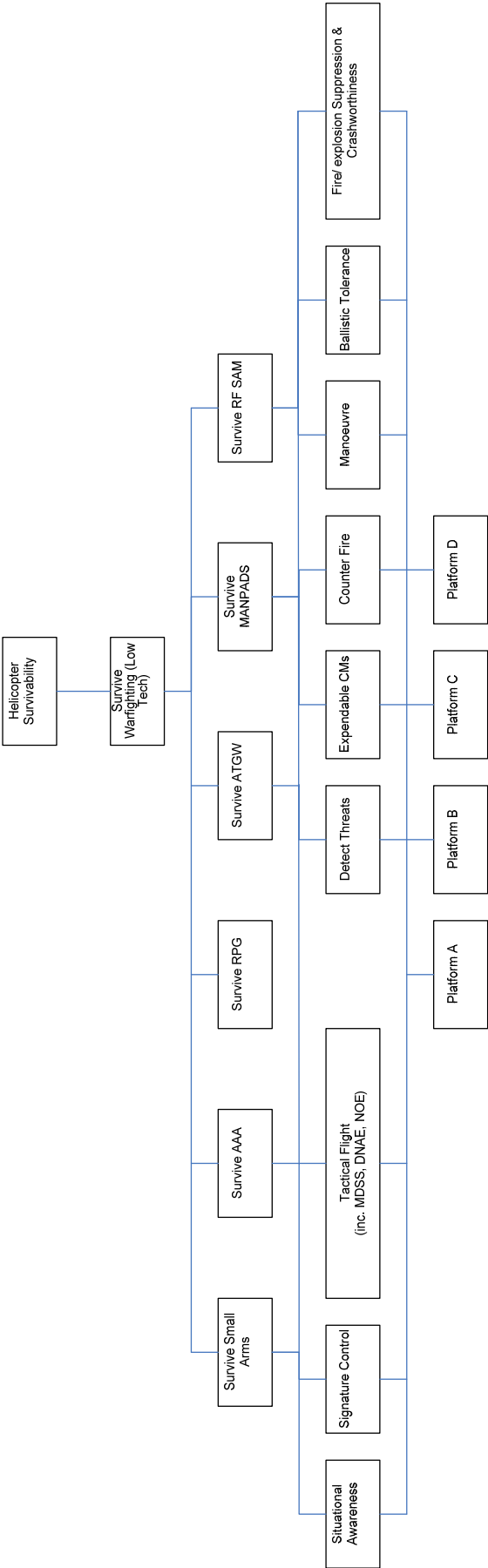
**Figure 4-17 - Survivability hierarchy used in the AHP example.**
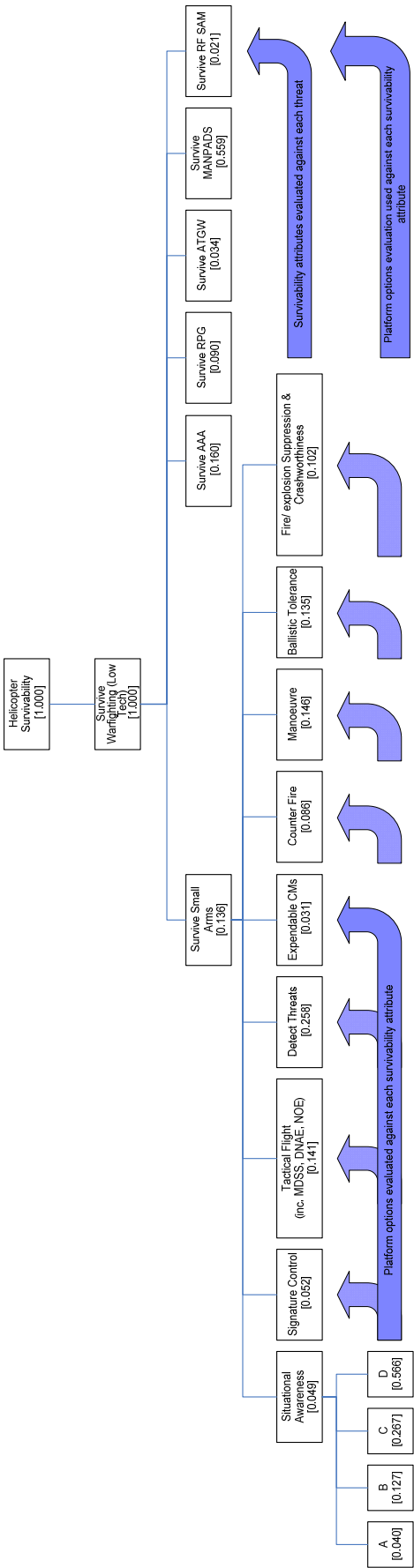
**Figure 4-18 – Partially expanded survivability hierarchy showing example weightings.**

### *4.7.2    Results*

*Evaluation of the threat matrix*

The first matrix compared the relative importance with respect to 'survive warfighting' of each threat using pair-wise comparisons. For example, how important is 'survive small arms' compared with 'survive AAA?' A score from one ninth to nine was given according to the scale shown in Table 4-10.

This process was repeated for each pairwise comparison until all 15 judgements were made. Some pairwise comparison examples:

How important are small arms compared with a MANPADS? A MANPADS is very strongly more important within the low technology warfighting scenario, hence a score of 1/7. This comparison is shown in Table 4-10.

How important are small arms compared with an RF SAM? Small arms are significantly more important within the low technology warfighting scenario, hence a score of 9.

**Table 4-10 – Example pairwise comparison for small arms and MANPADS within a low technology warfighting scenario.**

| Attribute | Relative importance | AHP scale |
|-----------|---------------------|-----------|
| Small arms | Extreme | 9 |
| | Very strong | 7 |
| | Strong | 5 |
| | Moderate | 3 |
| | Equal | 1 |
| | Moderate | 1/3 |
| | Strong | 1/5 |
| | Very strong | 1/7 |
| MANPADS | Extreme | 1/9 |

The resulting threat matrix is shown in Table 4-11.

**Table 4-11 - Threat matrix.**

|  | Small arms | AAA | RPG | ATGW | MANPADS | RF SAM |
|---|---|---|---|---|---|---|
| Small arms | 1 | 1 | 2 | 5 | 1/7 | 9 |
| AAA | 1 | 1 | 3 | 7 | 1/7 | 9 |
| RPG | ½ | 1/3 | 1 | 5 | 1/7 | 7 |
| ATGW | 1/5 | 1/7 | 1/5 | 1 | 1/9 | 3 |
| MANPADS | 7 | 7 | 7 | 9 | 1 | 9 |
| RF SAM | 1/9 | 1/9 | 1/7 | 1/3 | 1/9 | 1 |

*Evaluation of the survivability attributes*

Six matrices of 36 pairwise comparisons were then completed to consider all of the survivability attributes against each threat (216 pairwise comparisons in total). One of these example matrices is shown in Table 4-12.

**Table 4-12 - Relative importance of survivability attributes with respect to small arms.**

|  | SA | SC | TF | DT | EC | CF | M | BT | FEC |
|---|---|---|---|---|---|---|---|---|---|
| Situational awareness (SA) | 1 | 1 | 1/3 | 1/5 | 1 | 1/3 | 1 | 1/3 | 1/3 |
| Signature control (SC) | 1 | 1 | 1/2 | 1/3 | 3 | 1/3 | 1/3 | 1/3 | 1/3 |
| Tactical flight (TF) | 3 | 2 | 1 | 1 | 3 | 3 | 1 | 1 | 1 |
| Detect threats (DT) | 5 | 3 | 1 | 1 | 5 | 5 | 3 | 3 | 3 |
| Expendable countermeasures (EC) | 1 | 1/3 | 1/3 | 1/5 | 1 | 1/5 | 1/5 | 1/5 | 1/3 |
| Counter fire (CF) | 3 | 3 | 1/3 | 1/5 | 5 | 1 | 1/3 | 1/3 | 1 |
| Manoeuvre (M) | 1 | 3 | 1 | 1/3 | 5 | 3 | 1 | 1 | 3 |
| Ballistic tolerance (BT) | 3 | 3 | 1 | 1/3 | 5 | 3 | 1 | 1 | 1 |
| Fire/explosion & crashworthiness (FEC) | 3 | 3 | 1 | 1/3 | 3 | 1 | 1/3 | 1 | 1 |

*Evaluation of the platform options*

At the next level in the hierarchy, the performance of each platform option was evaluated against each survivability attribute (54 pairwise comparisons in total). See Table 4-13 for an example with respect to one attribute: situational awareness.

**Table 4-13 - Comparison of the relative performance of platform options with respect to situational awareness.**

|  | Platform A | Platform B | Platform C | Platform D |
|---|---|---|---|---|
| Platform A | 1 | 1/5 | 1/7 | 1/9 |
| Platform B | 5 | 1 | 1/3 | 1/5 |
| Platform C | 7 | 3 | 1 | 1/3 |
| Platform D | 9 | 5 | 3 | 1 |

*Comparison of the AHP and QFD methods*

Table 4-14 and Figure 4-19 compare the threat weighting results from the AHP with the QFD risk method. Only the low technology warfighting scenario within the QFD method was compared with the AHP example to provide a fair test. Table 4-14 also shows that the weightings for the QFD low technology warfighting scenario and QFD 'Risk' all scenarios are very similar. This suggests that overall weightings are still representative of individual scenarios and implies a robustness of the QFD approach.

**Table 4-14 - Threat weightings for a warfighting (low technology) scenario for the AHP and QFD 'risk' methods and a comparison against all scenarios using the QFD 'risk' method.**

| Threat | AHP method (warfighting low tech only) | QFD 'risk' method (warfighting low tech only) | QFD 'risk' method (all scenarios) |
|---|---|---|---|
| MANPADS | 0.56 | 0.41 | 0.39 |
| AAA | 0.16 | 0.14 | 0.16 |
| Small arms | 0.14 | 0.14 | 0.12 |
| RPG | 0.09 | 0.14 | 0.14 |
| ATGW | 0.03 | 0.05 | 0.03 |
| RF SAM | 0.02 | 0.14 | 0.16 |
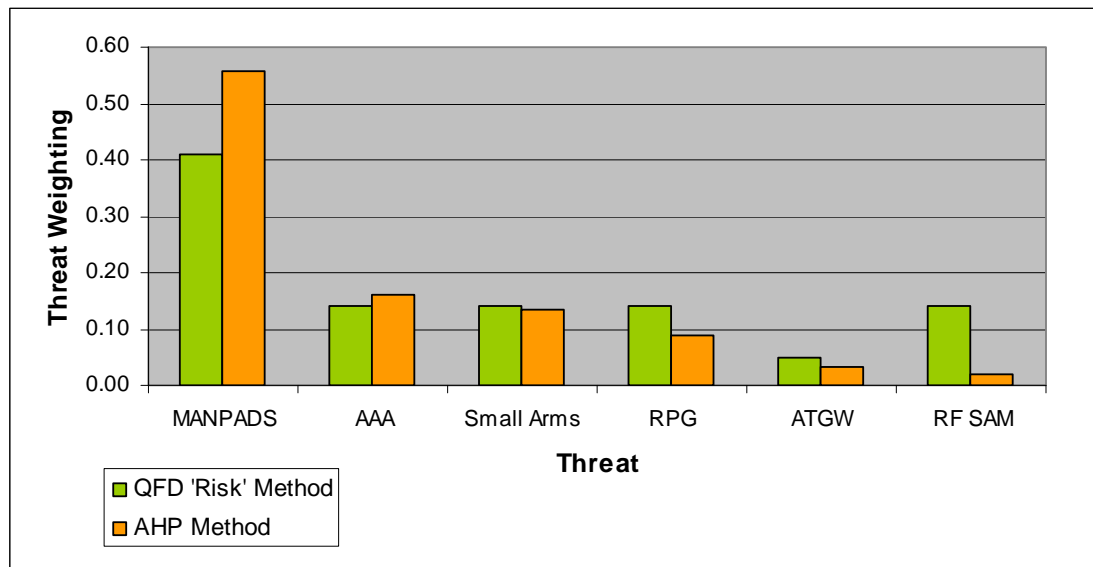
**Figure 4-19 - Threat weighting for a warfighting (low technology) scenario using the AHP and QFD 'risk' methods.**

These results show that the methods provide similar results, except where the AHP method provides a significantly higher MANPADS weighting and much lower RF SAM weighting. These differences are a result of the QFD 'Risk' approach incorporating a consequence score, so raising the weighting of less likely, but more lethal threats. The RF SAM score is sensitive to the likelihood score as it has a high consequence score (9) and the risk is the product of the two. Some would consider that the threat in a low-tech scenario by definition would imply a score of zero for RF threats, in which case the RF SAM score would be zero.

Table 4-15 and Figure 4-20 compare the platform survivability weightings for the AHP and QFD 'Risk' methods.

**Table 4-15 - Platform survivability weightings for AHP and QFD 'risk' methods.**

| Platform | QFD 'risk' method | AHP method |
|----------|-------------------|------------|
| Baseline | 0.04 | 0.04 |
| Basic | 0.11 | 0.13 |
| Intermediate | 0.25 | 0.27 |
| Advanced | 0.60 | 0.57 |
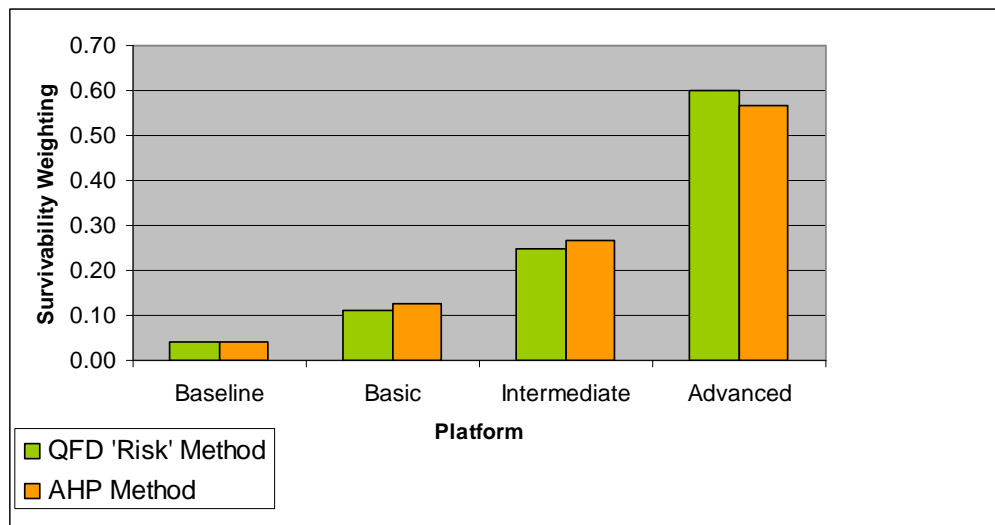
**Figure 4-20 - Platform survivability weightings for AHP and QFD 'risk' methods.**

The overall platform survivability weighting results were similar for both the QFD 'Risk' and the AHP methods, implying robustness. The AHP method provides some robustness in terms of consistency checking; however, it is considerably more time-consuming to populate.

### *4.7.3*   *Discussion*

The following advantages, disadvantages and observations were made regarding the AHP method.

*Advantages:*

- The method is good at deriving robust weightings.

- The method provides a score to check the judgements for consistency.

*Disadvantages:*

- The method requires a high number of judgements. In the simple example only one scenario was considered, but 285 judgements were required. To compare directly with the QFD method, 1140 judgements would have been required.

- It is time consuming to populate the matrices.

- There is less transparency compared with QFD because of the requirement for matrix calculations.

*General:*

The high number of judgements required by AHP and the time taken to provide them, reduces the usefulness of this method for this particular application. The QFD and AHP results were broadly similar, suggesting that the AHP method does not provide a significant advantage compared with the simpler and more transparent QFD method.

The pairwise comparison part of the AHP method could, however, be used to help derive the initial scenario weightings to feed into the first QFD matrix. This would help to provide greater robustness of the QFD method.

### 4.7.4    *Conclusion*

The project did not develop this particular application of the AHP any further because of the large number of judgements required and apparent lack of advantage over the simpler and more transparent QFD method. Sensitivity analysis of the AHP results was not conducted because of the fundamental limitations of the method and the decision to cease development.

## 4.8    Probabilistic methods

### 4.8.1    *Introduction*

The author found that the principles of safety management, outlined in Defence Standard 00-56 (Ministry of Defence 2007c and 2007d), could be applied to the survivability problem (Law et al 2006). These principles included taking a risk assessment approach to reduce the survivability risks to as low as reasonably practicable (ALARP). The study also recommended the development of a survivability key user requirement (KUR) incorporating objective and threshold targets for survivability that could be derived based upon a survivability assessment. The threshold target would be equivalent to the current operational survivability standard and the objective target would be a survivability standard theoretically achievable with 'state of the art' technology. This approach is consistent with Defence Standard 00-56, which states that ALARP tolerability criteria should be defined on the basis of some level of assessment. The difference between the targets could be equated to the boundaries of what is a broadly acceptable risk and unacceptable risk, as shown in Figure 4-21. These boundaries can then be mapped to a theoretical probability of survival or loss rate.

Considering the ALARP triangle, if a new threat or mission took the platform into the 'red,' the 'intolerable risk' region, then a survivability upgrade would need to be investigated. Alternatively, some other method of defeating the threat or conducting the mission would need to be found. It is recognised that operational commanders constantly assess the operational risks versus the benefits. Highly important missions may justify higher levels of

survivability risk to be taken. At the force level, it may be worth limited numbers of platforms taking higher risk, to protect the larger force, so maximising survivability at the force level. Understanding survivability risk levels helps commanders and the acquisition community to make their decisions.



**Notation:** Ps Probability of survival
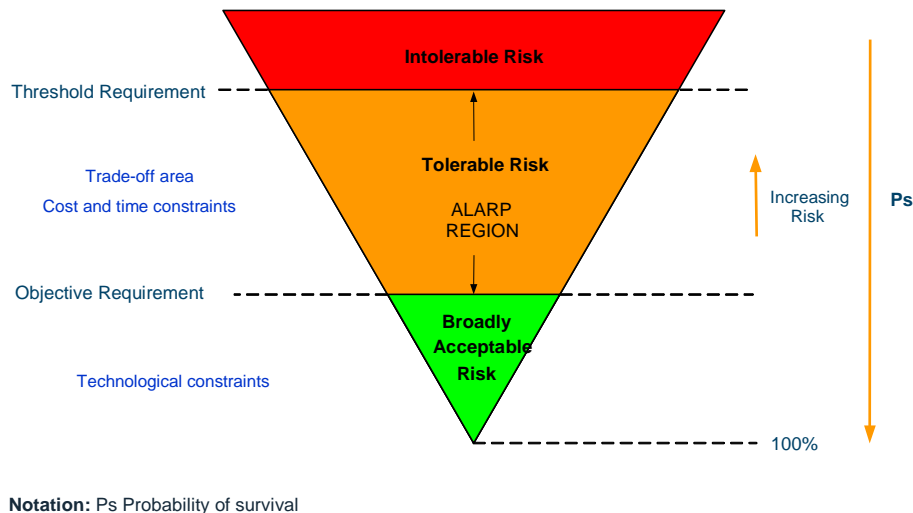
**Figure 4-21 - ALARP triangle applied to survivability**

The principles identified by the Nuclear Safety Directorate in their ALARP checklist (Vaughan 2002) can also be applied to the survivability domain. One of these principles is that quantitative ALARP requires that the reduction in risk is estimated. A probabilistic survivability model would potentially provide a good framework and quantitative method for this estimation process. Furthermore, probability of survival is a good candidate metric and would support quantifiable objective and threshold targets within URDs that could be flowed down into SRDs. The QFD and AHP methods developed previously were semi-quantitative, and therefore, not able to derive probability of survival. A new model was therefore required to satisfy the requirement for a probabilistic quantitative approach, hence the development of the probabilistic fault-tree approach outlined in the next section.

Another ALARP principle is that where there are high levels of uncertainty, a 'precautionary' approach should be adopted. The 'precautionary principle' involves 'erring' on the side of caution with respect to likelihood and consequence (HSE 2002). Applying this approach to the problem suggests that where input data are uncertain, the survivability assessment should assume 'worst case' until better data become available. It is recognised that whilst the worst case scenarios should be considered, it may not be possible to design a system to meet the associated requirements with an acceptable level of risk or cost. In these scenarios it may be more appropriate to conduct the mission in another way. On operations it would be the responsibility of the operational commander to make informed decisions taking

into account survivability assessment information amongst other factors affecting the mission.

### *4.8.2 Method*

#### *Probabilistic fault-tree concept*

Given the probabilistic nature of the survivability problem and the similarity of the concepts of a hazard and a threat, the author identified the potential application of using a fault-tree approach to model survivability. The probabilistic fault-tree analysis approach had not been used before to analyse integrated survivability in the complete sense of the definition, although some vulnerability / lethality tools do use a similar approach to model the kill chain, for example INTAVAL. The concept was developed by the author and version 1.0 of the Integrated Survivability Assessment Model (ISAM) was created. A colleague developed the associated software code.

#### *ISAM*

ISAM structures the helicopter survivability systems within a functional breakdown, to determine a probability of platform survival, based upon a defined threat environment and mission set. The survivability chain starts with 'what is the probability of encountering a threat?' Given a threat encounter, 'what is the probability of an engagement?' Given an engagement, 'what is the probability of a hit?' Given a hit, 'what is the probability of a kill?' Evaluating this sequence gives the probability that the platform is killed, $P_k$. Probability of survival is the reciprocal of this, i.e. $1 / P_k$.

The modelling framework is flexible enabling the user to develop their own system 'fault tree'. This allows the user to define the system of interest, for example it could be a helicopter or another air vehicle. The ISAM top-level structure is illustrated with example technologies in Figure 4-22 (Law et al. 2007).

**Figure 4-22 - ISAM Structure.**

*Fault-tree structure*

The results from ISAM are calculated using a probabilistic approach which can either be user defined, via the design window, or the user can import a default design. The design uses probability operations, such as AND, OR and NOT and can be stored in the ISAM project format.

ISAM will calculate the appropriate probability function based on any user-defined design using the following logic function types:

- AND is the standard probable AND function $(A \times B \times C)$ It must have 2 or more inputs.

- OR is the standard probable OR function $1 - ((1-A) \times (1-B) \times (1-C))$

   It must have 2 or more inputs.

- NOT is the standard probable NOT function $(1-A)$. It must have one input.

- MIN selects the minimum of any number of input values. It must have 2 or more inputs.

- MAX selects the maximum of any number of input values. It must have 2 or more inputs.

- INPUT functions require the user to input probability values in the threat laydown stage. These cannot have any inputs. It is these input functions that will be used when scoring a platform.

The calculations involved at the different assessment levels are detailed below. The entire ISAM design is calculated against each threat in the threat list using the scores entered by the user and the functions as created in the design. For example, in Figure 4-23; result = A OR B $= 1 - \left( (1 - A)(1 - B) \right)$.
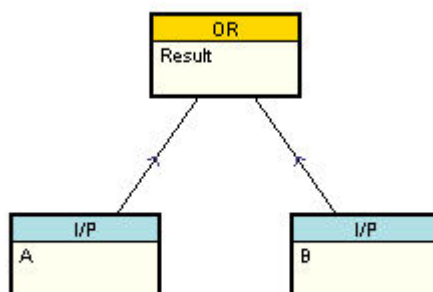


**Figure 4-23 - ISAM OR Function.**

This threat level probability of survival does not take into account the rate of encounter. It is a probability of survival given an encounter.

*Mission-level equations*

Mission-level survivability considers the likelihood of each threat being present in a mission i.e. the probability of survival includes the rate of encounter. The threat-level probability of survival is combined with the rate of encounter using the Poisson approximation i.e.

$$P(S) = e^{-qr}$$

where q = 1-p, p = threat level probability of survival and r = the rate of encounter.

ISAM calculates a 'sequential mission survivability', which is the probability of surviving all of the threats in a mission. The mission survivability is calculated by considering:

'Probability of surviving threat 1 in the mission' AND probability of surviving threat 2 in the mission' AND etc...

i.e. the probability of surviving all threats = $P_{sth1} \times P_{sth2} \times P_{sth3} \times \cdots$ etc

where $P_{sth}$ = Probability of surviving the threat.

*Scenario-level equations*

ISAM calculates a 'sequential scenario survivability', which is the probability of surviving all of the defined missions. This takes into account the numbers of each mission over the platforms lifetime, as detailed in the missions pages. The scenario survivability is calculated by considering:

'Probability of surviving mission 1' AND probability of surviving mission 2' AND etc...

i.e. The probability of surviving all missions is then:

$$P_{sm1}^{N_{m1}} \times P_{sm2}^{N_{m2}} \times P_{sm3}^{N_{m3}} \times \ldots$$

where

$P_{sm}$ = Probability of surviving the mission

$N_m$ = Number of missions

*Platform-loss equations*

The probability of survival output from ISAM is a theoretical result, not a 'real' number and is based upon the input data. For the purposes of understanding the output in terms of an equivalent loss rate, the following equations can be used:

Percentage loss = $(1 - P(S)) \times 100$

Number of predicted Losses = $(1 - P(S)) \times Fleet\ Size$

Missions until 90% Loss = $\dfrac{-1}{\log P(S)}$

*Technical evaluation*

The performance of different equipment is evaluated by subject matter experts who take account of trials' results, modelling and expert judgement. A standard questionnaire format was developed and used to capture information such as: name of evaluator, system performance, uncertainty, evidence source (including references), assumptions, comments and caveats. The assumptions included information about the proportion of night versus daytime missions, terrain type, aircraft altitude and weather conditions. These data are stored in a spreadsheet as part of the audit trail for the ISAM result.

*Evaluating rate of encounter*

The research developed a process for evaluating the rate of encountering threats. These data were then input into ISAM.

Military advisors first generate a mission set for the platform under consideration taking into account the platform role within the context of the defence scenarios (first blue box in Figure 4-22). Military advisors and Dstl specialists consider the threats in each mission and design a possible threat scenario. The mission set is ratified by a military judgement panel (MJP) either prior to the MJP being convened or at the start of the convened MJP. The MJP

consists of 'current' operators and stakeholders, for example: requirements managers, JHC, AWC, MWC and the Directorate of Army Aviation (DAAvn).

The MJP is held to establish a likelihood of encounter. During the MJP each scenario and mission is briefed to the operators. The operators then plan the mission including flight path and flight profile and tactics. This plan is then examined against the previously defined threat laydowns and comments on how the plan would change given threat engagements are captured. This exercise provides a useful lead into the threat scoring element where threat categories are scored based upon the question: 'How likely is the threat to have the opportunity and intent to engage? The question does not ask how capable the threat is - this is a function of the helicopter and is dealt with later on in ISAM.' This question is evaluated based on a scale of 0 to 6, 0 being the threat will not be in the scenario, 6 being you are likely to have multiple encounters with a threat in this scenario. This is conducted for broad threat categories such as MANPADS or AAA. These data are collated in a spreadsheet and then information on the proliferation of threats is used to weight the MJP scores between specific threats (e.g. SA-7, SA-14) and a 'rate of encounter' is derived. These values are calculated by a spreadsheet and then transferred into ISAM. This spreadsheet is retained as part of the audit trail of a project.

The threat list can either be user defined or the default list can be imported by the user. Threat lists can be exported from the project file in the form of an ISAM database file, which is suitable for import into other ISAM projects.

The threat environment is dependent on the use of the platform; it would be possible to have 100% survivability simply by not using the platform in a threatening environment. Similarly, a heavily protected platform could have a worse probability of survival than a platform with no protection, simply because it is more likely that it will be used in a threatening environment. The model therefore needs to consider a realistic set of missions that the platform being assessed is likely to undertake. It also needs to consider where the platform will be deployed. Furthermore the missions and scenarios need to be prioritised and weighted in accordance with how often they will be carried out.

*Generating the rate of encounter in detail*

A military judgement panel (MJP) will generate a number of missions for the platform being assessed. For ease, the example below shows three missions that take place in the same area using different routes. The MJP will also generate the threat scenarios for the area of operation. The example in Figure 4-24 shows two main battle tanks MBT1 and MBT2, one armoured fighting vehicle AFV1, two infantry soldiers INF1 and INF2 and one air defence gun AD1.
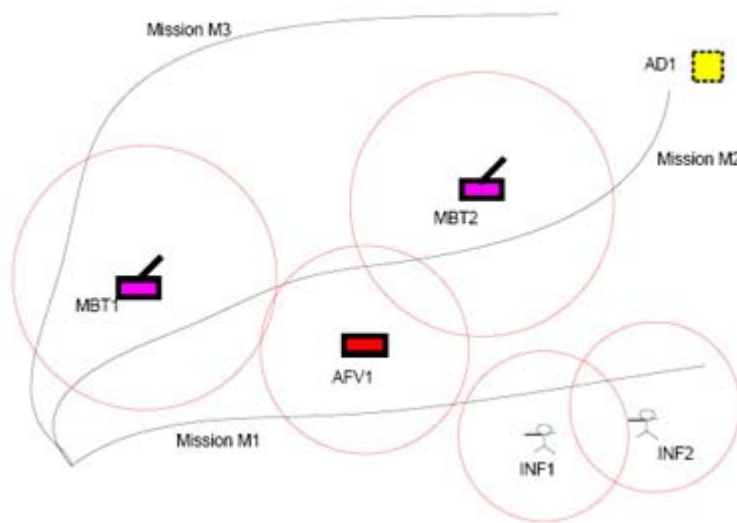
**Figure 4-24 - Example threat scenario.**

Considering the maximum engagement range of each threat platform (red circles):

- During mission M1 the platform encounters one AFV and two infantry soldiers;

- During mission M2 the platform encounters two MBTs and one AFV (AD1 will be considered later);

- During mission M3 the platform encounters one MBT.

The number of encounters is summarised in Table 4-16.

**Table 4-16 - Number of encounters.**

| Threat / mission | M1 | M2 | M3 |
|------------------|----|----|----|
| MBT | 0 | 2 | 1 |
| AFV | 1 | 1 | 0 |
| Infantry | 2 | 0 | 0 |

In practice, it may not be known how many encounters will occur or where threats are located, so consider the situation where mission M2 takes the helicopter into range of an air-defence gun. The MJP assesses that there is only a low probability, say 20%, that this threat will be present. So, the MJP session now needs to score not only the quantity of encounters, where these are likely, but also the probability of encountering threats that are less certain. An MJP scale was developed, as shown in Table 4-17.

**Table 4-17 - MJP scoring scale.**

| Score | Rate | Meaning |
|---|---|---|
| 6 | > 1 / 1 | Multiple encounters (more than once per mission) e.g. Multiple threat systems are the target. |
| 5 | 1 / 1 | Encounter is likely (every mission) e.g. Threat system is target. |
| 4 | 1 / 2 | High chance of encounter (1 in 2 missions) e.g. Threat system in target area. |
| 3 | 1 / 10 | Medium chance of encounter (1 in 10 missions) e.g. Threat system in theatre and potential transit threat. |
| 2 | 1 / 20 | Low chance of encounter (1 in 20 missions) e.g. Threat in theatre but normally dealt with by another asset. |
| 1 | 1 / 100 | Very low chance of encounter (1 in 100 missions) e.g. Threat is in theatre but not in scenario. |
| 0 | Never | No encounter with this threat in this mission e.g. Threat not in theatre. |

Rate values in between the scoring categories can also be used. Score 6 can be further evaluated separately from the MJP, with the aid of a military advisor, to assign a specific number of encounters. For the example MJP session the scores are outlined in Table 4-18.

**Table 4-18 - Example encounter rates.**

| Threat / mission | M1 | M2 | M3 |
|---|---|---|---|
| MBT | 0 | 2 | 1 |
| AFV | 1 | 1 | 0 |
| Infantry | 2 | 0 | 0 |
| AD | 0 | 0.2 | 0 |

During mission M2 there is an encounter with two MBTs, one AFV, and a 20% chance of an encounter with an air defence gun, AD1. Let us assume that both the MBTs are fitted with a gun and may have a SAM, the AFV has a gun and a SAM and the infantry may have a SAM or guns and the AD unit is a gun only. These assumptions are summarised in Table 4-19.

**Table 4-19 – Weapon assumptions.**

| Threat | Weapons | |
|---|---|---|
| | **Gun** | **SAM** |
| MBT | Yes | Maybe |
| AFV | Yes | Yes |
| Infantry | Maybe | Maybe |
| AD | Yes | No |

The "maybe" category provides an opportunity to use ORBAT information, combined with historical analysis and expert judgement, to provide a probability that the threat platform has, and will use, each of the specific weapons. In this simple example we could assume that one quarter of the MBTs that we encounter (in this scenario) will have a SAM in addition to its main gun. The infantry soldier may carry a gun OR a SAM and from historical analysis and ORBAT data we can ascertain that there is a 20% chance that he will have a SAM, so in the table above we can now enter these values in terms of probabilities.

Care must be taken when considering whether these are mutually exclusive or not. In the case of the infantry, we decide he must only have one or the other weapon. The total score in this case must add up to 1. The MBT, however, may have one or both weapons and may choose to use one or the other or both at the same time. The updated rate of encounters for each weapon by specific platform type are summarised in Table 4-20.

**Table 4-20 – Updated rate of encounter.**

| Threats | Weapons | |
|---|---|---|
| | **Gun** | **SAM** |
| MBT | 1 | 0.25 |
| AFV | 1 | 1 |
| Infantry | 0.8 | 0.2 |
| AD | 1 | 0 |

The result from Table 4-20 can then be combined with the mission scoring (using the AND function) to give an overall rate of encounter of the weapon on that platform, r;

i.e. rate of encounter of the weapon r = (rate of encounter of weapon given that the platform has been encountered) * (rate of encounter of the platform).

So the overall rate of encounter, r, is given in Table 4-21.

**Table 4-21 - Rate of encounter by mission.**

| Platforms | Weapons | r | | |
|-----------|---------|------|------|------|
| | | M1 | M2 | M3 |
| MBT | Gun | 0 | 2 | 1 |
| | SAM | 0 | 0.5 | 0.25 |
| AFV | Gun | 1 | 1 | 0 |
| | SAM | 1 | 1 | 0 |
| Infantry | Gun | 1.6 | 0 | 0 |
| | SAM | 0.4 | 0 | 0 |
| AD | Gun | 0 | 0.2 | 0 |

*Generating probability of survival*

Now that we have a rate of encounter, r, and the unweighted probability of survival, p, we can now generate a probability of survival, P(S) using the formula:

$$P(S) = e^{-r(1-p)}$$

See Appendix F for a derivation of this formula.

*Assumptions and limitations*

The main limitation with the method is derivation of suitable input data. Many of the data are estimated based upon expert judgement, so the generated output data should not be used to try and quantify actual loss rates in a 'real world' environment. The output is a comparative measure to be used to compare different platform options (Law et al 2007).

Rate of encounter is a significant driver, which will change under real-world operational circumstances; hence, another assumption is that the probability of encountering threats data is reasonably valid. The other limitations of ISAM are:

- Only single platforms are considered.

- Multiple threat engagements are not covered by default, although specific combinations can be added as a separate 'threat' on the threat list.

- Recoverability is not considered.

- Third party systems (e.g. off-board jamming) are not currently considered.

*Model and data verification*

Verification checks that a model is consistent with its specification and fulfils its intention. The following procedures are necessary for verification of a model:

- Management of the specification, as this is the benchmark against which the model system is compared.

- Testing of individual components as they are added to the model.

- System testing of the model, as each new model component is added.

- A documented test plan to cover the above activities.

The following verification activities were conducted:

- Expert mathematical review of the probability of survival formula.

- Manually checking the model and updates using test data and a spreadsheet.

- Providing the model and documentation to a user with no prior knowledge of ISAM to check that the model and documents are 'fit for purpose.'

- Comparison with other models. Identical data were input into ISAM and the Land Systems Integrated Survivability Analysis and Assessment Code (ISAAC) to check for consistency.

- Probability of encounter was reviewed and changed to rate of encounter. MJP scoring was developed to incorporate a scoring system for multiple encounters and a poisson approximation to combine P(s) and P(e).

- Mathematical review recommended that P(s) and the logic function AND was used to combine P(s) over all the threats and missions. If this resulting probability was too small, then the missions should be calibrated against known mission results.

*Model and data validation*

The validation of the model was assessed against three categories:

- Input data.

- Model processes.

- Model outputs.

The following validation activities were conducted:

- Scientific and technical review by subject matter experts.

- Military judgement panels provided feedback on the processes used in the assessment and military advisors have been involved in reviewing this input data.

- Independent review from Director General Scrutineering and Analysis (DG(S&A)).

- Independent technical review from a senior subject matter expert from another domain.

- Data from Vietnam were used to calibrate probability of survival by considering the number of losses compared to the number of sorties (Law and Wells 2005). Also the number of RAF losses resulting from accidents gave a bench-mark figure for the number of losses expected. This has since been used to compare with all the results from ISAM, to provide some calibration.

- The Vietnam data were again used to calibrate probability of survival but in more detail than before as it considered different types of roles such as lift, attack and find. Again, this has been used to compare with all the results from ISAM since to provide some calibration (Law 2005).

- For all projects for which ISAM has been used, the data collected for the design inputs has been provided by subject matter experts who have used validated models and trials results to derive the input data where possible.

Whilst it is an aspiration to be able to validate ISAM with real life data, in reality the real life data set is not large enough. ISAM is validated to level 1 (i.e. validation by review) for combined operational effectiveness investment appraisal (COEIA) studies. Validation against real events (i.e. level 2 validation) is not fully possible because of a lack of real event data, although some aspects have been completed (Law et al 2007).

### 4.8.3 Results

ISAM can be used to compare different platform options, highlight weaknesses in survivability for a given platform and to carry out balance of investment analysis to inform trade-off decisions throughout the acquisition process. ISAM could also help to inform research objectives and priorities. The rotorcraft fault-tree structure has been aligned with the functional nature of a generic survivability systems requirement document to support the acquisition process, including the integrated test evaluation and acceptance (ITEA) process.

ISAM has been mathematically verified and has undergone limited validation. It was found to adopt a sound structure and approach. As a relative survivability assessment model it is valid; however, limitations with the input data and associated assumptions prevent it from

quantifying actual 'loss rates.' It provides an estimate of survivability risk, based upon the available input data.

### 4.8.4 Discussion

The following advantages, disadvantages and observations were made regarding the ISAM method.

*Advantages*

- It provides a quantitative estimate of risk based upon the input data.

- It is consistent with and supports a risk assessment and ALARP approach.

- It has a comprehensive verification record.

- It is 'fit for purpose' for relative survivability assessments.

*Disadvantages*

- There is limited input data availability in some instances.

- Stakeholders can have a perception that the probability of survival output is a 'real' number or they find the output difficult to understand.

- The probability of survival output can look very similar between options, however this is still a real discriminator and can equate to very large differences in loss rates over the duration of a campaign.

*Best practice*

There has been significant work across Dstl in the area of integrated survivability modelling. As a result of sharing this research methodology, the ALARP approach is now being used across the land and maritime domains. Collaboration on integrated survivability models has assisted Dstl Land Battlespace Systems Department in their development of the Integrated Survivability Analysis and Assessment Code (ISAAC) and Dstl Naval Systems Department's development of the Maritime Integrated Survivability Simulation (MISSION) to analyse specific domain questions.

*Application of the survivability methodology*

The survivability methodology and ISAM were taken forward to develop the survivability KUR for an acquisition programme, including objective and threshold targets. The methodology was also used to help to optimise the survivability design by quantifying the relative performance of different survivability options against the mission set. In practice, a number of advantages with the approach were found:

- A methodical, auditable and repeatable method was demonstrated.

- The structured approach to the derivation of representative scenarios and missions helped the team to fully understand the survivability requirement.

- A relative survivability assessment could be conducted to compare the survivability performance of different options.

- The methodology was used to support the survivability design and business case.

There were also a number of disadvantages that will need to be considered to improve the methodology in the future:

- Modelling integrated survivability requires a high-level model that needs some derived or subjective input data. 'Hard' data are not always available or possible to incorporate within such a high-level model.

- The input data have associated uncertainty, particularly any subjective judgements. This can attract criticism from stakeholders.

- The survivability threshold and objective targets were too abstract for stakeholders. The probability of survival metric was always perceived to be high, even when converted to an equivalent loss rate per 10 000 hours (in line with how accident rates are presented).

- Some stakeholders have difficulty with the method being used to assess compliance against the survivability KUR, because of the uncertainty of the input data.

- Not all important system parameters were captured within the probability of survival metric, although the ISAM framework could allow their inclusion, for example sensor false alarm rate and system reliability. These could be input as a rate of occurrence per hour or mission.

From discussion of the merits and disadvantages with the practical application of the methodology, a number of conclusions have been drawn:

- The concept to use a risk assessment approach and to reduce survivability risks to ALARP is valid and appropriate and has been adopted as best practice across the domains.

- Good engineering judgement and best practice backed up with appropriate analysis (including modelling and simulation) should be fit for purpose to demonstrate ALARP.

- ISAM a useful relative assessment tool.

- Integrated survivability models can show where synergies and interactions exist so that they can be modelled separately at an appropriate level of detail. The synergies and interactions are often too complex to be fully integrated within one quantitative model. ISAM should therefore be supported by an overall influence diagram that shows all interactions and highlights the key areas that have been analysed in further detail elsewhere.

- The acquisition community require a survivability KUR that contains hard targets that can be demonstrated, measured and assessed. The MJP process developed by the project could be used to identify the threats to be defeated and their priority.

- Specific threatening situations require development that then becomes the 'test case'. They should represent the entire spectrum of operations and be used throughout the acquisition process. This would enable a consistent survivability requirement to be set and then designed and tested for.

## 4.9    Input data

### 4.9.1    *Model classification and utility*

Models used in survivability analysis can be characterised by the part of the survivability problem that they deal with and their level of detail. Classification types that can be used are: survivability, susceptibility, vulnerability and recoverability. The levels of detail can be characterised as illustrated in Figure 4-25. Taking a 'bottom-up' approach, the more detailed 'engineering-level' or 'physics-level' models can be used to inform the 'platform-level' system models, that then inform the 'mission-level' models, that then inform the 'campaign / fleet-level' models. Taking a 'top-down' approach, there is also potential for higher-level models to provide guidance to lower-level areas, for example using campaign models to help to derive required survivability targets. These targets can then be flowed down to enable the setting of technology level targets, for example the required signature target.

A coherent modelling strategy is dependent upon the models being compatible with one another, i.e. the data output from one being compatible with the data input of a higher-level model. Integrated platform system level models are reliant on input data being available in the 'right' format.
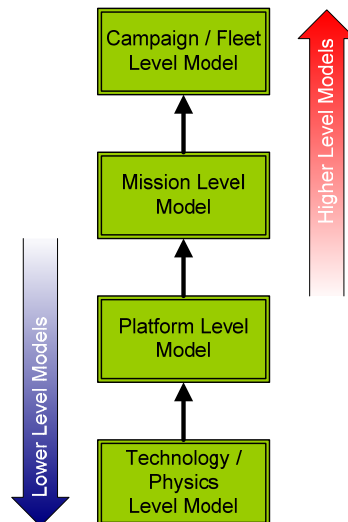
**Figure 4-25 – Characterisation of models by detail level.**

## 4.9.2    *Example Models*

Example models used in survivability analysis have been included in Table 4-22. As an example, QinetiQ has developed a physics level acoustic signature prediction tool called HELIACT (HELIcopter Acoustic Contouring Tool) that can be used to calculate the dBA noise contour and other metrics (QinetiQ 2004). This provides an indication of the likelihood of a helicopter cueing an enemy threat position for the scenario under consideration. The output from such a model could 'feed' a higher-level susceptibility model or integrated survivability model.

**Table 4-22 - Example air domain models.**

| Model name | Level | Domain | Type |
|---|---|---|---|
| SIMMAIR | Campaign | Air | Wargaming |
| BANTAM | Campaign | Air | Fleet sizing |
| HOVERS | Mission | Air | Mission – MITL simulation |
| FLAMES | Mission | Air | One-on-one or many-on-many |
| PAM | Platform | Air | Susceptibility system level |
| CAMEO-SIM | Platform | Joint | IR/EO signatures |
| INTAVAL | Platform | Air | Vulnerability |
| HELIACT27 | Physics level | Air | Susceptibility - acoustic signature |

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[27] QinetiQ 2004

### 4.9.3 *Derivation of manoeuvrability input data*

*Introduction*

Most survivability-related input data are classified; however, it is possible to show an unclassified example of how input data can be derived from a physical model. Manoeuvrability is an important survivability attribute and also contributes towards mission effectiveness. Helicopter manoeuvrability is largely influenced by available power, aerodynamic constraints and payload.

*Method*

The equation for power required for level flight was used to evaluate the climb rate for a Chinook and a Lynx helicopter. It was assumed that the ability to climb was proportional to the ability to manoeuvre. This is a reasonable assumption, although there are other aerodynamic constraints dependent upon the flight condition at the time of the manoeuvre.

The power required by the main rotor for general forward flight can be approximated as follows (see for example Newman 1994, or Leishman 2006):

$$P = \frac{kC_T{}^2}{2\mu} \times PF + \frac{\sigma\delta}{8}\left(1 + n\mu^2\right) \times PF + \frac{1}{2}\rho V^3 f + WV_C$$

When in the hover, this equation is replaced by:

$$P_{hover} = \left( \frac{kC_T{}^{\frac{3}{2}}}{\sqrt{2}} + \frac{\sigma\delta}{8} \right) \times PF$$

The terms used to evaluate the power required equations are defined in the nomenclature.

The following assumptions have been made:

- $\Omega R$ is the rotor tip speed when in the hover, this has been assumed to be 215 m/s for Lynx and 225 m/s for Chinook.

- The advance ratio has been approximated as:

$$\mu \approx \frac{V}{\Omega R}$$

- The power correction factor, $k$ is taken to be 1.15.

- The blade average drag coefficient, $\delta$ is assumed to be equal to 0.008.

- $n$ is assumed to be 4.5 for the purposes of this equation.

- The co-efficient of flat plate drag, $c_f$, has been taken as 0.0040 for Lynx and 0.0049 for Chinook.

- Engine power is flat rated at sea level to +20K.

- Dry air has been assumed.

The power required curve for level flight is theoretical for the rotor and does not account for the tail rotor or accessories. The additional power required as a percentage of main rotor power for helicopter components are detailed in Table 4-23.

**Table 4-23 – Typical additional power required as a percentage of main rotor power.**

| Component | Additional Power (%) |
|---|---|
| Tail rotor (straight and level flight) | 5 |
| Tail rotor (manoeuvre) | 15 |
| Auxiliaries | 10 |
| Mechanical losses | 5 |

For the manoeuvre case, the total power required, therefore is approximated as the main rotor power plus 30%.

Power required to climb, $P_C$ is evaluated by the term:

$$P_c = WV_C$$

To evaluate the realistic power required, we increase the main rotor power required by 30%.

$$P_{realistic} = P_{required} \times 1.3$$

The power margin (excess power), $\Delta P$ is evaluated by:

$$\Delta P = P_{installed} - P_{realistic} = WV_C$$

so, $\quad V_C = \dfrac{\Delta P}{W}$

The concept of vertical climb rate being proportional to manoeuvrability was discussed with a helicopter pilot. The caveat that there are other aerodynamic constraints dependent upon the flight condition at the time of the manoeuvre should also be remembered. Table 4-24 was generated based upon the pilot's advice.

**Table 4-24 - Manoeuvrability / climb rate score**

| Manoeuvrability score | Climb rate, $V_C$ (ft / minute) | Climb rate, $V_C$ (m/s) |
|---|---|---|
| High | $V_C > 2500$ | $V_C > 12.7$ |
| Medium | $1750 \leq V_C \leq 2500$ | $8.89 \leq V_C \leq 12.7$ |
| Low | $1000 \leq V_C < 1750$ | $5.08 \leq V_C < 8.89$ |
| Zero | $V_C < 1000$ | $V_C < 5.08$ |

*Results*

The above equations and losses were evaluated within Microsoft® Excel® and realistic power-required curves generated for Chinook and Lynx, as shown in Figure 4-26 and Figure 4-27 respectively. Example data have been included within Appendix G.

**Power required for level flight (Chinook 17 000 kg AUM, ISA +20)**
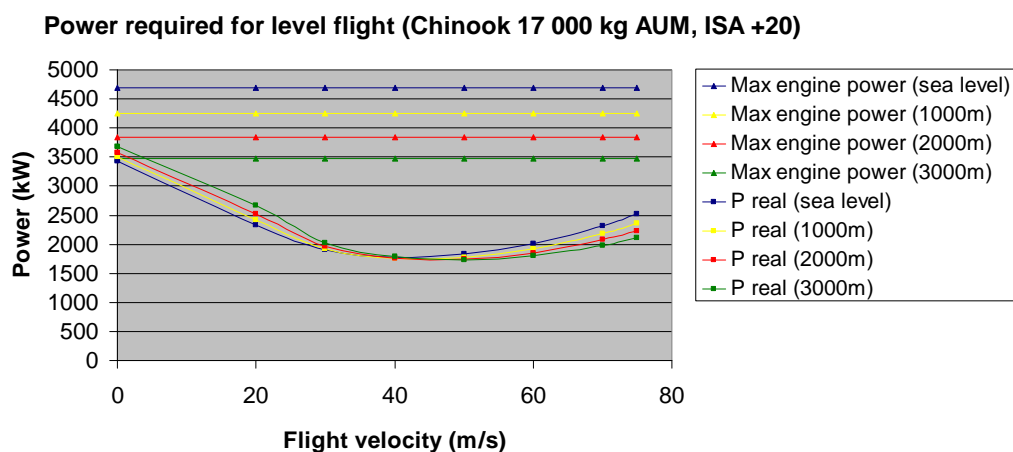


**Figure 4-26 - Power required for level flight for Chinook.**

**Power required for level flight (Lynx 5 125 kg AUM, ISA +20)**
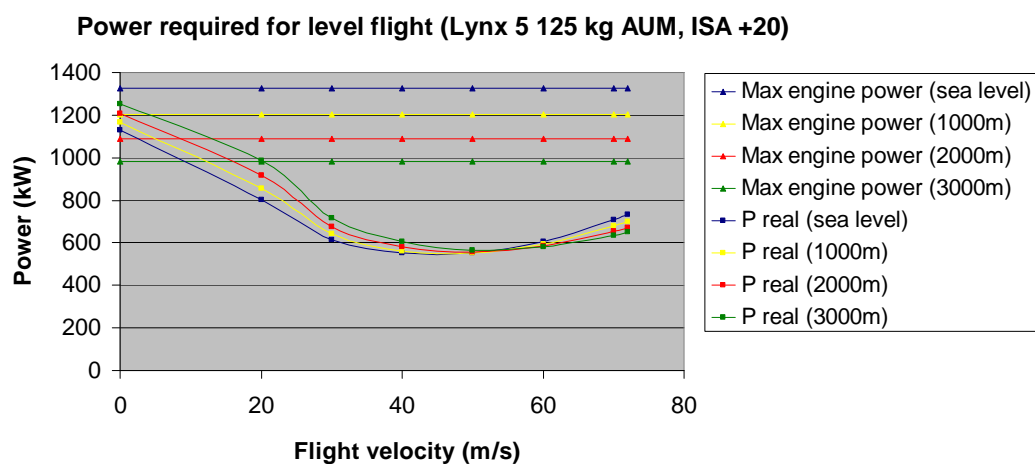


**Figure 4-27 - Power required for level flight for Lynx.**

Table 4-25 was evaluated from the above equations for a range of input conditions. The manoeuvrability score depends upon the scenario and associated environmental conditions and the payload. Taking central Afghanistan as an example, the average terrain height is 1800 m and the atmospheric conditions could be at an International Standard Atmosphere (ISA) plus 20 °C. The manoeuvre measure of effectiveness could be based upon the possible climb rate from the hover near ground level (2 000 m).

For example, in Table 4-25, Chinook would score 'high' for an all up mass (AUM) of 16 000 kg. An empty Chinook has a mass of 10 185 kg (Boeing 2009), leaving 5 815 kg for payload (including fuel) in this example. Appropriate parameters can be input into the model to simulate different scenarios, vignettes and missions.

**Table 4-25 - Manoeuvre scores for Chinook and Lynx.**

| Platform | AUM (kg) | Altitude above sea level (m) | Atmosphere | Theoretical vertical climb rate from the hover (m/s) | Manoeuvre score |
|----------|----------|------------------------------|------------|------------------------------------------------------|-----------------|
| Chinook | 17 000 | 2 000 | ISA +20 | -1 | Zero |
| Chinook | 16 000 | 3 000 | ISA +20 | -13 | Zero |
| Chinook | 16 000 | 2 000 | ISA +20 | 17* | High |
| Chinook | 16 000 | 1 000 | ISA +20 | 47* | High |
| Chinook | 16 000 | 0 | ISA +20 | 79* | High |
| Lynx | 5 125 | 3 000 | ISA +20 | -53 | Zero |
| Lynx | 5 125 | 2 000 | ISA +20 | -23 | Zero |
| Lynx | 5 125 | 1 000 | ISA +20 | 7 | Low |
| Lynx | 5 125 | 0 | ISA +20 | 38* | High |

* These theoretical vertical climb rates are unlikely in practice because of aerodynamic constraints. Vertical drag has not been considered at these speeds.

*Discussion*

The manoeuvre score derived here could be used to inform the evaluation of the platform options matrix within the QFD method. Higher fidelity manoeuvre data required by a probabilistic model such as ISAM would require input from a man-in-the-loop simulation facility such as HOVERS. This simulation facility would enable threat and platform interactions (including tactics) to be assessed in the required level of detail.

This example has shown that data provided by feeder models requires interpretation by subject matter experts before input into system level integrated survivability models. Feeder model input parameters need to be consistent with the scenarios and the platform role.

## 4.10 Discussion

This section discusses the research outputs and how they can be used at different stages of a military helicopter's life cycle. The main research outputs were:

- A helicopter survivability assessment process.

- An influence diagram method.

- A QFD method.

- A probabilistic method.

- A method to derive input data for the rate of encountering threats.

Wider issues resulting from application of the above methods have also been discussed. These wider issues were:

- General acquisition insights.

- The rationale for considering combat losses separately from accidental losses.

- Capability level analysis.

### 4.10.1 Helicopter survivability assessment process

The research has developed a helicopter survivability assessment process that has situated survivability modelling with the associated inputs and outputs to support the military helicopter life cycle. The process supports areas such as: demonstrating that survivability risks had been reduced to ALARP, requirements definition and ITEA.

The process set out a way of defining threatening situations in a robust and repeatable manner. The process also established the requirements for a method to assess survivability risk so that existing platforms could be benchmarked and then future upgrades or new platforms could be measured against the benchmark. This probabilistic method is discussed in Section 4.10.4.

At the early concept phase the process can be used to help establish helicopter roles, missions and threatening situations. The process could take information from and inform the following products that then support the URD:

- Doctrine papers.

- Concept of employment (CONEMP).

- Requirement definition study.

- Use study (using Defence Standard 00-60).

- Through life capability management (TLCM) process and the through life management plan (TLMP).

Doctrine papers and the CONEMP would be used by the military judgement panel to help to define the missions and associated threatening situations. It is likely that working up missions could well feed back into these documents, for example, the military judgement panel may well conceive additional doctrine or CONEMP requirements as they progress through the process. From the author's experience, developing threatening situations has also elicited requirements from a survivability and mission perspective which has then informed the requirement definition study. The use study captures many of the DLOD issues and would benefit from the influence diagram approach discussed in the next section. The process also supports TLCM by providing a measure of effectiveness and the ability to benchmark the capability from a survivability perspective. The threatening situations could support the capability audit process by identifying gaps in protection that require resolution by raising options or conducting capability investigations to identify suitable survivability options.

The process has benefited from a number of iterations and has improved as a result of lessons learnt from application to the acquisition case study. The process is generic and is still valid if different methods were used to conduct the system-level survivability assessment. The probabilistic ISAM model was used for the acquisition case, as it best met the requirement at that time. However, there is nothing to stop another suitable method being used to conduct the 'survivability assessment' function, provided that the appropriate probability of survival output can be provided.

It is recognised that the process and model need to be iterated a number of times during the helicopter life cycle, for example at each step in the systems engineering Vee-diagram. As testing determines actual performance, the results should be checked within the model to understand the impact upon overall survivability.

The process now needs to be expanded to include the influence diagram method for capturing the wider DLOD issues.

### 4.10.2 *Influence diagram method*

A survivability influence diagram was developed to describe the problem space, identify interactions and provide synthesis. This holistic, synthetic approach, as defined by Hitchins (2005) helps to deal with a problem that has many diverse aspects. It supports the 'bringing

together' step and provides an illustrative tool to enable creativity. These steps are otherwise difficult to trace using other methods. The influence diagram quickly conveyed the cross-capability problem to the reader, including the 'softer' issues and DLODs. Well drawn diagrams take time to produce and evolve over a number of iterations to get the right balance between the higher and lower levels of detail.

Influence diagrams should be considered for use more often as a starting point in all systems engineering work for the reasons already provided. The operational analysis (OA) domain would also benefit, but then OA is really part of systems engineering, because it conducts user requirement analysis and definition. Influence diagrams could be used to support the following activities within the helicopter life cycle:

- To capture requirements within the requirement definition study by providing an effective visual tool to stimulate stakeholder engagement. This activity would then support the generation of the URD.

- To help to structure URDs and SRDs and identify critical areas to be brought out with overarching KURs and key system requirements (KSRs).

- To identify interacting programmes and supporting capabilities, for example how the wider situational awareness picture enhances survivability.

- To enable the checking for completeness to make sure that all areas are covered and nothing is missed, including aspects that are difficult to quantify, such as training and concepts and doctrine.

- To identify important areas that require additional analysis to understand and quantify using other methods.

- To support the TLCM process by identifying areas that make up a capability goal and critical areas that require a measure of effectiveness to be defined.

### 4.10.3 QFD method

The research has developed a hybrid QFD risk approach that provides a semi-quantitative method to assess survivability. This approach has improved the QFD method by developing a 'risk' component to the threat matrix such that likelihood of encounter and consequence are considered. This provides a more realistic solution. Including platform role or task within the scenarios has also provided clarity and a more complete approach.

QFD was found to be more effective than the AHP for this particular application; however, the AHP process did achieve a similar result as the QFD approach, so providing a useful check and implying robustness of the QFD method. The QFD method is appropriate at the early design stage and could be used as a top-level tool for managing survivability. Issues

highlighted using such a method could then be investigated further using good engineering judgement supported by appropriate physics-level models. The method has two key advantages: transparency (i.e. a clear audit trail) and its ability to focus communication. After all, successful systems engineering is all about good communication across organisational boundaries.

QFD could be used to support the following activities within the helicopter life cycle:

- To focus stakeholder workshops and facilitate discussions to elicit requirements and interactions as part of requirement definition studies.

- To help prioritise requirements within the requirement definition study.

- To help identify technology options for meeting the requirement that merit further investigation within the concept phase.

- Once influence diagrams have been developed, QFD could offer a semi-quantitative approach to assess the DLODs and the softer issues.

- To capture requirements quickly and show an audit trail for urgent statement of user requirements (USURs) on UORs.

The semi-quantitative nature of the QFD method leads to numbers that are not real. These results are suitable for helping to prioritise requirements, but they cannot provide the quantifiable estimate of risk needed to demonstrate ALARP. This is where the probabilistic method (discussed in Section 4.10.4) provides the most utility.

### 4.10.4 *Probabilistic method*

The probabilistic fault-tree approach implemented within ISAM provided a quantitative method for assessing survivability risk. This method was developed to provide a way to demonstrate that survivability risks had been reduced to ALARP.

The method evaluates probability of survival and can perform conversion into an equivalent metric such as losses per 10 000 hours to be consistent with how accident loss rates are presented. The method was mathematically rigorous and well verified. A supporting rate of encounter method was also developed to derive appropriate threat input data (see section 4.10.5).

The probabilistic method provides an assessment method and measure of effectiveness that could be used to support the following activities within the helicopter life cycle:

- Developing and assessing TLCM capability goals and measures of effectiveness.

- In support of COEIA survivability aspects.

- Developing URDs including the performance envelope on the survivability KUR. This would be derived for a 'test environment' set of defined threatening situations.

- Developing performance envelopes within the SRD, including KSRs.

- Supporting survivability option down-selection and trade-off analysis.

Problems with the method included the lack of available input data with confidence limits in some areas. The method was used to support acquisition; however, stakeholder perceptions were mixed because of the uncertainty associated with the rate of encountering threats (this is discussed further in Section 4.10.5). There is still some further work to be done, especially given that: "A systems engineer is a facilitator that brings together multiple stakeholders and unifies opinion. If all parties believe that the approach is sufficiently robust and valid then the systems engineer has been successful in their aim" (Sparks 2006).

Probability of survival is an appropriate metric for measuring survivability and setting the KUR. This issue is how to generate the target values in a robust way, such that the KUR is measurable and traceable, the SRD can be contracted against and the ITEA can be conducted.

Areas for further work to address these limitations are as follows:

- An authoritative and consistent threatening situations definition should be developed for helicopters that represent the entire spectrum of operations. These situations would become the 'test environment' that can be used throughout the life cycle from selection of design concepts through to test and evaluation of delivered solutions.

- Development of a framework of supporting analysis tools that can provide probabilistic input into ISAM and allow derivation of confidence limits and error bars. This systems level framework would be capable of informing more detailed design work later in the life cycle and could be enabled through a MATLAB® based approach.

### 4.10.5   Method to derive rate of encounter

A method was developed to derive the 'rate of encounter' input data for a probabilistic approach such as ISAM. The method was required to ensure that the threat environment was defined in a consistent and robust way and was compatible with the probabilistic approach required to demonstrate ALARP.

The process, method and mathematics are robust and have been tested and improved where necessary on a number of occasions to support analysis and decision making on an acquisition programme. The output from this approach can also be used to feed other models

and studies. For example, the derived threatening situations are useful for MOD and industry to formulate system requirements and provide a context to inform system design and behaviour modelling. This approach is currently being used to support the CDAS TDP.

Ultimately, the numbers generated for 'rate of encounter' are an estimate only. Even historical data are an estimate, because we only know what has been shot down or damaged and even this dataset is incomplete; for example, crash investigation is not always possible in a conflict zone. We do not necessarily know how many engagements there have been as some will be undetected or unreported and therefore limited validation is possible. Furthermore much of this information is classified and not freely available. This is not an excuse to not even attempt to quantify the problem, but it is important to understand what the numbers mean in practice and any associated limitations on the method.

To address accuracy and uncertainty, confidence limits should be established and presented using error bars. Provided that assessments are carried out using the same rate of encounter assumptions then the method provides a useful way to take into account the threat environment. To provide an integrated survivability assessment, some evaluation of the rate of encountering threats will need to be provided, even if these are 'test conditions' so that survivability attributes can be balanced. This would require specific threatening situations to be developed that represent the entire spectrum of helicopter operations and that could be used throughout the acquisition process. This would enable a consistent survivability requirement to be set and then designed and tested for.

### 4.10.6  General acquisition insights

Platforms are increasingly being deployed within different situations to those that they were originally designed for and against a rapidly changing threat. This often leads to platforms being quickly upgraded, as part of a UOR programme. Speed is essential, and consequently there is less time to conduct analysis and not always time to develop models. Quick, flexible methods are therefore more useful than methods that are 'built into' the acquisition process and more difficult to change. Therefore, flexible methods are needed to support different applications.

Generic influence diagrams and QFD risk models support a quick turnaround and can include the 'softer' issues, including DLODs. The example of helicopter DAS procured under UOR from operation TELIC brings out the importance of not just equipment, but also adequate T&E and training. The wider DLODs are potential 'showstoppers' and must be considered from the outset. Influence diagrams are a good way to support this early planning.

The generic integrated survivability process (Fig 4-1) works for UORs, although the activities will need to be tailored to meet UOR timescales. Where an assessment or model already exists, it may be possible to update this as part of a UOR.

There appears to be a shift in terms of what is valued in systems engineering and lifecycle thinking. Previously performance was the main consideration. Now flexibility is increasingly important, particularly for helicopters, so that they can be quickly upgraded and re-roled. This requirement has led to the need for flexible architectures and a parameter set to assess them.

### 4.10.7  *The rationale for considering combat losses separately from accidental losses*

The research considered combat losses separately from accidental losses because of existing definitions and domain boundaries. The accepted definition for 'survivability' was used that refers to the man-made hostile environment only and does not include the natural hostile environment. This definition was consistent with the customer requirement at the start of the research and was used to bound the problem within the author's scope of work and his functional team structure.

Survivability and safety have traditionally been considered within their two separate domains for practical reasons to do with safety and security. The safety domain is more concerned with systems that are flight safety critical, compared to the survivability domain (although there are some exceptions, for example, the safe arming of expendable countermeasures). Flight safety systems (such as flight control systems) require higher levels of certification, leading to longer development times and higher cost. Certification to flight safety standards is not appropriate for survivability systems, because they have to be upgraded quickly and more frequently than flight safety critical systems. Delays integrating survivability systems introduced as a result of certification to flight safety standards would potentially lead to lower levels of survivability and greater combat losses.

From a security standpoint, the survivability domain is more concerned with sensitive classified information compared to the safety domain. It is therefore easier to manage classification and focus expertise by keeping the domains separate.

Having conducted the research, the author believes that there would be value in considering accidental losses within a more comprehensive 'survivability' analysis for the following reasons:

- Accidental losses are important.

- There is a 'grey area' between safety and survivability, for example when the survivability countermeasure to a threat, requires an aircraft to fly at low level, which then increases the safety related risk of controlled flight into terrain (CFIT).

- The interaction between survivability and safety attributes, for example, crashworthy structures and fuel systems provide both survivability and safety advantages.

- Considering survivability and safety requirements together would enable better synergy and potentially improve platform system design.

- This approach would enable a better balance to be struck between safety and survivability risk mitigations.

- Flight safety issues such as LVL / DVE (including helicopter brownout) are starting to be considered within the survivability domain in the US.

- Sensor systems could potentially provide DAS, LVL / DVE and ISTAR benefits if combined as part of an integrated sensor suite. This approach requires considering as part of the overall requirement definition and analysis process at the outset, not individually within domain 'stovepipes'.

As an area for further work, safety risks could be considered alongside survivability threats within the analysis methods. For example, the risk of helicopter loss because of 'brownout' or CFIT could be estimated based on past data and applied to the scenarios under assessment. Flight safety data is more widely available than hostile loss data so this should not be a difficult enhancement to make.

### 4.10.8   Capability level analysis

The influence diagram in Figure 4-5 illustrated that survivability cannot be traded in isolation. Other relevant military capabilities also need to be considered, for example: mobility (payload / range), lethality, $C^4I$, sustainability and other mission capabilities. An investigation of capability-level analysis methods across defence should be undertaken to ensure a coherent and compliant approach to systems engineering that adopts best practice from across the domains.

Sparks (2006) has developed a concept for analysis of future soldier systems across the five NATO capability domains: survivability, sustainability, mobility, lethality and $C^4I$ (command, control, communications, computers and intelligence). The Technology Research Elements Benefits Analysis Tool (TREBAT) is an example of a high-level capability analysis tool that has been developed for use within the air domain. Further value could be realised by further cross domain collaboration in the area of capability level analysis.

## 4.11 Summary

This chapter has implemented the research approach developed in Chapter 3 and presented the research outputs and associated discussion. The following conclusions have been drawn:

### 4.11.1 *Process*

The policy to reduce survivability risks to ALARP is appropriate and has now been widely adopted within the UK survivability domain. The research has developed a helicopter survivability assessment process that has situated survivability modelling with the associated inputs and outputs to support the military helicopter life cycle. The process supports areas such as: demonstrating that survivability risks had been reduced to ALARP, requirements definition and ITEA. The process would benefit further from DLOD analysis using the influence diagram method.

### 4.11.2 *Methods*

A number of methods have been tested for assessing survivability and the following conclusions have been drawn:

- The influence diagram method was effective at: describing the problem space, identifying interactions, providing synthesis and providing an illustrative tool to enable creativity. These steps are otherwise difficult to trace using other methods.

- The QFD method can compare options and provide a relative weighting, however, the output is an unreal number that does not directly relate to probability of survival.

- To comply with ALARP principles, a probabilistic approach is required that links probability of survival to quantifiable outcomes.

- The probabilistic approach implemented within ISAM is consistent with the ALARP approach.

- Limitations in available input data for the rate of encountering threats leads to a probability of survival that is not a real number that can be used to assess actual loss rates. However, the method does support an assessment across platform options, provided that the 'test environment' remains consistent throughout the assessment.

- To support the helicopter life cycle a consistent 'test environment' requires definition. This would demand specific threatening situations to be developed that represent the entire spectrum of helicopter operations and that could be used throughout the acquisition process. This would enable a consistent survivability requirement to be set and then designed and tested.

- A framework of supporting analysis tools requires development that can provide probabilistic input into ISAM and allow derivation of confidence limits and error bars. This systems level framework would be capable of informing more detailed design work later in the life cycle and could be enabled through a MATLAB® based approach.

### 4.11.3  Wider issues

A number of wider issues were established and discussed, and the following conclusions were drawn:

- System flexibility is increasingly important, particularly for helicopters, so that they can be quickly upgraded and re-roled. This requirement has led to the need for flexible architectures and a parameter set to assess them.

- Having conducted the research, the author believes that there would be value in considering accidental losses within a more comprehensive 'survivability' analysis. This approach would enable a better balance to be struck between safety and survivability risk mitigations. As an area for further work, safety risks could be considered alongside hostile threats within the analysis methods.

# 5 CONCLUSIONS AND RECOMMENDATIONS

This chapter provides conclusions arising from the research outputs and how they relate to the research question. It also provides recommendations arising from the conclusions and identifies areas for future research.

## 5.1    Introduction

As defined in Section 1.2, the aim of this work was to answer the following research question: "How can helicopter survivability be assessed in an integrated way so that the best possible level of survivability can be achieved within the constraints and how will the associated methods support the acquisition process?"

The question has been answered by firstly understanding the problems, developing a process and methods to solve them and then testing the methods on an acquisition case study. The utility of the methods within a military helicopter's life cycle has been discussed along with the lessons learnt.

## 5.2    Main Conclusions

A number of conclusions regarding integrated helicopter survivability have been drawn:

- This research identified the relevance of the ALARP principle to survivability and applied it to the integrated helicopter survivability problem for the first time.

- In order to demonstrate that a level of survivability is acceptable, evidence must be provided that survivability risks have been reduced to ALARP.

- The influence diagram method was effective at capturing the wider survivability interactions, including DLODs and softer issues that are often difficult to quantify.

- Influence diagrams and QFD methods are effective visual tools to elicit stakeholder requirements and improve communication across organisational and domain boundaries.

- The semi-quantitative nature of the QFD method leads to numbers that are not real. These results are suitable for helping to prioritise requirements early in the life cycle, but they cannot provide the quantifiable estimate of risk needed to demonstrate ALARP.

- A 'hybrid' QFD risk method was developed to amalgamate the risk assessment approach with the QFD method. The result was a more robust threat matrix that was less prone to inadvertent biasing and so enables a more balanced result.

- The AHP method was effective at quantifying subjective judgements in a consistent manner. The method requires a high number of judgements to be made and was found to be too labour intensive to populate for this particular application.

- The probabilistic approach implemented within ISAM was developed to provide a quantitative estimate of 'risk' to support the approach of reducing survivability risks to ALARP. ISAM adopts a sound structure and approach that has been

mathematically verified and has undergone limited validation. As a relative survivability assessment tool it is valid; however, it should not be used to quantify actual loss rates.

- The survivability methodology and ISAM have been applied to an acquisition programme, where it has been tested to support the survivability decision making and design process.

- Threatening situations require development that span the complete spectrum of helicopter operations. These situations would provide the survivability 'test environment' and be used throughout the helicopter life cycle from selection of design concepts through to test and evaluation of delivered solutions. They would be updated as part of the TLCM process.

- A framework of survivability analysis tools requires development that can provide probabilistic input data into ISAM and allow derivation of confidence limits and error bars. This systems level framework would be capable of informing more detailed survivability design work later in the life cycle and could be enabled through a MATLAB® based approach.

- The ability to adapt and upgrade a system is an important survivability attribute. System integration is expensive and necessary, given that platforms may remain in service for approximately 30 years and threats adapt quickly. Helicopter platforms therefore require flexible system architectures enabling increased capability and easier and faster upgrade.

- Survivability is an emerging system property that influences the whole system capability. There is a need for holistic capability level analysis tools that quantify survivability along with other influencing capabilities such as: mobility (payload / range), lethality, situational awareness, sustainability and other mission capabilities. System dynamics has much to offer in this regard, particularly the central tool: the influence diagram. The influence diagram can be used to identify key interactions across capability areas that can be investigated further using additional modelling techniques.

- There would be value in considering accidental losses within a more comprehensive 'survivability' analysis. This approach would enable a better balance to be struck between safety and survivability risk mitigations and would lead to an improved, more integrated overall design.

- The 'quest' to develop whole system survivability models has brought together technical specialists from diverse but interrelated disciplines. The communication

benefits in bringing the right people together and asking the right questions will continue to stimulate progress in this complex area. This will enable the defence community to continually improve delivery of integrated survivability.

## 5.3    Recommendations

Based upon the foregoing work, a number of recommendations are made.

- The concept of reducing survivability risks to ALARP should continue to be applied to the helicopter survivability domain.

- Systems dynamics techniques are considered for further use by Dstl and the wider MOD, particularly within the survivability and operational analysis domains to improve understanding of the problem space, take a more holistic approach (including all the DLODs) and to better balance capability, of which survivability is one important element. As an area for further work, the influence diagram method should be formally incorporated within the survivability assessment process.

- A survivability 'test environment' of threatening situations requires further development that spans the complete spectrum of helicopter operations.

- A framework of survivability analysis tools requires development that can provide probabilistic input data into tools such as ISAM and be capable of informing detailed survivability design work later in the life cycle.

- An investigation of capability level analysis methods across defence should be undertaken to ensure a coherent and compliant approach to systems engineering that adopts best practice from across the domains. These capability analysis methods will incorporate survivability as well as the other capability areas.

- As an area for further work, safety risks should be considered alongside hostile threats within the survivability analysis methods.

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# 7 APPENDICES

## 7.1 Appendix A – Survivability definitions

Survive is to: "continue to live or exist, especially after coming close to dying or being destroyed or after being in a difficult or threatening situation" (Anon. 2003a).

Survive is to: "continue to live or exist after (a passage of time or a difficult or dangerous experience)" (Anon. 2003b).

Survive is to: "continue to live or exist in spite of (an accident or ordeal)" (Pearsall 2002).

Survivability can be defined as: "The capability of a system to avoid or withstand a man made hostile environment without suffering an abortive impairment of its ability to accomplish its designated mission." Survivability consists of susceptibility and vulnerability. Susceptibility is defined as: "the degree to which a weapon system is open to effective attack due to one or more inherent weaknesses." Vulnerability is defined as: "the characteristic of a system that causes it to suffer a definite degradation (loss or reduction of capability to perform its designated mission) as a result of having been subjected to a certain (defined) level of effects in an unnatural (man-made) hostile environment. Vulnerability is determined by the system's design and any features that reduce the amount and effects of damage when the system takes one or more hits" (Anon. 2000).

"(DoD) Concept which includes all aspects of protecting personnel, weapons, and supplies while simultaneously deceiving the enemy. Survivability tactics include building a good defense; employing frequent movement; using concealment, deception, and camouflage; and constructing fighting and protective positions for both individuals and equipment" (Anon 2001).

"Aircraft combat survivability (ACS) is defined here as the capability of an aircraft to avoid or withstand a man-made hostile environment" (Ball 2003).

"Survivability: The ability to complete a mission successfully in the face of a hostile environment" (Anon. 2004).

"The capability of a system and crew to avoid or withstand a manmade hostile environment without suffering an abortive impairment of its ability to accomplish its designated mission" (Anon. 1999).

"Survivability is the ability of a system to fulfill its mission, in a timely manner, in the presence of attacks, failures, or accidents" (Lipson 2000).

"Survivability may be defined as the ability of the system to continue to provide useful functionality and performance in a hostile threat environment, including after damage has been inflicted" (Emerton 2000).

## 7.2 Appendix B – UK rotorcraft incidents

**Table 7-1 - UK rotorcraft incidents.**

| Date | Operation | Location | Service | Platform | Fatalities | Injuries | Damage category | Cause and notes | Reference |
|------|-----------|----------|---------|----------|-----------|----------|-----------------|-----------------|-----------|
| 22/03/03 | Op Telic | | RN | Sea King Mk7 | 4 | 0 | 5 | Collision | BBC |
| 22/03/03 | Op Telic | | RN | Sea King Mk7 | 3 | 0 | 5 | Collision | BBC |
| ??/06/03 | Op Telic | Al-Majar al-Kabir | RAF | Chinook | | 1 | | Hostile fire | The Times |
| 22/12/03 | | | Army | Gazelle AH1 | 2 | | | | |
| 19/07/04 | Op Telic | Basra air station | RAF | Puma HC1 | 1 | 2 | 5 | Crashed on landing. Inappropriate downwind approach to land. | MOD 2004 |
| 09/09/04 | Training | Czech Republic | Army | Lynx Mk9 | 6 | 0 | 5 | Wire strike | BBC |
| 08/12/04 | UK SAR | Off the coast of Cornwall | RN | Lynx Mk3 | 4 | 0 | 5 | Aircraft malfunction | BBC & MOD 2005 |
| 21/02/05 | Bosnia | Kakanj | Army | Lynx | 0 | 3 | ? | Wires. Minor injuries to the crew. | BBC |
| 03/03/05 | Op Telic | 120 miles east of Oman | RN | Lynx Mk8 | 0 | 0 | 5 | BOI ongoing, crashed into the sea. Aircraft sunk to sea bed. 3 crew survived. | BBC |
| 06/05/06 | Op Telic | Basra | RN | Lynx AH Mk7 | 5 | 0 | 5 | BOI Report - MANPAD | MOD 2006 |
| 10/01/07 | Training | RLG Tern Hill | DHFS | Squirrel | 0 | 2 | 5 | Collision near ground at RLG Tern Hill | MOD 2007 |
| 10/01/07 | Training | RLG Tern Hill | DHFS | Squirrel | 1 | 2 | 5 | | MOD 2007 |
| 18/03/07 | UK | Crossmaglen | Army | Lynx Mk7 | | 6 | 5 | Struck ground during approach to land | MOD 2007 |
| 15/04/07 | Op Telic | Iraq | RAF | Puma HC1 | 2 | 0 | 5 | Two aircraft collided on approach on NVGs. | MOD 2007 |
| 15/04/07 | Op Telic | Iraq | RAF | Puma HC1 | 0 | 0 | 4 | | MOD 2007 |

| Date | Operation | Location | Service | Platform | Fatalities | Injuries | Damage category | Cause and notes | Reference |
|---|---|---|---|---|---|---|---|---|---|
| 27/05/07 | Op Telic | Iraq | RAF | Puma HC1 | 0 | 0 | 4 | Aircraft blew over on dispersal in severe winds during sand storm. | MOD 2007 |
| 27/05/07 | Op Telic | Iraq | RAF | Puma HC1 | 0 | 0 | 4 | | MOD 2007 |
| 08/08/07 | | | RAF | Puma HC1 | 3 | 9 | 4 | During trooping serial, aircraft impacted ground. | MOD 2007 |
| 05/09/07 | Training | | Army | AB212 | 0 | 2 | 5 | Impacted ground while low and slow. | MOD 2007 |
| 21/11/07 | | | RAF | Puma HC1 | 2 | 2 | 5 | Impacted ground after abortive overshoot from brown-out landing. | MOD 2007 |
| 04/09/08 | Enduring Freedom | FOB Edinburgh, Helmand province | Army | Apache | 0 | 0 | ? | Enemy action ruled out. | Jennings 2008 |
| 20/08/09 | Enduring Freedom | North of Sangin, Helmand Province | RAF | Chinook | 0 | 0 | 5 | Came under attack from machine gun and RPG fire as it took off. Crew made an emergency landing and were rescued. The aircraft was destroyed by a NATO air strike. | Bingham and Harding 2009 |
| 30/08/09 | Enduring Freedom | 10km east of Sangin, Helmand Province | RAF | Chinook | 0 | 0 | 5 | Hard landing and then destroyed by NATO forces. | Prince 2009 |

## 7.3    Appendix C – Rotorcraft accident data

**Table 7-2 - Rotorcraft accident data for the RAF, (Defence Aviation Safety Centre 2005).**

| Year | Hours | Cat 4/5 losses | Loss rate per 10 000 flying hours |
|------|-------|----------------|-----------------------------------|
| 1980 | 61213 | 2 | 0.33 |
| 1981 | 61764 | 2 | 0.32 |
| 1982 | 68043 | 0 | 0.00 |
| 1983 | 71603 | 0 | 0.00 |
| 1984 | 74841 | 3 | 0.40 |
| 1985 | 75467 | 2 | 0.27 |
| 1986 | 77163 | 0 | 0.00 |
| 1987 | 71069 | 1 | 0.14 |
| 1988 | 75471 | 1 | 0.13 |
| 1989 | 71867 | 3 | 0.42 |
| 1990 | 71216 | 3 | 0.42 |
| 1991 | 65689 | 3 | 0.46 |
| 1992 | 67989 | 3 | 0.44 |
| 1993 | 64376 | 3 | 0.47 |
| 1994 | 64277 | 1 | 0.16 |
| 1995 | 65159 | 0 | 0.00 |
| 1996 | 65183 | 0 | 0.00 |
| 1997 | 61304 | 1 | 0.16 |
| 1998 | 70874 | 0 | 0.00 |
| 1999 | 72077 | 1 | 0.14 |
| 2000 | 69080 | 1 | 0.14 |
| 2001 | 64114 | 2 | 0.31 |
| 2002 | 63803 | 2 | 0.31 |
| 2003 | 62678 | 0 | 0.00 |
| 2004 | 30070 | 1 | 0.33 |
| TOTAL | 1666390 | 35 | 0.21 |

From 2007 the Directorate of Aviation Regulation and Safety (DARS) subsumed the MOD Aviation Regulatory and Safety Group (MARSG), the Defence Aviation Safety Centre (DASC) and the Military Aviation Regulatory Team. Consequently, the accident data reporting format changed for 2005 onwards. Between 2005 and 2007, tri-service damage category 4/5 helicopter accident rates were 0.88, 0.1 and 0.23 per 10 000 flying hours in operational theatres, non-operational and combined respectively (Ministry of Defence 2007b).

## 7.4    Appendix D – Survivability assessment process
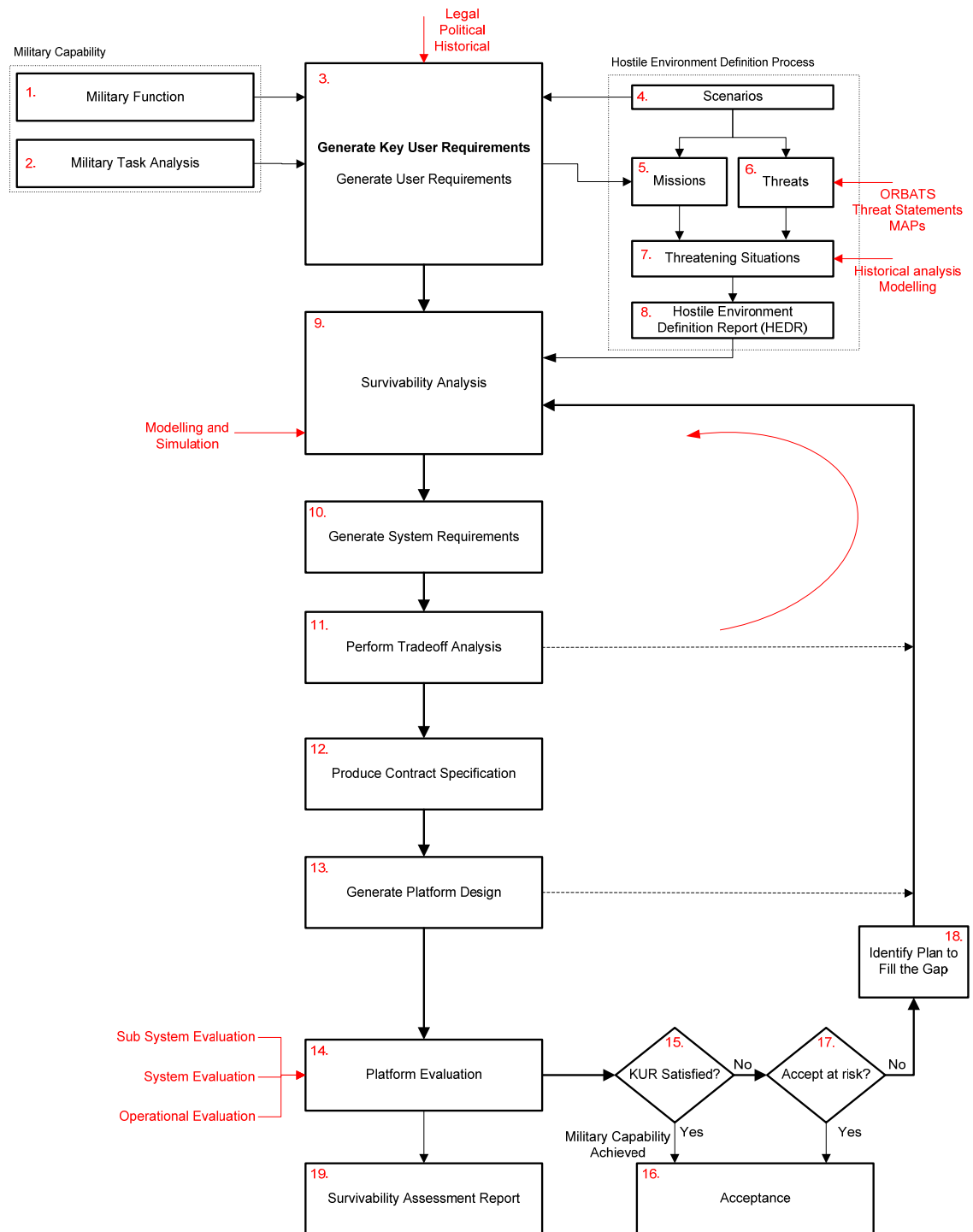


**Figure 7-1 - Survivability assessment process (Law et al. 2006).**

## 7.5 Appendix E – QFD 'roof' evaluation and explanations

These values represent the author's views and should be taken as examples for illustrative purposes only.

Situational awareness (SA) and mission decision support systems (MDSS) have a high interrelationship, because SA provides the information that enables mission decisions to be made. For example, communication of data to the platform could allow the Recognised Air Picture (RAP) to be updated in real time, allowing the mission plan to be optimised in flight. 'Pop-up' threats detected by a third-party asset and communicated to the platform could be avoided by real time re-routing, by calculating the route of least risk. MDSS is an enabler to providing NEC.

SA and signature control have a medium interaction because SA provides the pilot with some ability to control the signature of the platform as experienced by a threat. For example, if SA was to inform the pilot of a visual observer on the ground, then the pilot could orientate the platform to provide the optimum aspect in order to minimise the visual and acoustic signatures, and therefore, minimise probability of detection. Alternatively, the pilot could use terrain to reduce signature, knowing the position of the threat.

SA and DNAE have a medium interaction, because DNAE capability provides SA in night, low light and adverse weather conditions.

SA and NOE have a medium interaction, because SA would provide information on when it was appropriate to fly NOE and would also be an enabler.

SA and detect threats have a high interaction, because the SA provided by third party detection, declaration and communication of the threat to the platform is one method by which the platform can 'detect' threats. Communication of the Combined Operating Picture (COP) to the platform would provide a high level of SA commensurate with improved threat detection.

SA and expendable countermeasures have a low interaction, because improved SA would assist the pilot to deploy the countermeasure most effectively. SA could also provide an input to the countermeasure system, assisting with automatic dispensing.

SA and counter fire have a high interaction, because SA is required in order to provide an effective counter fire response. The gunner needs to know the position of the threat on the ground and the pilot needs to provide the gunner with a stable gun platform at an aspect that allows the gunner to engage the threat, in between manoeuvring to avoid the threat.

SA and manoeuvre have a high interaction, because SA is required in order to provide an effective manoeuvre. SA would provide information on what the threat is likely to be as well as possible 'safe' places to use to avoid hostile fire.

MDSS and signature control have a high interaction, because knowledge of the platform signature allows 'safe routing' to be conducted. The mission can be pre-planned, and then potentially re-planned in flight, to reduce the signature as much as possible by using terrain masking and optimum flight profiles.

MDSS and DNAE have a high interaction, because navigation, terrain and tactical data are required to provide both of these capabilities.

MDSS and NOE have a high interaction, because MDSS is an enabler to NOE flight. Mission planning can be used to work out optimum NOE flight profiles.

Signature control and DNAE have a medium interaction, because operating at night reduces visual signature. The ability to operate in adverse weather can also reduce signature, for example in poor visibility.

Signature control and NOE have a high interaction, because the ability to operate NOE provides a means of reducing signatures.

Signature control and detect threats have a low interaction, because it is desirable to detect the threat before the threat detects the platform.

Signature control and expendable countermeasures have a high interaction, because signature and countermeasures have to be designed as a system. Reducing signature can help to make expendable countermeasures more effective, by making the countermeasure an even more desirable target compared with the platform.

Signature control and counter fire have a low interaction, because firing back at the enemy will increase visual signature because of the tracer and muzzle flash. This would be particularly pronounced during low visibility conditions such as darkness.

Signature control and manoeuvre have a high interaction, because the aspect of the aircraft with respect to the threat has a high influence on the resulting signature.

DNAE and NOE have a high interaction, because DNAE is an enabler to flying NOE. For example, clearly defined visuals in low light and at night would be essential in order to safely fly at low level.

DNAE and detect threats have a medium interaction because DNAE would assist the operator in detecting some threats in low light levels and in adverse weather. Night time and

adverse weather conditions may also effect the operation of threat detection equipment such as missile warning systems.

DNAE and expendable countermeasures have a medium interaction, because the SA provided to the pilot by DNAE may influence his decision to deploy expendables manually on a preventative basis. In addition, flares have the potential to 'blind' night vision sensors.

DNAE and counter fire have a medium interaction, because the ability for the pilot and crew to accurately detect and prosecute the target would be improved by DNAE capability. Rules of engagement and the desire to minimise collateral damage may also require accurate visual identification and targeting at night and in poor weather.

DNAE and manoeuvre have a medium interaction, because manoeuvring at low level and within terrain requires visibility of the ground in order to make an effective and safe manoeuvre. Such a manoeuvre may need to be carried out at night or in poor weather conditions.

NOE and detect threats have a medium interaction, because operating NOE may reduce sensor coverage compared to flying at higher level.

NOE and expendable countermeasures have a high interaction, because at very low level an expendable may not provide a target for sufficient time before reaching the ground (Ball 2003). If a flare burns for some time on the ground, then there is also a risk of fire. Rules of engagement and operating over built up areas may preclude the use of flares for this reason.

NOE and counter fire have a medium interaction, because operating NOE puts the aircraft in closer range to potential threats on the ground. A counter-fire capability can provide a suppressive fire effect, which would dissuade certain threats from attacking the platform. A visible counter fire capability may also prevent the aircraft from being attacked in the first place, and can therefore, serve as an effective deterrent.

NOE and manoeuvre have a medium interaction, because the ability to operate at low level should allow for contingency manoeuvres. Operating NOE will put additional workload on the pilot making manoeuvre more difficult. Additionally, the aircraft has less potential energy to perform a manoeuvre and may need to gain height because of constraints imposed by the terrain.

NOE and ballistic tolerance have a low interaction, because operating at NOE puts the aircraft at closer range to small arms and AAA. At closer range rounds would be more likely to hit the aircraft and would be at higher velocity. These conditions would impose significant requirements on ballistic tolerance.

NOE and fire / explosion suppression have a low interaction for the same reason as above.

Detect threats and expendable countermeasures have a high interaction, because for the expendables to work they require the threat to be detected correctly in the first place.

Detect threats and counter fire have a low interaction, because counter fire could be used against some threats to prevent a second shot. It is assumed that the first shot would be detected by the platform and declared to the crew, such that they could prosecute the target.

Detect threats and manoeuvre have a medium interaction, because accurate detection and declaration of the threat to the crew could allow an effective manoeuvre to be made. The interaction was not assessed to be high, because manoeuvre alone will not defeat all threats.

Expendable countermeasures and manoeuvre have a high interaction because deploying countermeasures will normally be associated with a manoeuvre, in order to increase countermeasure effectiveness. The tactics, training and procedures (TTPs) combine these attributes to maximise chances of survival.

Counter fire and manoeuvre have a high interaction, because the ability to fire back will depend upon the evasive manoeuvre being performed. A balance must be struck between manoeuvring to avoid the threat, whilst at the same time suppressing it. The pilot must provide a flight path that allows the gunner to prosecute the threat, whilst at the same time manoeuvring effectively.

Counter fire and ballistic tolerance have a medium interaction, because firing back would conceivably put the aircraft within range of small arms and AAA threats. Ballistic tolerance would help to protect the aircraft in the event of being hit by such a round.

Counter fire and fire / explosion suppression have a medium interaction for the same reason given above. A round impacting the aircraft could cause a fire or explosion if it was to hit an unprotected fuel tank or fuel system component.

Manoeuvre and ballistic tolerance have a low interaction, because performing a manoeuvre could conceivably present a less well protected part of the aircraft to the threat. This consideration would need to be taken into account at the design stage. Knowledge of the ballistic tolerance performance of the aircraft would assist the pilot in making an effective manoeuvre, whilst presenting a well protected aspect to the threat.

Ballistic tolerance and fire / explosion suppression have a high interaction, because these attributes would ideally be designed in together at the early design stage. For example, a fuel tank could be designed to be ballistically tolerant, in the sense that it would re-seal after being hit by a round. A potential fire or explosion risk created by any fuel that leaked during the re-seal process could be mitigated using a fire / explosion suppression system, such as an inert gas.

Ballistic tolerance and 'crashworthiness' have a medium interaction, because they would need to be considered together at the early structural design stage. A 'crashworthy' structure could also build in ballistic tolerance by the intelligent placement of material and primary and secondary systems. Where possible, secondary systems can be placed around primary ones to provide an element of 'weight neutral' protection.

Fire / explosion suppression and 'crashworthiness' have a high interaction because to be truly crashworthy a platform must allow the occupants to escape in the event of a crash. Clearly, fire is a major hazard in the event of a crash and crashworthy fuel systems that employ fire / explosion suppression can be designed to mitigate this risk.

## 7.6 Appendix F – Derivation of probability of survival

This derivation was performed by Earwicker (2007).

If we define $r$ as the rate of encounter, i.e.

$$r = Np_r \; (1)$$

where: $N$ - number of missions.

$p_r$ - probability of encountering threat on a mission.

If we assume a *Poisson Distribution* then the probability of encountering a threat $i$ times in $N$ missions is given as

$$P(i \mid N) = {}_N C_i \, p_r^i (1 - p_r)^{N-i} \; (2)$$

where: ${}_N C_i$ - is the *Binomial Coefficient* and is defined as the number of $i$-subsets that can be created from $N$ items.

The *Binomial Coefficient* can be expressed in terms of the subset $i$ and the total set $N$ giving

$$P(i \mid N) = \frac{N!}{i!(N-i)!} \, p_r^i (1 - p_r)^{N-i} \; (3)$$

*Poisson's Theorem* states that (3) can be approximated by

$$P(i \mid N) \approx \exp(- Np_r) \frac{(Np_r)^i}{i!} \; (4)$$

If we now substitute (1) into (4) we obtain the expression

$$P(i \mid N) \approx \exp(-r) \frac{r^i}{i!} \; (5)$$

If we now define $p$ as our probability of surviving a threat, then our probability of surviving a threat *if* we encounter it is given as

$$P(S) = \sum_{i=0}^{\infty} p^i \exp(-r) \frac{r^i}{i!} = \exp(-r) \sum_{i=0}^{\infty} \frac{(pr)^i}{i!} \; (6)$$

Then by the use of the *Taylor Series* we can express the summation in (6) as an exponent, giving

$$P(S) = \exp(-r)\exp(pr) = \exp(-r(1 - p)) \; (7)$$

## 7.7 Appendix G – Example power required for level flight calculations

### Table 7-3 - Chinook at sea level (ISA+20)

| Category | Symbol | Parameter | Units | Chinook | Chinook | Chinook | Chinook | Chinook | Chinook | Chinook | Chinook | Chinook |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Constants | k | Induced power factor | | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 |
| | g | Acc due to gravity | m/s^2 | 9.80665 | 9.80665 | 9.80665 | 9.80665 | 9.80665 | 9.80665 | 9.80665 | 9.80665 | 9.80665 |
| | n | | | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 |
| Platform specifics | σ | Solidity | | 0.085 | 0.085 | 0.085 | 0.085 | 0.085 | 0.085 | 0.085 | 0.085 | 0.085 |
| | δ | Blade average drag coefficient | | 0.008 | 0.008 | 0.008 | 0.008 | 0.008 | 0.008 | 0.008 | 0.008 | 0.008 |
| | R | Rotor radius | m | 9.145 | 9.145 | 9.145 | 9.145 | 9.145 | 9.145 | 9.145 | 9.145 | 9.145 |
| | N | No. rotor discs | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | | Tip speed | m/s | 225 | 225 | 225 | 225 | 225 | 225 | 225 | 225 | 225 |
| | m | Mass | kg | 16000 | 16000 | 16000 | 16000 | 16000 | 16000 | 16000 | 16000 | 16000 |
| | Pmax | Max engine power | W | 4695000 | 4695000 | 4695000 | 4695000 | 4695000 | 4695000 | 4695000 | 4695000 | 4695000 |
| | Pactual | Actual max engine power | W | 4695000 | 4695000 | 4695000 | 4695000 | 4695000 | 4695000 | 4695000 | 4695000 | 4695000 |
| | Cf | Coefficient of flat plate drag | | 0.0049 | 0.0049 | 0.0049 | 0.0049 | 0.0049 | 0.0049 | 0.0049 | 0.0049 | 0.0049 |
| Case specifics | V | Flight velocity | m/s | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 75 |
| | Vc | Climb velocity | m/s | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Altitude | m | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Temperature offset | K | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Calculated values | ρ | Air density | kg/m^3 | 1.145471811 | 1.145472 | 1.145472 | 1.145472 | 1.145472 | 1.145472 | 1.145472 | 1.145472 | 1.145472 |
| | ρ0 | Air density at sea level | kg/m^3 | 1.145471811 | 1.145472 | 1.145472 | 1.145472 | 1.145472 | 1.145472 | 1.145472 | 1.145472 | 1.145472 |
| | W | Weight | N | 156906.4 | 156906.4 | 156906.4 | 156906.4 | 156906.4 | 156906.4 | 156906.4 | 156906.4 | 156906.4 |
| | T | Thrust | N | 156906.4 | 156906.4 | 156906.4 | 156906.4 | 156906.4 | 156906.4 | 156906.4 | 156906.4 | 156906.4 |
| | A | Rotor disc area | m^2 | 525.4692275 | 525.4692 | 525.4692 | 525.4692 | 525.4692 | 525.4692 | 525.4692 | 525.4692 | 525.4692 |
| | CT | | | 0.005149249 | 0.005149 | 0.005149 | 0.005149 | 0.005149 | 0.005149 | 0.005149 | 0.005149 | 0.005149 |
| | PF | | | 6856133233 | 6.86E+09 | 6.86E+09 | 6.86E+09 | 6.86E+09 | 6.86E+09 | 6.86E+09 | 6.86E+09 | 6.86E+09 |
| | μ | | | 0 | 0.044444444 | 0.088889 | 0.133333 | 0.177778 | 0.222222 | 0.266667 | 0.311111 | 0.333333 |
| | f | Flat plate drag area | m^2 | 3.111306062 | 3.111306 | 3.111306 | 3.111306 | 3.111306 | 3.111306 | 3.111306 | 3.111306 | 3.111306 |
| Hover case | Pi | Induced power | W | 0.000300468 | 0.0003 | 0.0003 | 0.0003 | 0.0003 | 0.0003 | 0.0003 | 0.0003 | 0.0003 |
| | Po | Profile power | W | 0.000085 | 0.000085 | 0.000085 | 0.000085 | 0.000085 | 0.000085 | 0.000085 | 0.000085 | 0.000085 |
| | Phover | | W | 2642822 | 2642822 | 2642822 | 2642822 | 2642822 | 2642822 | 2642822 | 2642822 | 2642822 |
| | Phover margin | | W | 2052178 | 2052178 | 2052178 | 2052178 | 2052178 | 2052178 | 2052178 | 2052178 | 2052178 |
| Transit case | Pi | Induced power | W | #DIV/0! | 0.000343035 | 0.000172 | 0.000114 | 8.58E-05 | 6.86E-05 | 5.72E-05 | 4.9E-05 | 4.57E-05 |
| | Po | Profile power | W | 0.000085 | 8.57556E-05 | 8.8E-05 | 9.18E-05 | 9.71E-05 | 0.000104 | 0.000112 | 0.000122 | 0.000128 |
| | Pp | Parasite power | W | 0 | 1781.956695 | 14255.65 | 48112.83 | 114045.2 | 222744.6 | 384902.6 | 611211.1 | 751763 |
| | WVc | | W | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | P | Power required (theoretical) | W | #DIV/0! | 2941626 | 1793694 | 1461470 | 1367673 | 1405399 | 1546143 | 1783796 | 1939506 |

**Table 7-4 - Lynx data 1000m ASL (ISA +20)**

| Category | Symbol | Description | Units | Lynx | Lynx | Lynx | Lynx | Lynx | Lynx | Lynx | Lynx | Lynx |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Constants | k | Induced power factor | | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 |
| | g | Acc due to gravity | m/s^2 | 9.80665 | 9.80665 | 9.80665 | 9.80665 | 9.80665 | 9.80665 | 9.80665 | 9.80665 | 9.80665 |
| | n | | | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 |
| Platform specifics | $\sigma$ | Solidity | | 0.079 | 0.079 | 0.079 | 0.079 | 0.079 | 0.079 | 0.079 | 0.079 | 0.079 |
| | $\delta$ | Blade average drag coefficient | | 0.008 | 0.008 | 0.008 | 0.008 | 0.008 | 0.008 | 0.008 | 0.008 | 0.008 |
| | R | Rotor radius | m | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 |
| | N | No. rotor discs | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | | Tip speed | m/s | 215 | 215 | 215 | 215 | 215 | 215 | 215 | 215 | 215 |
| | m | Mass | kg | 5125 | 5125 | 5125 | 5125 | 5125 | 5125 | 5125 | 5125 | 5125 |
| | Pmax | Max engine power | W | 1328000 | 1328000 | 1328000 | 1328000 | 1328000 | 1328000 | 1328000 | 1328000 | 1328000 |
| | Pactual | Actual max engine power | W | 1203312 | 1203312 | 1203312 | 1203312 | 1203312 | 1203312 | 1203312 | 1203312 | 1203312 |
| | Cf | Coefficient of flat plate drag | | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 |
| Case specifics | V | Flight velocity | m/s | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 72 |
| | Vc | Climb velocity | m/s | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Altitude | m | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 | 1000 |
| | | Temperature offset | K | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Calculated values | $\rho$ | Air density | kg/m^3 | 1.03792125 | 1.03792125 | 1.037921 | 1.037921 | 1.037921 | 1.037921 | 1.037921 | 1.037921 | 1.037921 |
| | $\rho0$ | Air density at sea level | kg/m^3 | 1.145471811 | 1.145471811 | 1.145472 | 1.145472 | 1.145472 | 1.145472 | 1.145472 | 1.145472 | 1.145472 |
| | W | Weight | N | 50259.08125 | 50259.08125 | 50259.08 | 50259.08 | 50259.08 | 50259.08 | 50259.08 | 50259.08 | 50259.08 |
| | T | Thrust | N | 50259.08125 | 50259.08125 | 50259.08 | 50259.08 | 50259.08 | 50259.08 | 50259.08 | 50259.08 | 50259.08 |
| | A | Rotor disc area | m^2 | 128.6796351 | 128.6796351 | 128.6796 | 128.6796 | 128.6796 | 128.6796 | 128.6796 | 128.6796 | 128.6796 |
| | CT | | | 0.008140731 | 0.008140731 | 0.008141 | 0.008141 | 0.008141 | 0.008141 | 0.008141 | 0.008141 | 0.008141 |
| | PF | | | 1327362684 | 1327362684 | 1.33E+09 | 1.33E+09 | 1.33E+09 | 1.33E+09 | 1.33E+09 | 1.33E+09 | 1.33E+09 |
| | $\mu$ | | | 0 | 0.046511628 | 0.093023 | 0.139535 | 0.186047 | 0.232558 | 0.27907 | 0.325581 | 0.334884 |
| | f | Flat plate drag area | m^2 | 1.189020214 | 1.189020214 | 1.18902 | 1.18902 | 1.18902 | 1.18902 | 1.18902 | 1.18902 | 1.18902 |
| Hover case | Pi | Induced power | | 0.00059728 | 0.00059728 | 0.000597 | 0.000597 | 0.000597 | 0.000597 | 0.000597 | 0.000597 | 0.000597 |
| | Po | Profile power | | 0.000079 | 0.000079 | 0.000079 | 0.000079 | 0.000079 | 0.000079 | 0.000079 | 0.000079 | 0.000079 |
| | Phover | | W | 897669 | 897669 | 897669 | 897669 | 897669 | 897669 | 897669 | 897669 | 897669 |
| | Phover margin | | W | 305643 | 305643 | 305643 | 305643 | 305643 | 305643 | 305643 | 305643 | 305643 |
| Transit case | Pi | Induced power | | #DIV/0! | 0.000819281 | 0.00041 | 0.000273 | 0.000205 | 0.000164 | 0.000137 | 0.000117 | 0.000114 |
| | Po | Profile power | | 0.000079 | 7.97691E-05 | 8.21E-05 | 8.59E-05 | 9.13E-05 | 9.82E-05 | 0.000107 | 0.000117 | 0.000119 |
| | Pp | Parasite power | | 0 | 617.0546734 | 4936.437 | 16660.48 | 39491.5 | 77131.83 | 133283.8 | 211649.8 | 230314.4 |
| | WVc | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | P | Power required (theoretical) | W | #DIV/0! | 1193983 | 657623 | 493204 | 432557 | 425011 | 456143 | 521887 | 539135 |

**Table 7-5 - Atmospheric constants**

| | |
|---|---|
| Sea level standard atmospheric pressure p0 = 101325 Pa | 101325 |
| Sea level standard temperature T0 = 288.15 K | 288.15 |
| Earth-surface gravitational acceleration g = 9.80665 m/s2. | 9.80665 |
| Temperature lapse rate L = -0.0065 K/m | -0.0065 |
| Universal gas constant R = 8.31447 J/(mol·K) | 8.31447 |
| Molecular weight of dry air M = 0.0289644 kg/mol | 0.0289644 |

**Table 7-6 - Air density calculations.**

| Altitude h, m | 0 | 500 | 1000 | 1500 | 2000 | 2500 | 3000 |
|---|---|---|---|---|---|---|---|
| Temperature offset, K | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| Temperature T, K | 308.15 | 304.9 | 301.65 | 298.4 | 295.15 | 291.9 | 288.65 |
| Pressure p, Pa | 101325 | 95460.94 | 89874.76 | 84556.28 | 79495.56 | 74682.94 | 70109.01 |
| Density kg/m3 | 1.145 | 1.091 | 1.038 | 0.987 | 0.938 | 0.891 | 0.846 |

**Table 7-7 - Chinook theoretical climb rate data for 16 000kg AUM and ISA +20.**

| Platform | Chinook | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Flight Velocity | 0 | 20 | 30 | 40 | 50 | 60 | 70 | 75 |
| Max engine power (sea level) | 4695000 | 4695000 | 4695000 | 4695000 | 4695000 | 4695000 | 4695000 | 4695000 |
| P level flight (sea level) | 2642822 | 1793694 | 1461470 | 1367673 | 1405399 | 1546143 | 1783796 | 1939506 |
| P real (sea level) | 3435669 | 2331802 | 1899911 | 1777975 | 1827019 | 2009986 | 2318935 | 2521357 |
| P inst - P real | 1259331 | 2363198 | 2795089 | 2917025 | 2867981 | 2685014 | 2376065 | 2173643 |
| Vc climb rate (m/s) | 79 | 148 | 175 | 182 | 179 | 168 | 149 | 136 |
| Climb rate score | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| Max engine power (1000m) | 4254177 | 4254177 | 4254177 | 4254177 | 4254177 | 4254177 | 4254177 | 4254177 |
| P level flight (1000m) | 2692207 | 1857545 | 1479093 | 1355392 | 1366349 | 1478394 | 1682674 | 1819339 |
| P real (1000m) | 3499869 | 2414809 | 1922821 | 1762009 | 1776254 | 1921912 | 2187476 | 2365141 |
| P inst - P real | 754308 | 1839368 | 2331357 | 2492168 | 2477923 | 2332265 | 2066702 | 1889037 |
| Vc climb rate (m/s) | 47 | 115 | 146 | 156 | 155 | 146 | 129 | 118 |
| Climb rate score | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| Max engine power (2000m) | 3845752 | 3845752 | 3845752 | 3845752 | 3845752 | 3845752 | 3845752 | 3845752 |
| P level flight (2000m) | 2753530 | 1941635 | 1512041 | 1356479 | 1340142 | 1423935 | 1596106 | 1714652 |
| P real (2000m) | 3579589 | 2524125 | 1965654 | 1763422 | 1742184 | 1851115 | 2074938 | 2229047 |
| P inst - P real | 266163 | 1321626 | 1880098 | 2082330 | 2103567 | 1994637 | 1770814 | 1616704 |
| Vc climb rate (m/s) | 17 | 83 | 118 | 130 | 131 | 125 | 111 | 101 |
| Climb rate score | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| Max engine power (3000m) | 3468035 | 3468035 | 3468035 | 3468035 | 3468035 | 3468035 | 3468035 | 3468035 |
| P level flight (3000m) | 2827396 | 2048296 | 1561775 | 1371931 | 1327463 | 1383201 | 1524302 | 1625541 |
| P real (3000m) | 3675615 | 2662785 | 2030308 | 1783510 | 1725701 | 1798162 | 1981593 | 2113203 |
| P inst - P real | -207580 | 805249 | 1437727 | 1684524 | 1742333 | 1669873 | 1486442 | 1354831 |
| Vc climb rate (m/s) | -13 | 50 | 90 | 105 | 109 | 104 | 93 | 85 |
| Climb rate score | 0 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |

**Table 7-8 - Lynx theoretical climb rate data for 5 125kg AUM, ISA +20**

| Platform | Lynx | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Flight Velocity | 0 | 20 | 30 | 40 | 50 | 60 | 70 | 72 |
| Max engine power (sea level) | 1328000 | 1328000 | 1328000 | 1328000 | 1328000 | 1328000 | 1328000 | 1328000 |
| P level flight (sea level) | 870398 | 618371 | 472713 | 423681 | 426093 | 467610 | 545281 | 565169 |
| P real (sea level) | 1131518 | 803882 | 614527 | 550786 | 553920 | 607893 | 708865 | 734719 |
| P inst - P real | 196482 | 524118 | 713473 | 777214 | 774080 | 720107 | 619135 | 593281 |
| Vc climb rate (m/s) | 38 | 102 | 139 | 152 | 151 | 141 | 121 | 116 |
| Climb rate score | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| Max engine power (1000m) | 1203312 | 1203312 | 1203312 | 1203312 | 1203312 | 1203312 | 1203312 | 1203312 |
| P level flight (1000m) | 897669 | 657623 | 493204 | 432557 | 425011 | 456143 | 521887 | 539135 |
| P real (1000m) | 1166969 | 854910 | 641165 | 562324 | 552514 | 592985 | 678453 | 700876 |
| P inst - P real | 36342 | 348401 | 562146 | 640987 | 650797 | 610326 | 524859 | 502436 |
| Vc climb rate (m/s) | 7 | 68 | 110 | 125 | 127 | 119 | 102 | 98 |
| Climb rate score | 1 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| Max engine power (2000m) | 1087787 | 1087787 | 1087787 | 1087787 | 1087787 | 1087787 | 1087787 | 1087787 |
| P level flight (2000m) | 928638 | 704436 | 519153 | 446004 | 428187 | 449000 | 503197 | 517916 |
| P real (2000m) | 1207230 | 915767 | 674899 | 579805 | 556643 | 583700 | 654155 | 673291 |
| P inst - P real | -119443 | 172020 | 412888 | 507982 | 531144 | 504087 | 433631 | 414495 |
| Vc climb rate (m/s) | -23 | 34 | 81 | 99 | 104 | 98 | 85 | 81 |
| Climb rate score | 0 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| Max engine power (3000m) | 980948 | 980948 | 980948 | 980948 | 980948 | 980948 | 980948 | 980948 |
| P level flight (3000m) | 963563 | 759835 | 551221 | 464492 | 435966 | 446429 | 489370 | 501656 |
| P real (3000m) | 1252632 | 987786 | 716587 | 603839 | 566756 | 580358 | 636181 | 652152 |
| P inst - P real | -271684 | -6838 | 264360 | 377108 | 414192 | 400590 | 344766 | 328795 |
| Vc climb rate (m/s) | -53 | -1 | 52 | 74 | 81 | 78 | 67 | 64 |
| Climb rate score | 0 | 0 | 9 | 9 | 9 | 9 | 9 | 9 |

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