CRANFIELD UNIVERSITY

FRANCISCO JAVIER ROMERO ROJO

DEVELOPMENT OF A FRAMEWORK FOR OBSOLESCENCE RESOLUTION COST ESTIMATION

SCHOOL OF APPLIED SCIENCES

PhD THESIS
Academic Year: 2007 - 2010

Supervisors: Prof. Rajkumar Roy and Dr. Essam Shehab
March 2011

CRANFIELD UNIVERSITY

SCHOOL OF APPLIED SCIENCES

PhD THESIS

Academic Year 2007 - 2010

FRANCISCO JAVIER ROMERO ROJO

Development of a Framework for Obsolescence Resolution Cost Estimation

Supervisors: Prof. Rajkumar Roy and Dr. Essam Shehab

March 2011

This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

THIS PAGE IS INTENTIONALLY LEFT BLANK

ABSTRACT

Currently, manufacturing organisations worldwide are shifting their business models towards Product-Service Systems (PSS), which implies the development of new support agreements such as availability-based contracts. This transition is shifting the responsibilities for managing and resolving obsolescence issues from the customer to the prime contractor and industry work share partners. This new scenario has triggered a new need to estimate the Non-Recurring Engineering (NRE) cost of resolving obsolescence issues at the bidding stage, so it can be included in the support contract. Hence, the aim of this research is to develop an understanding about all types of obsolescence and develop methodologies for the estimation of NRE costs of hardware (electronic, electrical and electromechanical (EEE) components and materials) obsolescence that can be used at the bidding stage for support contracts in the defence and aerospace sectors.

For the accomplishment of this aim, an extensive literature review of the related themes to the research area was carried out. It was found that there is a lack of methodologies for the cost estimation of obsolescence, and also a lack of understanding on the different types of obsolescence such as materials and software obsolescence. A systematic industrial investigation corroborated these findings and revealed the current practice in the UK defence sector for cost estimation at the bidding stage, obsolescence management and obsolescence cost estimation. It facilitated the development of an understanding about obsolescence in hardware and software. Further collaboration with experts from more than 14 organisations enabled the iterative development of the EEE-FORCE and M-FORCE frameworks, which can be used at the bidding stage of support contracts to estimate the NRE costs incurred during the contracted period in resolving obsolescence issues in EEE components and materials, respectively. These frameworks were implemented within a prototype software platform that was applied to 13 case studies for expert validation.

Keywords: Obsolescence Management, DMSMS, Product-Service Systems

THIS PAGE IS INTENTIONALLY LEFT BLANK

ACKNOWLEDGEMENTS

I would like to take the opportunity to thank all the people who have collaborated on this project and those who have supported me during this time.

First and foremost, I must sincerely thank my supervisors Professor Rajkumar Roy and Dr Essam Shehab, and my project manager Dr Kalyan Cheruvu. Their guidance, constructive criticism and advice have been determinant for the success of this thesis. Thanks also to Professor Steve Evans, my subject advisor, for his valuable input during the first two years of the PhD.

It has been a great pleasure working with my colleagues in the PSS-COST project Johnny, Mac and Tola. All of the staff and students in the Manufacturing Department contributed to make this research an enjoyable and rewarding experience. In particular, I am grateful to Teresa and Emanuela for their support with the paperwork.

I am thankful to the funding bodies of this research the Engineering and Physical Sciences Research Council (EPSRC) and the Cranfield University's Innovative Manufacturing Research Centre (IMRC); and its industrial collaborators MoD DE&S, BAE Systems, GE Aviation, Rolls Royce, Lockheed Martin, Thales Aerospace, Selex Galileo, APMP, SBAC, Galorath and Cognition.

I would like to express my gratitude to Phil Wardle, Martin Call, Phil Mason Stuart Kelly and Adrian Gath, for their superb collaboration in the development of this project. I would also like to acknowledge Terry Rees-Pedlar, John Clatworthy, Tony Cheesmar, Dave Broadley, Ian Blackman, Dave Nuttall, David Gort, David Lynch, Aury Sanguinet, Andy Long, Keith Houfe, Derek Loughlin, Lesley Dutton, Graham Perry, Paul Carter, Graeme Rumney, Terry Johns and all the COG members for their collaboration in this study.

Finally, I am ever grateful to my parents, Anselmo and Raquel, and the rest of my family for their ongoing love and support during my time in Cranfield, and to all the friends I have met here, especially Amir, João, Maksim, Nancy, Howard, Partha, Edu, Jan, Greg, Jami, Jeff, Mansoor, Tomasz, Marco, Pablo, Buphi, Sirish, Konrad, Jeremy, Alexis and Prakash; as well as those who have supported me from Spain, especially, Luis, Juan and Fernando. Lastly, I express my deepest gratitude to Lourdes for her love, care and encouragement during the writing-up of this thesis.

FRAN ROMERO

LIST OF PUBLICATIONS

Journal Papers

1. Romero Rojo, F.J., Roy, R. and Shehab, E. (2009). Obsolescence Management for Defence and Aerospace Systems: State of the Art and Future Trends. *International Journal of Advanced Manufacturing Technology (IJAMT)*, vol. 49, no. 9-12, pp. 1235-1250. DOI: 10.1007/s00170-009-2471-3

2. Romero Rojo, F.J., Roy, R., Shehab, E., Cheruvu, K. And Mason, P. (2011). A Cost Estimating Framework for Electronic, Electrical and Electromechanical (EEE) Components Obsolescence within the Use-Oriented Product-Service Systems Contracts. *Proceedings of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacture*, In Press. DOI: 10.1177/0954405411406774

3. Romero Rojo, F.J., Roy, R., Shehab, E. and Cheruvu, K. (2011). A Study on Obsolescence Resolution Profiles. Accepted for publication in *Proceedings of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacture,* In Press.

Conference Papers

1. Romero Rojo, F.J., Roy, R., Shehab, E. and Wardle, P. (2009). Obsolescence Challenges for Product-Service Systems in Aerospace and defence Industry. *The 1st CIRP Industrial Product-Service Systems (IPS2) Conference*, 1st – 2nd April 2009, Cranfield University, UK, pp 255-260.

2. Romero Rojo, F.J., Roy, R., Shehab E. and Cheruvu, K. (2010). A Cost Estimating Framework for Materials Obsolescence in Product-Service Systems*, 2010 ISPA/SCEA Conference*, San Diego, CA, USA, 8th – 11th June 2010.

3. Romero Rojo, F.J., Roy, R., Shehab, E., Cheruvu, K., Blackman, I. and Rumney, G.A. (2010). Key Challenges in Managing Software Obsolescence for Industrial Product-Service Systems (IPS2). *The 2nd CIRP Industrial Product-Service Systems (IPS2) Conference*, Sweden, 14th–15th April 2010.

4. Romero Rojo, F.J., Roy, R., Shehab, E., Call, M. and Wardle, P. (2011). Hardware obsolescence cost drivers for product support. Accepted for publication in *24th International Congress on Condition Monitoring and Diagnostics Engineering Management (COMADEM2011)*, Stavanger, Norway, 30th May – 1st June 2011.

5. Roy, R., Datta, P., Romero Rojo, F.J. and Erkoyuncu, J. (2009). Cost of Industrial Product-Service Systems (IPS2). *16th CIRP International Conference on Life Cycle Engineering*, Cairo, Egypt, 3rd – 6th May 2009.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AACE	Association for the Advancement of Cost Engineering
ABC	Activity-Based Costing
AHP	Analytic Hierarchy Process
AMMO	Ammunition
ASIC	Application Specific Integrated Circuit
BAe	British Aerospace
BoM	Bill of Materials
BS	British Standard
CADMID	Concept, Assessment, Demonstration, Manufacture, In-Service and Disposal
CADMIT	Concept, Assessment, Demonstration, Manufacture, In-Service and Termination
CERs	Cost Estimation Relationships
CfA	Contracting for Availability
COG	Component Obsolescence Group
COTS	Commercial off-the-shelf
CPU	Central Processing Unit
DA	Design Authority
DE&S	Defence Equipment and Support
DMEA	Defense MicroElectronics Activity
DMSMS	Diminishing Manufacturing Sources and Material Shortages
DoD	United States Department of Defence
DOI	Digital Object Identifier
DSP	Digital Signal Processing
EEE	Electronic, Electrical and Electromechanical
EEE-FORCE	Electronic, Electrical and Electromechanical - Framework for Obsolescence Robust Cost Estimation
EPSRC	Engineering and Physical Sciences Research Council
ERP	Enterprise Resource Planning
ES	European Standard
FFF	Form, Fit and Function
GAO	General Accounting Office

GE	General Electric
GEC	General Electric Company plc
H/W	Hardware
IEC	International Electrotechnical Commission
ILS	Integrated Logistics Support
IMRC	Innovative Manufacturing Research Centre
IT	Information Technology
ITT	Invitation To Tender
LCC	Life Cycle Cost
LCD	Liquid Crystal Display
LOT	Life-of-Type
LRU	Line-Replaceable Unit
LTB	Life-time Buy or Last-time Buy
MDAL	Master Data and Assumptions List
M-FORCE	Materials - Framework for Obsolescence Robust Cost Estimation
MOCA	Mitigation of Obsolescence Cost Analysis
MoD	United Kingdom Ministry of Defence
MOQ	Minimum Order Quantities
MS	Microsoft
MSI	Medium-Scale Integration
MTBF	Mean Time Between Failures
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NPV	Net Present Value
NRE	Non-Recurring Engineering
OCM	Obsolescence Cost Metrics
OEM	Original Equipment Manufacturer
OM	Obsolescence Management
OMP	Obsolescence Management Plan
ORPs	Obsolescence Resolution Profiles
PBL	Performance-Based Logistics
PBS	Product Breakdown Structure

PCB	Printed Circuit Board
PCN	Product Change Notification
PhD	Doctor of Philosophy
plc	Public Limited Company
PSS	Product-Service Systems
PSS-Cost	Whole Life Cost Modelling for Product-Service Systems
PTFE	Polytetrafluoroethyle
R2T2	Rapid Response Technology Trade
RAM	Random Access Memory
RoHS	Restriction of Hazardous Substances Directive
ROI	Return on Investment
ROM	Rough Order of Magnitude
ROM	Read Only Memory
S/W	Software
SBAC	Society of British Aerospace Companies
SDE	Software Development Environment
SRD	System Requirement Document
SSI	Small-Scale Integration
STE	Software Target Environment
UK	United Kingdom
URD	User Requirement Document
US	United States
VBA	Visual Basic for Applications
VLSI	Very-Large-Scale Integration
WBS	Work Breakdown Structure
WLC	Whole Life Cycle
WLCC	Whole Life Cycle Cost

THIS PAGE IS INTENTIONALLY LEFT BLANK

Chapter 1

1 INTRODUCTION

In sectors such as defence and aerospace, the life cycle of a system can be extended over many decades. These systems are usually composed of low volume complex electronics, which are affected by the fast changing market trends and the ongoing technical revolution in the electronics industry (Meyer et al., 2004). These are called sustainment-dominated systems, which are characterised by high costs associated with their redesign because of the strict requalification requirements (Singh and Sandborn, 2005) and little or no control over their supply chain because of their low production volumes (Condra, 1999; Sandborn, 2007a; Singh and Sandborn, 2005; Feng et al., 2007) (e.g. aircrafts, battleships, submarines). Due to the high costs and long life times associated with technology insertion and design refresh, these systems often fall behind the technology wave (Sandborn et al., 2007; Singh and Sandborn, 2006; Madisetti et al., 2000).

Many authors agree that the life cycle of the components is usually shorter than the life cycle of the system they are built in (Pecht and Das, 2000; Solomon et al., 2000; Feldman and Sandborn, 2007; Singh et al., 2004; Hitt and Schmidt, 1998; Josias et al., 2004; Condra, 1999; Feng et al., 2007; Meyer et al., 2003). This explains why many components are reaching the end-of-life at increased rates in many avionics and military systems (Solomon et al., 2000; Weaver and

Ford, 2003; Kerr et al., 2008; Cheung et al., 2009; Luke et al., 1999), and hence becoming no longer procurable, that is to say, obsolete. Furthermore, the rapid growth of the electronics industry, which is bringing about fast technological changes, and the diminishing demand for aged components, are exacerbating the obsolescence of electronic, electrical and electromechanical (EEE) components (Feldman and Sandborn, 2007; Howard, 2002; Craig et al., 2002; Frank and Morgan, 2007; Mont, 2004; Solomon et al., 2000; Tryling, 2007; Tomczykowski, 2003). This research is mainly focused on the defence and aerospace sectors. Frequently, for defence systems and avionics, 70-80% of the electronic components of the system become obsolete before the system has been fielded (Sandborn, 2007a; Solomon et al., 2000; Howard, 2002; Singh et al., 2004; Hitt and Schmidt, 1998; Singh and Sandborn, 2006; Livingston, 2000).

It is necessary to review the last 50 years of the history of the military to understand its current circumstances. In the 60s and 70s, the military was able to define and control design specifications and requirements of the system, because they were developed exclusively for the military (Josias et al., 2004). However, in the 80s the electronic components industry boomed (Josias et al., 2004), and the end of the Cold War put pressure on cutting military expenses (Singh and Sandborn, 2006). By the early 90s, manufacturers migrated away from the low volume military market and focused their efforts on the more profitable commercial market (Hitt and Schmidt, 1998; Redling, 2004; Humphrey et al., 2000). The consequence is that from the 80s onwards, obsolescence has become a major issue for the defence and the aerospace industry (Hitt and Schmidt, 1998; Torresen and Lovland, 2007; Barton and Chawla, 2003). Undoubtedly, obsolescence has become one of the main costs in the life cycle of sustainment-dominated systems (Pecht and Das, 2000; Solomon et al., 2000; Singh et al., 2004; Josias et al., 2004; Sandborn et al., 2007; Torresen and Lovland, 2007). For instance, the prime contractor for the Eurofighter project has declared that obsolescence is the No.2 risk to the project and it is taking vast amounts of money to design out obsolescence from one version of the aircraft to the next. The estimate of the total through-life obsolescence costs for the Nimrod MRA4 is £782.3M, according to the Obsolescence Scoping Exercise (QinetiQ ref: D&TS/CS/TR058826, Nov 2005). In United States, the obsolescence issues cost up to $750 million annually according to the US Navy estimations (Adams, 2005).

In the defence sector it is common to describe the life cycle using the CADMID cycle, which is divided into six phases: Concept, Assessment, Demonstration, Manufacture, In-Service and Disposal. The maintenance service required for sustainment-dominated systems during the in-service phase is generally covered by support contracts. Traditionally, these contracts were limited to the provision of transactional goods and services such as spares and repairs. Consequently, any obsolescence issue would be resolved reactively and the risk will lay directly on the customer, who will have to pay for it on a case-by-case basis. The costs incurred during this phase are much higher than the original purchase price (Singh and Sandborn, 2005), and for the military, the main objective is to obtain reliable operational capability for systems at the lowest possible cost (Redling, 2004). Therefore, the United Kingdom Ministry of Defence (MoD) and the US Department of Defence (DoD) are promoting a move towards new types of support agreement that provide better value for money such as capability and availability based contracts, also known as Performance-Based Logistics (PBL) (Johnsen et al, 2009; Stein and Wadey, 2008). The essence of availability contracts is that the suppliers are paid for achieving an availability target for the sustainment-dominated system (typically expressed as a percentage, e.g. “available 99.50% of the time”) and not just for the delivery of the product and spares/repairs. The increased level of service provides the customer with higher value at reduced through-life cost. This transition is shifting the responsibilities for managing and resolving obsolescence issues from the customer to the prime contractor and industry work share partners, who are in a better position to manage them in the most cost-effective way (Josias et al., 2004; Webb and Bil, 2010).

Prior to signing a support contract, a bidding process is usually followed to select the contractor that will provide better value for money to the customer. At this stage it is important to make accurate cost estimations for the support cost, as they will become the basis of the negotiation. This new scenario has triggered a new need to estimate the Non-Recurring Engineering (NRE) cost of obsolescence at the bidding stage, so it can be included in the support contract. The NRE cost of obsolescence represents the exclusive cost of resolving the obsolescence issues not considered as part of the maintenance routine.

1.1 Research Aim

As explained above, obsolescence is important in any complex engineering system with long life. Customers are shifting the risk management in the availability contracts to reduce whole life cost. This is why the study of obsolescence is becoming more important, especially to forecast, at the bidding stage, the impact that it will have during support contracts. In view of this research problem, the aim of this thesis is:

To develop an understanding concerning all types of obsolescence and develop methodologies for the estimation of NRE costs of hardware (EEE components and materials) obsolescence that can be used at the bidding stage for support contracts in the defence and aerospace sectors.

1.2 Support Contracts (Service Contracts)

Based on the life-cycle phases covered, the contracts in the defence and aerospace sector can be broadly divided into three types: design, manufacture and support (see Figure 1-1). In general, for big projects, each phase is contracted independently to incentivise competition among the possible contractors and ensure best value for money. However, this strategy is usually combined with keeping long-term partnerships, which incentivise industry to drive down costs but allow increased profits for good performance and delivery (DIS, 2005). Therefore it is common that design and manufacture are brought together under one contract, which will subsequently lead to a support contract.

The scope of this research is focused on support contracts, which is where obsolescence entails a major risk due to its long duration.

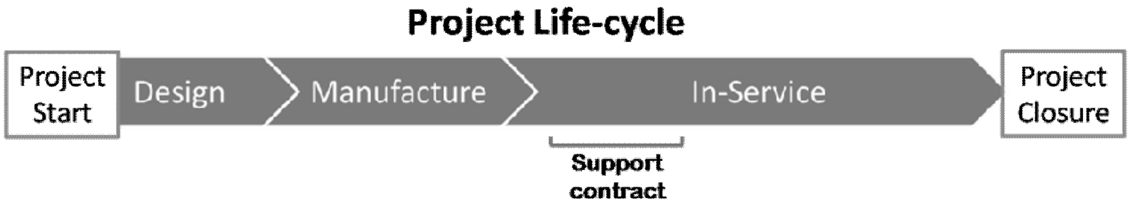


Figure 1-1 Project Life-cycle Phases

A support (service) contract refers to "an agreement to perform services relating to the maintenance or repair of a product for a specified duration" (Day and Fox, 1985). Support contracts may cover the whole in-service phase of the system or periods within it. It is common that the support contract is agreed for periods of five to ten years, and continuously renewed throughout the in-service phase.

Traditionally, the support of systems was only focused on maintenance and repair issues, such as delivery of spare/warranty parts, field service, and expert assistance. However, customers purchasing sustainment-dominated systems are currently moving towards new types of agreement that provide better value for money such as capability and availability based contracts (Stremersch et al., 2001; Mathieu, 2001; Goffin, 1999; Bosworth, 1995; Kumar et al., 2004), which are enabled by Product-Service System (PSS) business models (Kapletia and Probert, 2010).

A Product-Service System (PSS) can be defined as “an integrated product and service offering that delivers value in use” (Baines et al., 2007). Mont (2002) states that “the successful development of a PSS requires that manufacturers and service providers extend their involvement and responsibility to phases in the life cycle”. A PSS is generally classified into three main categories, as shown in Figure 1-2: (Behrend et al., 2003; Zaring, 2001; Brezet et al., 2001; Cook, 2004; Meier et al., 2010; Roy and Cheruvu, 2009; Datta and Roy, 2010).

1. Product-oriented, where the tangible product is owned by the consumer and additional services, such as maintenance, are provided. This business model is usually referred to as traditional spares and repairs contract.
2. Use-oriented, where the ownership of the tangible product can be retained by the service provider or transferred to the customer, but the service provider is responsible for ensuring that the product is available. This business model is usually referred to as an availability contract or Performance-Based Logistics (PBL).
3. Result-oriented, where the customer and service provider agree on a desired outcome without necessarily specifying the product involved. This business model is usually referred to as a capability contract.

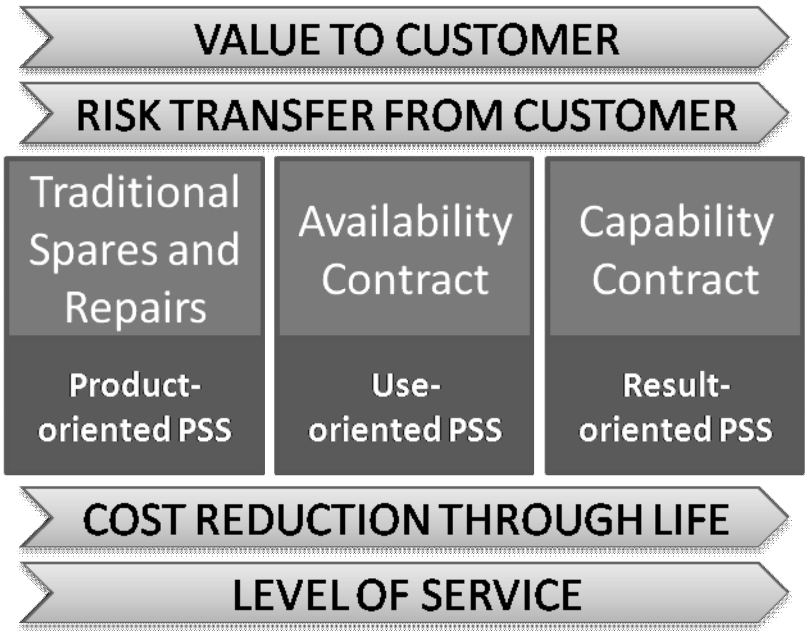


Figure 1-2 Types of PSS – Support Contracts

This evolution in support contracting requires a change in the business model, enabled by a transition in the contractor's culture. It incentivises the contractor to implement proactive measures that reduce through-life costs and increase system's availability. The key of this shift is to reward the contractor for the work done by the system rather than for the work done on the system (Vitasek et al., 2006; Johnsen et al., 2009; Ng and Nudurupati, 2010; Datta and Roy, 2010), aligning the interest of the contractor with the customer as shown in Figure 1-3. Therefore, the aim is to incentivise the contractor to implement proactive measures that reduce through-life costs and increase system's availability. However, during the support period, a key problem that may hinder the availability of these systems is obsolescence.

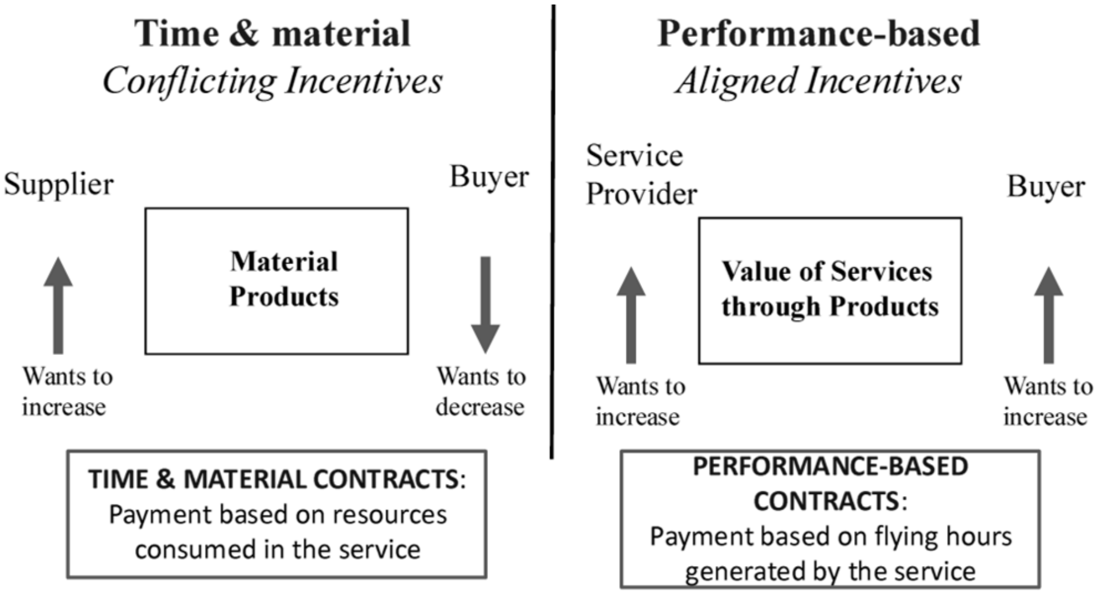


Figure 1-3 Traditional Support vs. Performance-Based Logistics (Adapted from (Kanda and Nakagami, 2006))

1.2.1 Availability Contracts (Performance-Based Logistics)

As explained above, support contracts are evolving towards Availability Contracts, also known as Performance-Based Logistics, rewarding the contractor for ensuring the availability of the system. Many authors agree that this type of contracts provide a win-win situation for both the customer and the contractor, improving readiness and availability of the system (Vitasek et al., 2006; Kapletia and Probert, 2010). In the US Navy there are many examples of material availability improvements after moving from traditional support contracts, such as the F/A-18 C/D system (availability increased from 67% to 85%) and the Aegis cruiser (availability increased from 62% to 94%) (Vitasek et al., 2006). Likewise, Guajardo et al. (2010) carried out an empirical study in which they conclude that system's reliability increases in 20-40% when moving from a traditional support contract to a Performance-Based contract.

According to Kumar et al. (2004), availability of a system depends on three main parameters, namely, reliability, maintainability and supportability as shown in Figure 1-4.

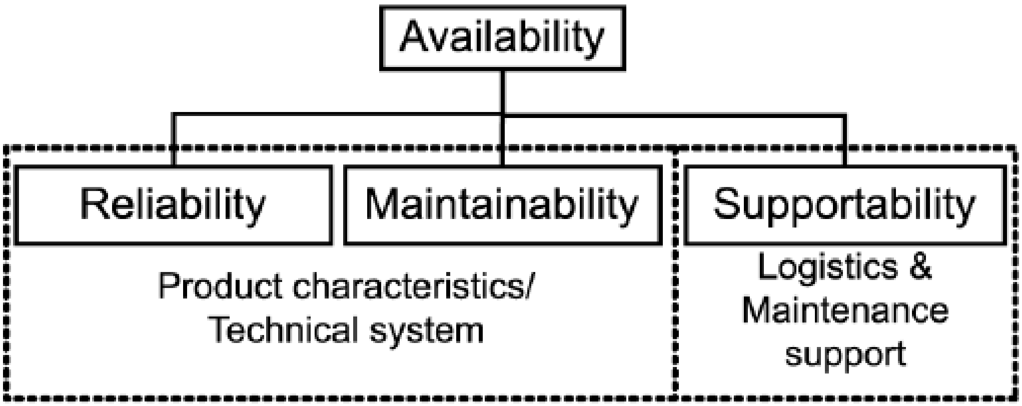


Figure 1-4 Elements of System Availability (Adopted from (Kumar et al., 2004))

- Reliability

It measures the frequency of failure in a system. This can be characterised by the failure rates of components (Kumar et al., 2004).

- Maintainability

It measures how safe, efficient, effective, accurate, and easy the maintenance actions related to the system can be performed (Kumar et al., 2004).

- Supportability

It measures how safe, cost effective, and easy, it is to support the product (e.g. logistics and maintenance support) (Kumar et al., 2004).

In terms of the bidding process followed in contracting for support, the literature is underdeveloped (Zitron, 2006). Therefore, information related to this process has to be captured directly from industry.

1.3 Introduction to Obsolescence

An obsolescence issue arises when a component is no longer; available from stock of own spares, procurable, nor produced by its original manufacturer at the original specifications (Singh et al., 2002; Meyer et al., 2004; Pecht and Das, 2000; Sandborn, 2007a; Solomon et al., 2000; Hoppin, 2002). Along these lines, obsolescence can be defined as "the loss or impending loss of original manufacturers of items or suppliers of items or raw materials" (Feldman and Sandborn, 2007). Pecht and Das (2000) regard a component as obsolete only when the technology that defines it is no longer implemented. However, in this research, and widely across industry and literature, the term obsolescence includes also discontinuance in the production of a component for any other reason such as financial or legal. Among the reasons for obsolescence the most common are enumerated as follows (COG, 2010).

- Technological progress -The innovation cycles, with which components come on the market, become ever shorter and even faster.
- Component manufacturers re-assess their product offerings and trim down many non-profitable lines.
- Changes in the standardization. Old standards are no longer available and are no longer maintained.
- Legislation changes. E.g. concerning asbestos, cadmium and lead tin solder (RoHS).
- The Original Manufacturer is no longer in business.
- The processes, tools and the knowledge for maintenance, update or improvement of software are no longer available.

Many authors (Pecht and Das, 2000; Feldman and Sandborn, 2007; Howard, 2002; Craig et al., 2002; Frank and Morgan, 2007; Mont, 2004) agree that electronic parts are becoming obsolete at a fast pace due to the rapid growth of the electronics industry and the potential impact on readiness and supportability are more immediate. Hitherto, the descriptions about the problem of obsolescence have been mainly related to EEE components, but it is not restricted to them. Obsolescence also concerns other parts of the system such as mechanical components, test equipment, processes and software. As shown in Table 1-1, the types of obsolescence can be grouped into three main categories; electronic, electrical and electromechanical (EEE) components, materials and software.

Table 1-1 Types of Obsolescence

	EEE	MATERIALS	SOFTWARE
Mechanical Components		●	
Processes and Procedures		●	
Software			●
Electronic Components	●		
Electrical Components	●		
Electromechanical Components	●		
Media	●	●	●
Skills and Knowledge		●	●
Manufacturing Tooling		●	
Test Equipment	●	●	●

➢ **Mechanical Components and Materials**

Mechanical parts in aging systems break down frequently and in unexpected ways (Howard, 2002). Failures of these parts can trigger obsolescence when the system reaches the aging phase due to the potential unavailability of spares and materials. As suppliers develop stronger, lighter, and more damage resistant materials, older materials become obsolete and phase out for new production (Howard, 2002). The new materials may be better in many respects, but do not always have the right mechanical or chemical properties to be a direct replacement for an older material. The lack of a direct replacement may drive a component redesign, and consequently it will have an impact on the Whole Life Cycle Cost (WLCC) of the system. Materials often become obsolete due to new environmental regulations such as the Restriction of Hazardous Substances Directive (RoHS) (Brewin, 2005). Moreover, it is common that during the in-service phase the materials are only required in small quantities. It clashes with the high Minimum Order Quantities (MOQ) imposed by many suppliers, hindering their sourcing and triggering obsolescence issues.

- **Processes and Procedures**

Changes in the environmental regulations are the most common drivers of obsolescence in manufacturing processes (Howard, 2002). In the light of this, a material obsolescence issue can make a manufacturing process obsolete and also the obsolescence of a manufacturing process can prevent the manufacture of a material (with a particular set of specifications) making it obsolete. Therefore, these two areas are usually interrelated.

- **Software and Media**

In most complex systems, as Sandborn (2007b) stated, “software life cycle costs (redesign, re-hosting and re-qualification) contribute as much or more to the total life cycle cost as the hardware, and the hardware and software must be concurrently sustained”. Although software obsolescence is one important aspect that should be considered to estimate the whole life cycle costs (WLCC) of a system, little attention has been paid to this area so far. Indeed very few organisations in the defence industry are managing and costing software obsolescence properly (Sandborn, 2007b; Merola, 2006; Sandborn and Plunkett, 2006).

The technology used for storing data, software and documents is continuously changing. The fact that new technologies bring benefits (e.g. higher storage capacity, lower physical space, and higher data-transmission speed) and in general are not compatible with older technologies implies that periodically the media and formats need to be upgraded.

- **Skills and knowledge**

The skills and knowledge available within the organisation need to be managed wisely in order to avoid losing them if they may be required for the sustainment of long-life systems. This is the only type of obsolescence that can be completely mitigated by deploying appropriate obsolescence management strategies such as: keeping a “skill register” database, identifying potential skill shortages and tackling them with training schemes, outsourcing, using standarisation (preferred technology) to minimise the number of programming tools used across the organisation. If the skills obsolescence is not tackled, it can drive obsolescence issues in other areas such as software.

- **Manufacturing tooling**

The manufacturing aids required to fabricate the components are regarded as ‘tooling’ (e.g. forging dies, holding fixtures, sheet metal patterns, casting molds) (Howard, 2002). Obsolete tooling may need to be refurbished or recreated. Otherwise, it may impact on the manufacturing process. Likewise, a change in the manufacturing process driven by a change in material or form may cause the tooling to become obsolete.

- **Test equipment**

The test equipment becomes obsolete at the end of the production phase because it is no longer required (Howard, 2002). However it may be necessary to test if a replacement for a component is form, fit, function, and interface compliant to tackle a component obsolescence issue.

At the moment, few authors (Howard, 2002; Merola, 2006; Sandborn and Plunkett, 2006 Dowling, 2000; Dowling, 2004) have studied in-depth the obsolescence problem outside the electronics area. However, the obsolescence impact in each of these areas should not be underestimated.

1.4 The PSS-COST Project

This thesis represents a contribution to a bigger project *“Whole Life Cost Modelling for Product-Service systems (PSS-Cost)”,* which aims to improve the cost estimation and affordability assessment of the whole life cycle of Product-Service Systems (PSS) in the defence and aerospace sectors at the bidding stage. In this project, four PhD researchers and one research fellow were involved but only the author was focused on studies regarding obsolescence. The research focus of the other three PhD candidates was affordability, design rework and service uncertainty. Although the introductory interviews were done together, the analysis of the data gathered was carried out individually.

1.5 The Collaborating Organisations

The main organisations that participated in this research project are: BAE Systems, UK Ministry of Defence (MoD), GE Aviation, Rolls-Royce, Thales Aerospace, SELEX Galileo and the Component Obsolescence Group (COG). Four of them helped the researcher to gain an overall understanding of the overall subject and the current situation in the defence and aerospace sector; five of them participated in the iterative development of the cost estimating frameworks; and all of them collaborated on the validation of the frameworks.

1.5.1 BAE Systems plc

BAE Systems is a global defence, security and aerospace company with approximately 100,000 employees worldwide. The company delivers a full range of products and services for air, land and naval forces, as well as advanced electronics, security, information technology solutions and customer support services. In 2009 BAE Systems reported sales of £22.4 billion (US$ 36.2 billion). BAE Systems is regarded as the second largest global defence company based on 2009 revenues (according to the Defense News Annual Ranking, published June 2010). Its headquarters are located in Farnborough, Hampshire, England. BAE Systems was formed on 30 November 1999 by the £7.7 billion merger of two British companies, Marconi Electronic Systems (MES), the defence electronics and naval shipbuilding subsidiary of the General Electric Company plc (GEC), and aircraft, munitions and naval systems manufacturer British Aerospace (BAe). BAE Systems is involved in several major defence projects, including the F-35 Lightning II, the Eurofighter Typhoon, the Astute class submarines and the Queen Elizabeth class aircraft carriers.

1.5.2 UK Ministry of Defence (MoD) - Defence Equipment & Support (DE&S)

Defence Equipment and Support (DE&S) equips and supports the UK's armed forces for current and future operations. Its headquarters is in Bristol with other sites across the UK and overseas. DE&S has a budget of approximately £14 billion and employs around 21,000 people.

DE&S acquires and supports equipment and services, including ships, aircraft, vehicles and weapons, information systems and satellite communications. As well as continuing to supply general requirements, food, clothing, medical and temporary accommodation, DE&S is also responsible for HM Naval Bases, the joint support chain and British Forces Post Office.

DE&S works closely with industry through partnering agreements and private finance initiatives in accordance with the Defence Industrial Strategy to seek and deliver effective solutions for defence. The DE&S Obsolescence Management team for Through-life Support, located in Glasgow (UK), has firmly collaborated in this research project.

1.5.3 GE Aviation

GE Aviation is the world's leading producer of large and small jet engines for commercial and military aircraft. They also supply aircraft-derived engines for marine applications and provide aviation services. One of the most significant developments at GE in recent years has been the transformation of GE Aviation into the world's leading integrated engine maintenance resource. GE Aviation is part of GE Technology Infrastructure, itself a major part of the conglomerate General Electric, one of the world's largest corporations. The headquarters of GE Aviation are located in Evendale, Ohio, US. The division that participated in the research project is based at Cheltenham, UK, and used to be called Smiths Aerospace until 2007, when they were acquired by GE Aviation. GE Aviation revenues in 2007 were $16.8 Billion, and it employs 39,000 people worldwide, operating in more than 50 locations worldwide.

1.5.4 Thales Group

The Thales Group is a French electronics company delivering information systems and services for the Aerospace, Defense, and Security markets. The headquarters are in Neuilly-sur-Seine, France. The company changed its name to Thales from Thomson-CSF in December 2000 shortly after the £1,300 million acquisition of Racal Electronics plc, a UK defence electronics group. It is now partially state-owned by the French State, and has operations in more than 50 countries. It has 68,000 employees and generated €12.9 billion in revenues in 2009.

In UK, Thales is the second largest defence electronics supplier, employing approximately 8,500 people in more than 40 locations across the country. They are leader in onboard equipment for civil and military aircraft. Thales has six main business domains in the UK:

- Transportation Systems, including Revenue Collection Systems, Integrated Communication and Supervision Systems, Rail Signalling for Main Lines and Rail Signalling for Urban Rail
- Air Operations, including Air Traffic Management, Surface Radar and Military Air Operations
- Defence & Security C4I Systems, including Radio Communication Products, Information Technology Security, Network & Infrastructure Systems, Protection Systems and Critical Information Systems
- Avionics, including Commercial Avionics, Military Avionics, Helicopter Avionics, In-Flight Entertainment, Electrical Systems, Training & Simulation and Microwave & Imaging Sub- Systems
- Defence Mission Systems, including Electronic Combat Systems, Airborne Mission Systems, Under Water Systems and Above Water Systems
- Land Defence, including Advanced Weapon Systems, Missile Electronics, Optronics, Armaments and Protected Vehicles

1.5.5 Rolls-Royce plc

Rolls-Royce is a global business provider of integrated power systems to be used on land, at sea and in the air. Their headquarters are located in London, UK, and their revenue was £10,414 million in 2009, employing around 38,900 people in 50 countries. Rolls-Royce is the world's second-largest maker of aircraft engines, behind General Electric. They operate in four sectors: civil and defence aerospace, marine and energy. Services are a core element of the Rolls-Royce business. These services are usually sold as a package within the "TotalCare" support, which covers the life span of the engine, aligned with an agreed cost per flying hour).

Currently, Rolls-Royce has a broad customer base comprising more than 600 airlines, 4,000 corporate and utility aircraft and helicopter operators, 160 armed forces, more than 2,000 marine customers, including 70 navies, and energy customers in nearly 120 countries, with an installed base of 54,000 gas turbines. Rolls-Royce is supporting more than 8,000 engines and auxiliary power units by in-service monitoring. The Rolls-Royce group's services include: field services, the sale of spare parts, equipment overhaul services, parts' repair, data management, equipment leasing, and inventory management services. The main products that Rolls-Royce makes are civil & military aero engines, marine propulsion systems and power generation equipment.

1.5.6 SELEX Galileo

SELEX Galileo, which is owned by Finmeccanica (Italy), is a major defence electronics company that specialises in surveillance, protection, tracking, targeting, navigation and control, and imaging systems. It is a leader in defence electronics markets, with a distinctive strength in airborne mission critical systems and a wide range of capabilities for the battlefield and for homeland security applications. SELEX Galileo has the UK head office located in Basildon, employing around 7,000 people in the United Kingdom, Italy and the United States. SELEX Galileo supplies and supports equipment around the world and generated €1,645 million in revenues in 2008.

1.5.7 Component Obsolescence Group (COG)

The Component Obsolescence Group (COG) is a non-profit making special interest group of like-minded professionals, from all levels of the supply chain and across all industries and relevant government agencies, concerned with addressing and mitigating the effects of obsolescence. COG was founded in the UK in 1997, but since that time several overseas companies in the USA, mainland Europe and elsewhere have joined. COG Membership has grown to over 200 companies worldwide and holds quarterly meeting throughout the UK, aiming to:

- Provide education and awareness of the factors which affect obsolescence.
- Identify and develop processes for addressing or mitigating the effects of obsolescence.
- Communicate and co-operate with other national and international organisations with similar goals.
- Stimulate discussion and action between members for the members benefit and to communicate this on to the wider world.

1.6 Thesis Structure and Summary

This section presents the structure of this thesis, which is illustrated in Figure 1-5. It outlines the activities that leaded to achieve the research aim.

In Chapter 2, a structured account of existing literature is critically analysed. The two key areas covered in this literature review are obsolescence and cost estimation. The objective is to provide a better understanding about the state of the art in these areas and identify any existing research gap.

Chapter 3 presents the objectives of this research, which have been deduced from the critical analysis of the existing literature. The research methodology developed to achieve these objectives is also presented in this Chapter. A thorough analysis of the possible approaches and strategies to design this research was carried out, and the justification of the methodology selected is based on it.

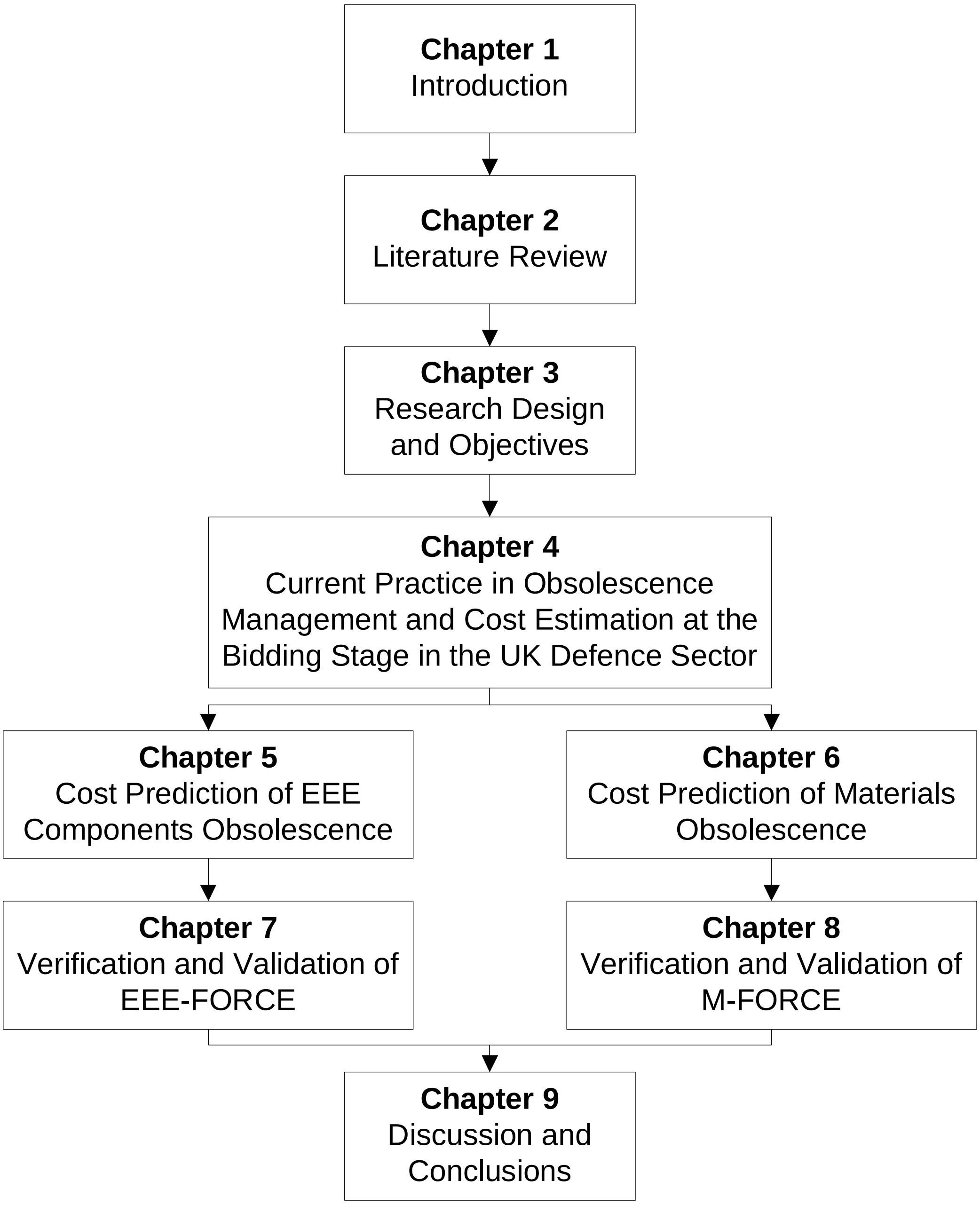


Figure 1-5 Thesis Structure

Chapter 4 presents the current practice in the UK defence sector for contracting (bidding process) and whole life cycle cost estimation at the bidding stage. It also describes the current practice in obsolescence management for EEE components and obsolescence cost estimation. In addition, it provides an understanding about software obsolescence, mainly based on industrial input due to the lack of existing research into this area in the literature.

In Chapter 5, the author presents the development of the "Electronic, Electrical and Electromechanical - Framework for Obsolescence Robust Cost Estimation" (EEE-FORCE) that can be used at the bidding stage of a support contract to estimate the NRE costs incurred during the contracted period in resolving EEE components obsolescence issues.

Chapter 6 provides an understanding about materials obsolescence and describes the development of the "Materials - Framework for Obsolescence Robust Cost Estimation" (M-FORCE), which can be used to estimate, at the bidding stage, the NRE cost of resolving materials obsolescence issues during the contracted period within the in-service phase.

The purpose of Chapter 7 is to describe the implementation of the EEE-FORCE framework in an Excel-based tool and its subsequent validation by means of seven case studies with current projects across the defence and aerospace industry, as well as qualitative validation with experts from different sectors.

Chapter 8 describes the implementation, verification and validation of the "Materials - Framework for Obsolescence Robust Cost Estimation" (M-FORCE). It has been implemented in an Excel-based tool and subsequently validated by means of six case studies with current projects across the defence, aerospace and shipping industry. Two of the case studies were related to the aerospace domain, one to the naval domain and three to the ammunition domain.

Finally, in Chapter 9 the work of this thesis is synthesised and the implications of the research findings are discussed. The main research contributions are stated, along with the limitations and the future research directions. Lastly, the overall conclusions are presented, demonstrating how the aim and the objectives have been achieved.

THIS PAGE IS INTENTIONALLY LEFT BLANK

Chapter 2

2 LITERATURE REVIEW

2.1 Introduction

This chapter presents the literature related to the two key areas covered in this research, namely obsolescence and cost estimation. The objective is to provide a better understanding about the state of the art in these areas and identify any existing research gap.

2.2 Obsolescence

2.2.1 Literature Review Strategy

A comprehensive investigation has been carried out in order to identify any publications related to the area of 'obsolescence'. For this purpose the main keywords used were: 'obsolescence', 'obsolete' and 'DMSMS' (Diminishing Manufacturing Sources and Material Shortages – this acronym is used in the U.S. to refer to obsolescence). The results were refined using keywords such as 'component', 'system', 'part', 'material', 'hardware', 'software', 'assembly' and 'LRU' ("Line-replaceable unit"). A number of databases were explored, including EBSCO, SCOPUS, CSA, SCIRUS, STINET, Science Direct, ProQuest, IEEE Xplore and Emerald. On top of that, searching tools such as 'Engineering Village', 'ISI Web of Knowledge' and 'Google' (Web and Scholar) were used.

The search was narrowed down to the military and aerospace sectors using keywords such as ‘military’, ‘defence’, ‘aerospace’ and ‘avionics’. The title and abstract of all the papers retrieved were manually explored and analysed to ensure that they are suitable for this survey. This investigation concludes that research on the ‘obsolescence’ topic commenced within the last 20 years and the trend has been increasing since then as shown in Figure 2-1. This graph is based on the 325 hits retrieved following the procedure explained above and limited to the period between 1996 and 2009, considering that the number of publications on this topic before 1996 can be regarded as insignificant.

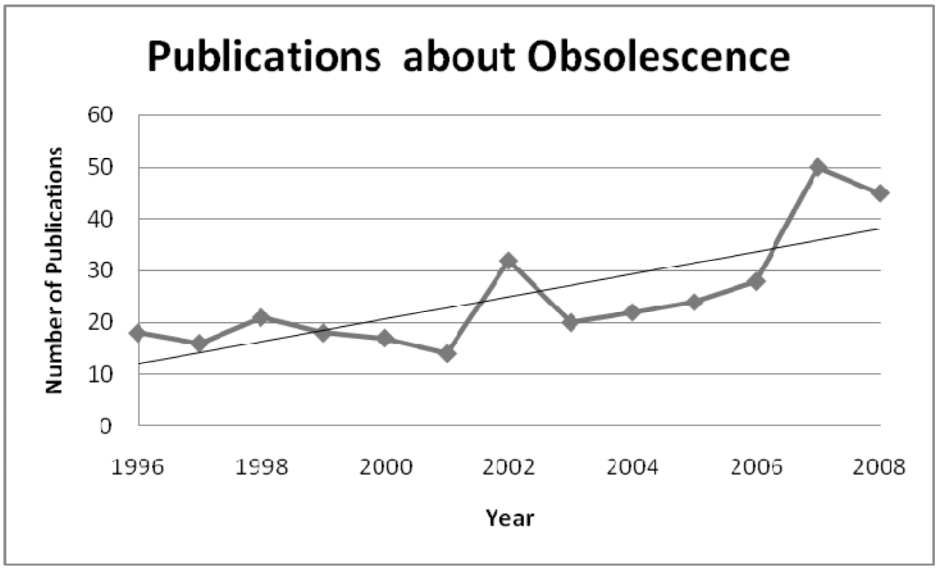


Figure 2-1 Yearly Publications on Obsolescence within the Defence & Aerospace Sector

All the relevant papers were read and analysed further. This allowed the identification of trends and key areas that were covered by many papers. Those areas are namely ‘mitigation & resolution approaches’, ‘design for obsolescence’, ‘obsolescence costing’ , ‘obsolescence management tools’, ‘COTS’ (Commercial off-the-shelf), ‘software obsolescence’, ‘electronics obsolescence’, ‘mechanicals obsolescence’, ‘component level’, ‘assembly level’, ‘system level’, and represent the research scope within the ‘obsolescence’ topic.

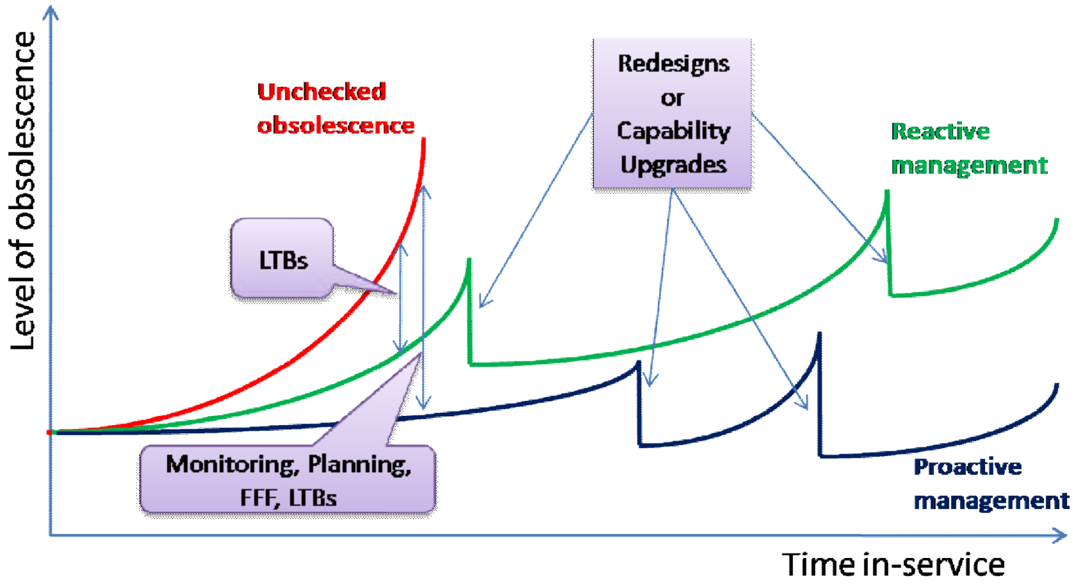
Table 2-1 Classification of key papers on 'obsolescence'

YEAR	AUTHOR(S)	MITIGATION & RESOLUTION APPROACHES	DESIGN FOR OBS.	OBS. COSTING	OBS. MANAGEMENT TOOLS	COTS	OBSOLESCENCE ASPECT			LEVEL		
							SOFTWARE	ELECTRONICS	MECHANICALS	COMPONENT	ASSEMBLY (LRU)	SYSTEM
1988	Leonard, J. et al.	■						■		■		
1996	Sjoberg, E. & Harkness, L.			■	■					■	■	
1997	Bray, O. & Garcia, M.	■						■				
1998	Pope, S. et al.		■					■				
1998	Hitt, E. & Schmidt, J.			■				■		■	■	
1998	Porter G.Z.	■		■				■	■	■		
1999	Condra, L.	■						■		■		
1999	Luke, J. et al.	■				■		■			■	
2000	Madisetti, V. et al.	■				■						■
2000	Humphrey, D. et al.	■						■		■		
2000	Pecht, M. & Das, D.	■						■		■		
2000	Solomon, R. et al.	■						■		■		
2000	Livingston, H.	■		■	■	■	■	■		■		
2000	Dowling, T.	■	■		■	■	■	■	■	■	■	■
2000	Livingston, H.	■	■	■	■	■	■	■		■	■	
2001	Marion, R.	■	■			■	■	■		■	■	
2002	Craig, R.		■			■						
2002	Howard, M.	■							■	■		
2002	Sandborn, P. & Singh, P.	■		■	■			■		■		
2002	Singh, P. et al.	■		■	■			■		■		
2003	Tomczykowski, W.	■		■						■		
2003	Meyer, A. et al.	■						■		■		
2003	Trenchard, M.					■		■		■		
2003	Barton, D. & Chawla, P.		■									
2003	Weaver, P. & Ford, M.	■				■	■	■		■	■	
2004	Herald, T. & Seibel, J.		■	■	■							
2004	Dowling, T.						■	■	■			■
2004	Josias, C. et al.				■	■		■		■		
2004	Meyer, A. et al.	■			■	■		■		■		
2004	Neal, T.	■		■			■	■		■	■	
2004	Redling, T.	■				■	■	■		■	■	
2004	MoD Cost Metrics Study	■		■				■		■		
2004	Sandborn, P.	■			■			■		■		
2004	Singh, P. et al.	■		■	■			■		■		
2004	Schneiderman, R.	■						■		■		
2005	Flaherty, N.	■		■				■		■		
2005	Baca, M.				■	■				■		
2005	Adams, C.	■		■		■		■		■		
2005	Sandborn, P. et al.	■			■			■		■		
2005	Singh, P. & Sandborn, P.		■	■	■	■		■		■		
2005	Weinberger, R.; Gontarek, D.	■										
2005	Seibel, J.S.	■		■	■	■	■					
2006	Behbahani, A.		■				■	■		■		■
2006	Francis, L.							■		■		
2006	Pecht, M. & Humphrey, D.	■						■		■		
2006	Manor, D.	■				■		■		■	■	
2006	Sandborn, P.; Plunkett, G.			■			■					
2006	Singh, P. & Sandborn, P.	■		■	■			■		■		
2006	Aley, J.	■			■					■	■	■
2007	Tryling, D.							■		■		
2007	Frank, B. and Morgan, R.	■			■	■		■		■	■	■
2007	Herald, T. et al.			■	■		■	■		■	■	■
2007	Torresen, J. & Lovland, T.	■	■			■		■		■		
2007	Sandborn, P. (a)			■			■					
2007	Sandborn, P. & Pecht, M.											
2007	Sandborn, P. (b)	■			■			■		■		
2007	Sandborn, P. et al.	■			■			■		■		
2007	Feldman, K. & Sandborn, P.	■	■	■	■			■		■		
2007	Feng, D. et al.	■		■				■		■		
2007	Sandborn, P. et al.				■							

The papers were classified according to those categories as illustrated in Table 2-1. This classification shows that most of the research on obsolescence has been focused on the electronic components, whereas not many papers have considered the obsolescence in other aspects of the system such as software or mechanicals. It can also be appreciated from this classification that most of the papers have dealt with obsolescence at the component level and neither at the assembly nor system level. This is justified by the fact that the electronic components are the part of the system that more frequently suffer the effects of obsolescence. Another fact that can be appreciated from this classification is that there are many papers where the obsolescence resolution and mitigation approaches are explored but just a few highlight the “design for obsolescence” as a key mitigation strategy. The classification also shows that there is no clear trend towards a particular area within the obsolescence topic in recent years.

2.2.2 Obsolescence Mitigation and Resolution

Until recently, managers and designers were unaware of how to manage obsolescence, so they tended to deal with it in a reactive mode, searching for ‘quick-fix’ solutions to resolve the obsolescence problem once it has appeared (Meyer et al., 2004; Howard, 2002). Several authors (Singh et al., 2002; Meyer et al., 2004; Josias et al., 2004; Torresen and Lovland, 2007) advised earnestly to apply obsolescence mitigation approaches in a proactive manner and involving all the projects related, in order to minimise the obsolescence problem. Herald et al. (2007) demonstrated with their research that by improving the obsolescence management, the costs related can be considerably reduced. Figure 2-2 shows how the evolution of the obsolescence level differs from implementing a proactive versus a reactive approach.



Key: FFF-Form, Fit and Function Replacement; LTBs-Last Time Buys

Figure 2-2 Evolution of the Level of Obsolescence Based on the Management Approach (Adapted from discussions at Defence Obsolescence Forum – Abbey Wood – 24th June 2008)

Traditionally, the military has dealt with obsolescence in a reactive mode (Josias et al., 2004). However, this approach is inadvisable because finding a solution with little advance warning is expensive (Frank and Morgan, 2007; Trenchard, 2003; Josias et al., 2004). Several authors (Meyer et al., 2004; Howard, 2002; Josias et al., 2004; Condra, 1999; Torresen and Lovland, 2007; Marion et al., 2001; Frank and Morgan, 2007; Sandborn et al., 2005; Francis, 2006; Leonard et al., 1988; Flaherty 2005) have highlighted the need to change from reactive to proactive approaches concerning obsolescence. However, it is necessary to emphasise that the level of 'proactiveness' that should be put in place depends on an initial assessment, at the component level, of the probability for a component to become obsolete and the impact that it would have on costs (Figure 2-3). If the obsolescence of the component has low impact on costs (e.g. because a form, fit and function (FFF) replacement is easy to be found), it may be worthwhile to decide to deal with that component in a reactive mode. Note that this decision is taken after performing the risk assessment, so this is part of a proactive obsolescence management. If the probability of becoming obsolete is low but it may have a high impact on costs, it is necessary to put in place proactive mitigation measures. If both the probability of becoming obsolete and the impact on costs are high, this component is regarded as 'critical' and hence it is necessary to emphasise the proactive mitigation strategy on it.

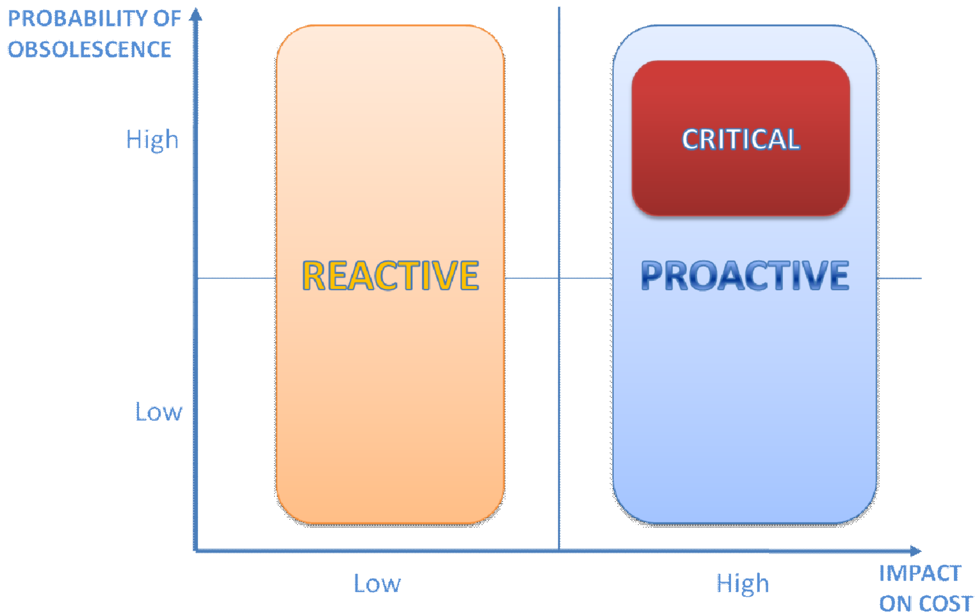


Figure 2-3 Evolution of the Level of Obsolescence Based on the Management Approach

In the literature the terms 'mitigation' and 'resolution' are frequently used interchangeably. However, the author considers that it is important to make a distinction between their meanings. The term 'mitigation' refers to the measures taken to minimise the impact or likelihood of having an obsolescence problem, whereas the term 'resolution' refers to the measures taken to tackle an obsolescence issue once it appears. The most common resolution approaches and mitigation strategies are described as follows.

2.2.2.1 Obsolescence Mitigation Measures

The strategy followed in the obsolescence management is usually a combination of mitigation measures. Obsolescence risk can be mitigated by taking actions in three main areas: supply chain, design and planning as shown in Figure 2-4.

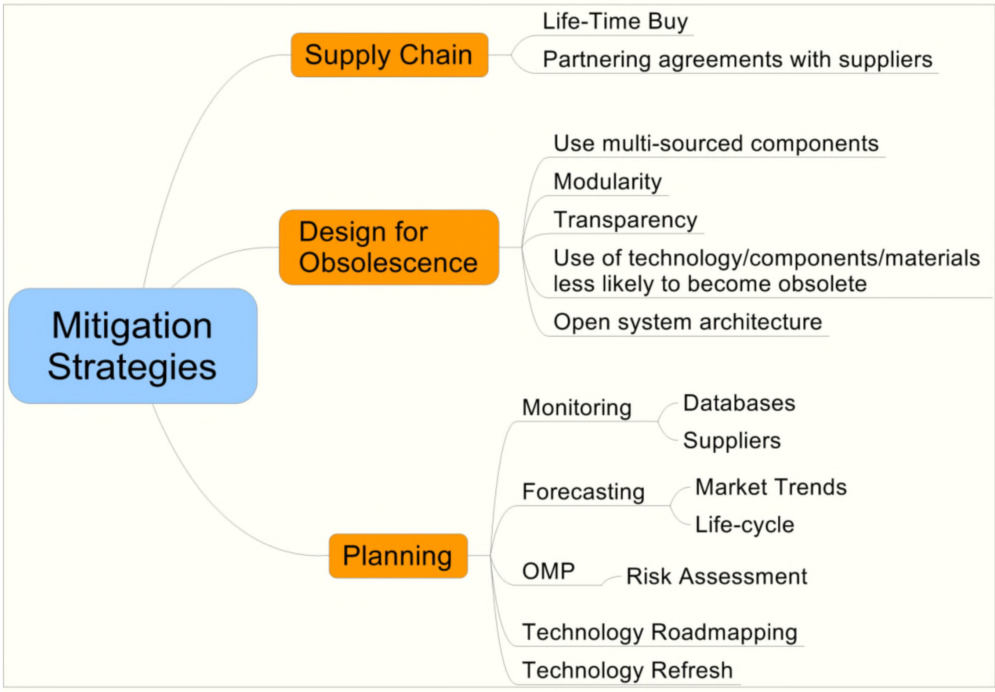


Figure 2-4 Obsolescence Mitigation Strategies

2.2.2.1.1 Supply Chain

The mitigation measures that can be taken in the supply chain are: Life-time Buy (LTB) and partnering agreements with suppliers.

- Life-time Buy (Life of Type)

The Life-time Buy (LTB) or Life-of-Type (LOT) approach involves purchasing and storing enough obsolete items to meet the system's forecasted lifetime requirements (Singh et al., 2002; Solomon et al., 2000; Frank and Morgan, 2007). Feng et al. (2007) addressed the optimisation of the process to determine the number of parts required for the life-time buy to minimise life-cycle cost. The key cost factors identified are: procurement, inventory, disposal and penalty costs (Feng et al., 2007).

The main benefit of this approach is that readiness issues are alleviated (Manor, 2006) and it avoids requalification testing. However, several drawbacks have been identified:

- Initial high cost, incurring in significant expenses in order to enlarge the stock (Feng et al., 2007; Manor, 2006).
- It is difficult to forecast the demand and determine life-time buy quantity accurately (Feng et al., 2007). Therefore, it is common to have excess or shortage of stock problems.
- This approach assumes that the system design will remain static (Feng et al., 2007). Any unplanned design refresh may make stock obsolete and hence no longer required.
- The customer is in a poor negotiation position because of the high dependence on a particular supplier (Weaver and Ford, 2003).

- Partnering Agreements with Suppliers

Nowadays, the defence industry has less control over the supply chain for COTS electronic components (Condra, 1999; Sandborn, 2007a; Feng et al., 2007). This type of components is becoming obsolete at an increasingly fast pace. Therefore, it is advisable to make partnering agreements with suppliers to ensure the continuous support and provision of critical components.

2.2.2.1.2 Design for Obsolescence

The fact that military systems will be affected by technology obsolescence during their lifetime is unavoidable (Sandborn, 2007a; Sjoberg and Harkness, 1996). Therefore, several authors (Meyer et al., 2004; Sandborn, 2007a; Redling, 2004; Marion et al., 2001; Petersen, 2000) suggested trying to address this threat at the design stage. Feldman and Sandborn (2007) pinpointed that “managing obsolescence via quickly turning over the product design is impractical because the product design is fixed for long periods of time”, highlighting the importance of doing it at the beginning of the project. Therefore, strategies such as the use of open system architecture, modularity and increase of standardisation in the designs will definitely ease the resolution of obsolescence issues that may arise at the component or line replaceable unit (LRU) level (Pope et al., 1998; Livingston, 2000; Dowling, 2000; Heilala et al., 2008, Perera et al., 1999).

Condra (1999) argued that the impact of electronic components obsolescence on the life cycle cost and functionality of a military aircraft can be drastically reduced considering the following guidelines:

- Managing the processes used to select and manage components to assure cost-effectiveness, reliability, safety, and functionality.
- Developing new approaches to using components manufactured for other industries (incorporating Commercial off-the-shelf (COTS)) (Baca, 2005).

Therefore, according to Condra (1999), the military should get ready to make use of electronic components designed for the commercial market. However, the incorporation of COTS in the system is a double-edged sword due to their shorter life-cycle. The author argues that this decision may increase the frequency of obsolescence issues in the system, exacerbating the problem.

- Use Multi-sourced Components

At the design stage it is important to take into account the number of suppliers and manufacturers that are producing a particular component (implementing a particular technology) before including that component in the Bill of Materials (BoM). It is necessary to make sure that the components included in the BoM can be provided by multiple suppliers to minimise the number of critical components.

2.2.2.1.3 Planning

Planning is an effective way of mitigating obsolescence. It implies the development of an Obsolescence Management Plan (OMP), a technology roadmap and the use of obsolescence monitoring tools.

- Technology Roadmapping

The use of Technology Roadmapping facilitates the selection of technologies to go ahead with, while considering timeframes. It enables the identification, evaluation, and selection of different technology alternatives (Bray and Garcia, 1997). Furthermore, it identifies technology gaps, which can be regarded as the main benefit of this approach because it helps to make better technology investment decisions (Bray and Garcia, 1997). The use of this technique may help to plan the technology refreshes that the system may require within the 'In-Service' phase of the CADMID cycle, resolving and preventing obsolescence issues.

- Monitoring

Nowadays, there are many commercial tools available that enable the monitoring of the BoM. In general they match the BoM with huge databases, providing information about the current state of each component (whether it is already obsolete or not) and a forecast about when it will become obsolete. The forecasting is based on an algorithm that takes into account several factors such as type of component and technology maturity. These algorithms are currently been improved to take into account other factors such as market trends. The monitoring tools may provide information about FFF alternatives to replace obsolete components. All this information provides the basis for the planning and proactive management of obsolescence.

- Obsolescence Management Plan (OMP)

It has become a common practice for the prime contractor to produce a document called the Obsolescence Management Plan (OMP) to satisfy the MoD demand. The OMP describes the proactive approach to be taken by the contractor to manage, mitigate and resolve obsolescence issues across the life-cycle of the program (DoD, 2005). This document provides the prime contractor and the customer with a common understanding of the obsolescence risk and allows the agreement of the most suitable obsolescence management strategy.

2.2.2.2 Obsolescence Resolution Approaches

When a part becomes obsolete, a resolution approach must be applied immediately to tackle the problem (Singh et al., 2002; Singh et al., 2004; Manor, 2006). It is important to make sure that no pre-existing capabilities are lost with the resolution approach selected (Redling, 2004). There are several resolution approaches in the literature which are described as follows, but the suitability of them depends on the individual case (Tomczykowski, 2003; Sjoberg and

Harkness, 1996). The different approaches are classified according to the replacement used into four categories. (Figure 2-5)

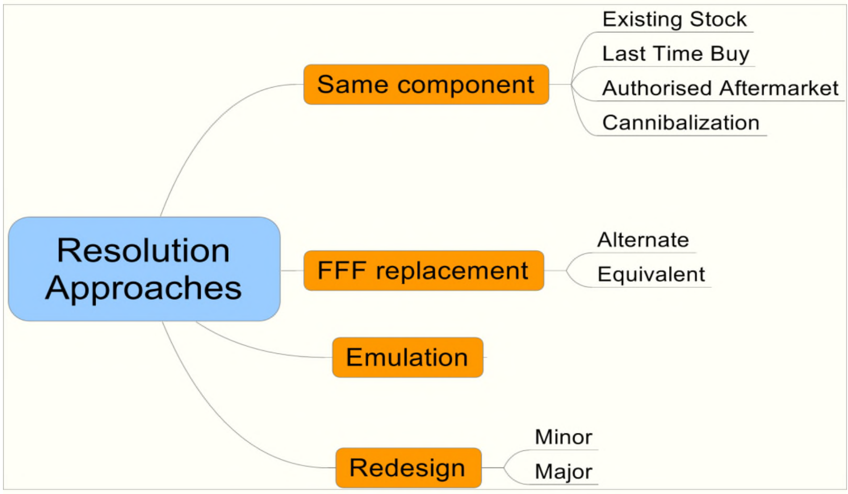


Figure 2-5 Obsolescence Resolution Approaches

2.2.2.2.1 Same Component

- Existing Stock

It is stock of the obsolete part available within the supply chain that can be allocated to the system. This is the first resolution approach that should be explored because it is inexpensive, but it is just a short-term solution. Therefore, a long-term solution should be implemented afterwards.

- Last-time Buy

The Last-time Buy (LTB) is the purchase and store of a supply of components, as a result of a product discontinuance notice from a supplier, sufficient to support the product throughout its life cycle or until the next planned technology refresh (Bridge Buy) (Meyer et al., 2004; Solomon et al., 2000; Feldman and Sandborn, 2007; Torresen and Lovland, 2007; Frank and Morgan, 2007). This resolution approach differs from the Life-time Buy in the fact that the Last-time Buy is triggered by a supplier announcing a future end of production whereas the Life-time Buy is a risk mitigation option triggered by the user's risk analysis.

The main advantage of this approach is that it allows extending the time since the Product Change Notification (PCN) is received until performing a redesign

(Torresen and Lovland, 2007; Manor, 2006). This is a common and effective approach, but in general it is used as a short-term solution until a more permanent solution can be placed (Howard, 2002; Weaver and Ford, 2003; Torresen and Lovland, 2007; Manor, 2006).

- Authorised Aftermarket Sources

Occasionally the obsolete part can be procured from third parties authorised by the Original Equipment Manufacturer (OEM), once the OEM has stop producing it (Singh et al., 2002; Solomon et al., 2000; Frank and Morgan, 2007). This is a beneficial solution because it is relatively inexpensive (Manor, 2006; Neal, 2004).

- Cannibalization (Reclamation)

The Cannibalization approach, also known as Reclamation, consists in using serviceable parts salvaged from other unserviceable systems (Singh et al., 2002; Meyer et al., 2004; Solomon et al., 2000). This approach is especially useful during the last stage of the in-service phase in legacy systems, but the used part may be just as problem-prone as the one it is replacing (Weaver and Ford, 2003).

- Other Approaches: Grey Market and Secondary Market

The grey market is the trade of new goods through distribution channels which are unauthorised, unofficial, or unintended by the original manufacturer. Some companies rely on the grey market as an alternative to performing a redesign. However, this is very risky due to the increasing probability of purchasing counterfeit components when using these sources (Battersby, 2008); especially in sectors such as the defence and aerospace, where counterfeit components can compromise the safety of people. Besides, testing of all the components to ensure that they are not a counterfeit is usually not feasible. Therefore, this is an inadvisable approach. It is tempting to buy obsolete components in the secondary market using internet tools such as eBay. However, several authors (Weaver and Ford, 2003; Manor, 2006) agree that "this is a chancy solution because the used part may be just as problem-prone as the one it is replacing". Furthermore, this approach is as prone to counterfeits as the grey market.

2.2.2.2.2 Form Fit Function Replacement (FFF)

There are two types of FFF replacement:

- Alternate

An alternate can be defined as "a part available that is equal to or better than that specified" (MoD, 2004; ARINC, 1999). The main benefit of this approach is that it is inexpensive (as requalification tests are not required) and frequently a long-term alternative (Howard, 2002; Redling, 2004; Manor, 2006). However, it is difficult to find a replacement with the same form, fit and function (Neal, 2004).

- Equivalent (Substitute)

An equivalent can be defined as "a part available whose performance may be less capable than that specified for one or more reasons (e.g., quality or reliability level, tolerance, parametric, temperature range)" (MoD, 2004). This resolution approach is also known as "substitute" in US DoD (ARINC, 1999). Equivalent items may perform fully (in terms of form, fit, and function) in place of the obsolete item but testing is required. Uprating is the process of assessing the capability of a commercial part to meet the performance and functionality requirements of the applications, taking into account that the part is working outside the manufacturers' specification range (Singh et al., 2002; Solomon et al., 2000; Humphrey et al., 2000; Pecht and Humphrey, 2006; Oblad, 1999).

2.2.2.2.3 Emulation

The emulation approach consists in developing parts (or software) with identical form, fit and function than the obsolete ones that will be replaced, using state of the art technologies (Singh et al., 2002; Solomon et al., 2000; Frank and Morgan, 2007). The emulator can be an interface software that allows continuing the use of legacy software in new hardware where otherwise the legacy software would not work properly. The fact that this solution is frequently based on COTS components with a build-in adapter (Leonard et al., 1988) can turn it into a short-term solution.

2.2.2.2.4 Redesign

The Redesign alternative involves making a new design for obsolete parts by means of upgrading the system, with the aims of improving its performance, maintainability and reliability, as well as enabling the use of newer components (Solomon et al., 2000; Frank and Morgan, 2007). Several authors (Howard, 2002; Singh and Sandborn, 2006; Feng et al., 2007) agree that this is the most expensive alternative (especially for the military, taking into account the re-qualification/re-certification requirements). Therefore, this long-term solution should be used as a last resort and when functionality upgrades (technology insertion) become necessary.

As part of the research carried out for this thesis, a new set of obsolescence resolution definitions has been developed based on a workshop arranged with experts from across the UK defence sector. These definitions are included in Chapter 5.

2.2.3 Obsolescence Costing

Traditionally, contracting for the support of a sustainment-dominated system did not include the cost of resolving obsolescence issues. The prime contractor used to be in charge of resolving those problems and the customer used to pay for it separately. However, the current contracting trend is moving towards contracting for availability (CfA). This type of contracts, in theory, is diverting the obsolescence risks from the customer to the prime contractor. In practice, the risk of obsolescence is shared between both parties in accordance with the clauses agreed in the contract. On the whole, this new way of contracting brings both parties to a new scenario in which they need to make accurate estimations of the obsolescence cost at the bidding stage. Both the prime contractor and the customer need to be confident that the cost estimates for the WLC are correct because of the long periods contracted for and the little profit margin of the prime contractor. Therefore, the cost estimations need to be reliable. In order to estimate the cost it is necessary to identify the cost drivers. It is identified the need for a cost model to estimate the total cost that will be incurred mitigating and resolving obsolescence issues. It should be capable of estimating the obsolescence cost even when information such as the BoM, the obsolescence predictions of a monitoring tool and the obsolescence management plan (OMP) are not in place yet. However, this tool should be just intended to assist in estimating the cost, considering that simple mathematical models cannot replace the expert judgment of the cost estimator (Meyer et al., 2004). There are many commercial tools, such as TruePlanning (PRICE Systems, 2008) and SEER (Galorath, 2008), designed to estimate the life cycle costs of systems. However, none of these tools is focused on accurately estimating obsolescence costs.

A major challenge for the estimation of costs related to obsolescence is the development of accurate cost metrics. The cost metrics allow the: selection of the most cost effective solution, cost avoidance analysis and assessment of the impact of obsolescence on whole life cycle costs (MoD, 2004). In 1999, the Department of Defence (DoD) in the United States was concerned about this, so they commissioned the Defense MicroElectronics Activity (DMEA) to develop cost factors for various obsolescence solutions. In 2001, the DoD commissioned a supplementary report but no significant data was received to justify changing the 1999 values. Due to differences in practices, cost and terminology between the US and UK, in 2004, the Ministry of Defence (MoD) in the UK commissioned QinetiQ and ARINC to derive a set of cost metrics that may be used for the estimation of costs related to obsolescence (See Figure 2-6). However, those cost metrics have been subjected to criticism and the MoD is aware that they need to be revalidated.

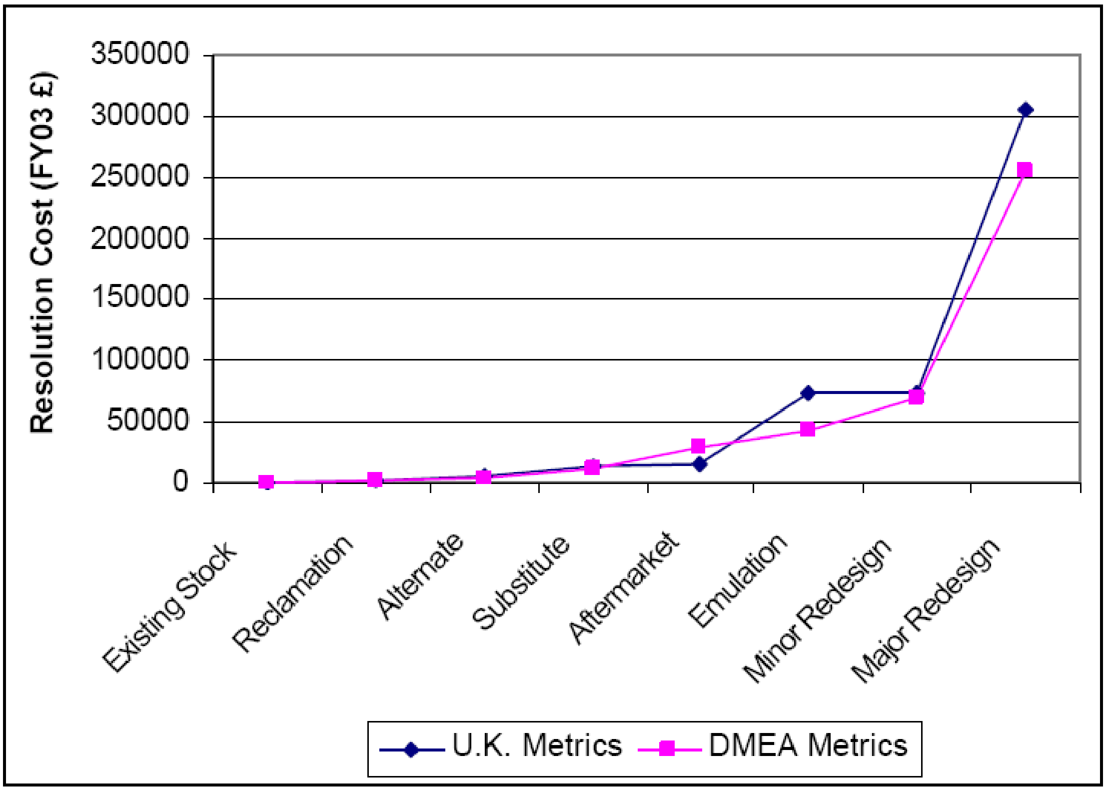


Figure 2-6 UK versus DMEA Resolution Cost Metrics (Adopted from MoD, 2004)

The costs estimated for each resolution alternative should be compared with the cost of maintaining the obsolete system and with the cost of redesigning it (Hitt and Schmidt, 1998). On the one hand, it is advised to “keep the old equipment until the cost of replacing it is less than the cost of maintaining it” (Marion et al., 2001). On the other hand, it may be sensible to assess the redesign cost, taking into account that it is divided into the development and acquisition costs, and component re-qualification costs (Sjoberg and Harkness, 1996).

2.2.4 Obsolescence Forecasting

According to what has been discussed so far, it is clear that obsolescence is a problem that should be tackled in a proactive manner. For this purpose, it is necessary to foresee when those obsolescence issues will appear. The following factors should be taken into account:

- Type of component (e.g. electronic or mechanical)

- Complexity of the component (e.g. low complexity such as resistors or high complexity such as microprocessors or LCD displays)
- Technology built in the component
- Level of maturity of the technology built in the component
- Number of suppliers of the component
- Market trends
- Changes in laws and regulations

Nowadays, most of the commercial monitoring tools (Blackman and Rogowski, 2008) (such as Q-Star, IHS, TACTRAC) incorporate an algorithm to forecast obsolescence dates based on the features of the component and the technology that it incorporates, making use of life cycle models. Besides, those algorithms are continuously been refined and it is expected that in the near future they may be capable to take into account other factors such as market trends.

Sandborn et al. (2005; Feldman and Sandborn, 2007) have developed a data mining based approach to forecast obsolescence of electronic parts. This approach combines life cycle curve forecasting (Solomon et al., 2000) with historical information about last-order or last-ship dates. However, much of this data is highly uncertain. Therefore, it is important to manage the following two types of uncertainties: (Singh et al., 2002)

- Uncertainty in the cost analysis inputs
- Uncertainty in dates

Although the data about the expected production lifetimes of parts available during a system's design phase may be incomplete and/or uncertain, it will allow the forecast of obsolescence and subsequent development of strategic approaches that will reduce sustainment costs (Sandborn, 2007a; Singh and Sandborn, 2005). Sandborn et al. (2005) expressed concern about the importance of the data at the system's design stage and developed data mining based algorithms that allow finding out more information, increasing the predictive capabilities. Frequently, the obsolescence forecasting is used not only for planning design refresh but also in order to avoid the inclusion of parts with high risk of imminent obsolescence in the BoM at the design stage (Sandborn, 2007a).

Various authors (Meyer et al., 2004; Sandborn et al., 2005) advised the use of obsolescence monitoring in order to obtain timely notification of any obsolescence risk. Nowadays, most of the organisations that are trying to manage obsolescence proactively are implementing commercial tools that allow the monitoring of the state of the components included in the BoM of any system. It provides information of possible FFF replacements for some obsolete items or even before the obsolescence problem arises. In the next section, the main obsolescence management tools are compared.

2.2.5 Obsolescence Management Tools Comparison

The main commercial and non-commercial tools available at present have been analysed, based on publicly available information about those tools such as brochures, user manuals and their internet webpages. The criteria considered to systematise the analysis and comparison of these tools were the following features:

- Obsolescence forecasting capabilities
- Obsolescence monitoring and identification of alternative components
- Mitigation Strategy Development
- Obsolescence cost estimating capabilities
- Hierarchical level in the Product Breakdown Structure (PBS) at which it can be used
- Types of Obsolescence

Table 2-2 illustrates that most of the tools are focused on the monitoring of the BoM and identification of alternative components for the obsolete ones. Furthermore, most of them are focused on electronic and electromechanical components, as they are more prone to obsolescence due to the ongoing change in technology. The Table shows that most of the existing tools do not address the obsolescence cost estimation problem. The MOCA and R2T2 tools estimate obsolescence costs roughly with the only purpose of comparing refreshment plan alternatives, rather than trying to make accurate cost estimation that can be used at the bidding stage for contract negotiation.

Table 2-2 Comparison of the main obsolescence management tools

OBSOLESCENCE TOOLS	Forecasting	Monitoring & Identification of Alternative Components	Mitigation Strategy Development	Costing	Level	Types of Obsolescence
Q-Star	✓	✓			C	o Electronics
ITOM	✓	✓			C	o Electronics o Electromechanical
Obsolescence Manager	✓	✓			C	o Electronics o Electromechanical
i2 TACTRAC + i2 Electronics Database	✓	✓			C	o Electronics o Electromechanical
Parts Plus	✓	✓			C	o Electronics
AVCOM	✓	✓	The MTI group can define it at component level		C	o Electronics o Non-electronics
OASIS		✓			C	o Electronics
MOCA tool			✓	✓	A	o Electronics
Se-Fly Fisher	✓		✓		S	o Electronics o Electrical o Mechanical o Software
R2T2	✓	✓	✓	✓	S	o Hardware Systems o Software Systems o IT Systems
CAPSXpert / CAPS BOM Manager		✓			C	o Electronics o Electromechanical
CAPS Forecast	✓				C	o Electronics o Electromechanical

C→ Component Level
A→ Assembly Level
S→ System Level

The models have been classified into three categories as shown in Table 2-2 (Herald et al., 2008):

- "Component Level" represents the models that forecast the next obsolescence event for each independent electronic component.
- "Assembly Level" represents the tools that manage an assembly (LRU), which is composed of components, determining the optimal time to change its baseline during production and operation due to part-level obsolescence.

- "System Level" represents those models that address the obsolescence for the entire system, taking into account different aspects such as hardware and software integration. Those models are able to forecast obsolescence at the system level, across the remaining life cycle and optimise the change frequency (Herald et al., 2008). The data inputs required for this type of model are not usually available in most databases.

Singh and Sandborn (2005) developed two different types of strategic planning approach:

- Material Risk Index (MRI)

  This approach analyzes the BoM of a product and grades for each component the likelihood of becoming obsolete (Sandborn, 2007a; Singh and Sandborn, 2005).

- Design Refresh Planning

  This method determines the optimum design refresh plan during the field-support-life of the product (Sandborn and Singh, 2002). According to Sandborn and Singh (2002), the design refresh plan minimises the life cycle sustainment cost of the product, defining the number of design refresh activities, their content and when they will be performed.

Some companies have developed a range of tools so that the customers can select the one that best suits their necessities. For instance, Total Parts Plus Inc. (Total Parts Plus, 2008) offers a basic tool "Parts Xpert™" and a superior tool "Parts Plus™"; in a similar manner "Q-Star™", "ITOM™" and "Obsolescence Manager™" belong to QinetiQ Ltd. (QinetiQ, 2008); "OASIS™" and "AVCOM™" belong to MTI Inc. (MTI, 2008a; MTI, 2008b); "CAPSXpert™", "CAPS BOM Manager™" and "CAPS Forecast™" belong to PartMiner Inc. (PartMiner, 2008).

Herald et al. (Herald et al., 2007; Herald and Seibel, 2004) have developed "Se-Fly Fisher" and the "Rapid Response Technology Trade" Study (R2T2™), which is the only tool that manages obsolescence at the system level. The R2T2 model can identify the ideal point for a technology refreshment, based on four main attributes: the technology life cycle, the current technology maturity, the technology change frequency and the technology double period (Herald and Seibel, 2004).

Singh, Sandborn and Feldman, from the University of Maryland, have designed a software tool that enables the prediction of the optimum design refresh plan (MOCA tool) (Singh et al., 2002; 2004; Feldman and Sandborn, 2007; Sandborn et al., 2005; 2007; 2010; Singh and Sandborn, 2005; 2006; Sandborn and Singh, 2002; Sandborn, 2004; 2007a). This tool simultaneously optimises multiple redesigns and multiple obsolescence mitigation approaches, based on forecasted electronic part obsolescence (Singh et al., 2002; 2004; Feldman and Sandborn, 2007; Sandborn, 2007a). PartMiner's Life Cycle Forecast data is derived using mathematical algorithms developed in conjunction with Sandborn and the University of Maryland.

In addition to the foregoing approaches, other obsolescence forecasting methods can be found in the literature:

- The simplest model was developed by Porter (1998). This method formulates refreshes as a function of the time, based on the Net Present Value (NPV) of last-time buys. A trade-off between design refresh costs and last-time buy costs is performed on a part-by-part basis (Porter, 1998).
- The “scorecard” approach has been traditionally used for life-cycle forecasting. Based on a set of technological attributes, the current life-cycle stage of a component can be determined (Solomon et al., 2000). However, this method has certain drawbacks: (Solomon et al., 2000)
    - The market trends are not accurately captured
    - It makes erroneous assumptions about the life-cycle curve
    - In the forecasting it is not shown a measure of confidence
- The “Availability Factor” method. This method is used to predict the obsolescence of products with similar technology and market characteristics,

based on market and technology factors (Solomon et al., 2000). However, this method has certain drawbacks:

- o This approach does not use the “life cycle curve” for the product.
- o It is not suitable to determine the life cycle stage of the part.

➢ Solomon et al. (2000) developed an approach able to predict the years to obsolescence and life cycle stage based on modelling the life cycle curve considering the characteristic of the parts and its technology. This methodology is composed of seven steps which are described in Figure 2-7.

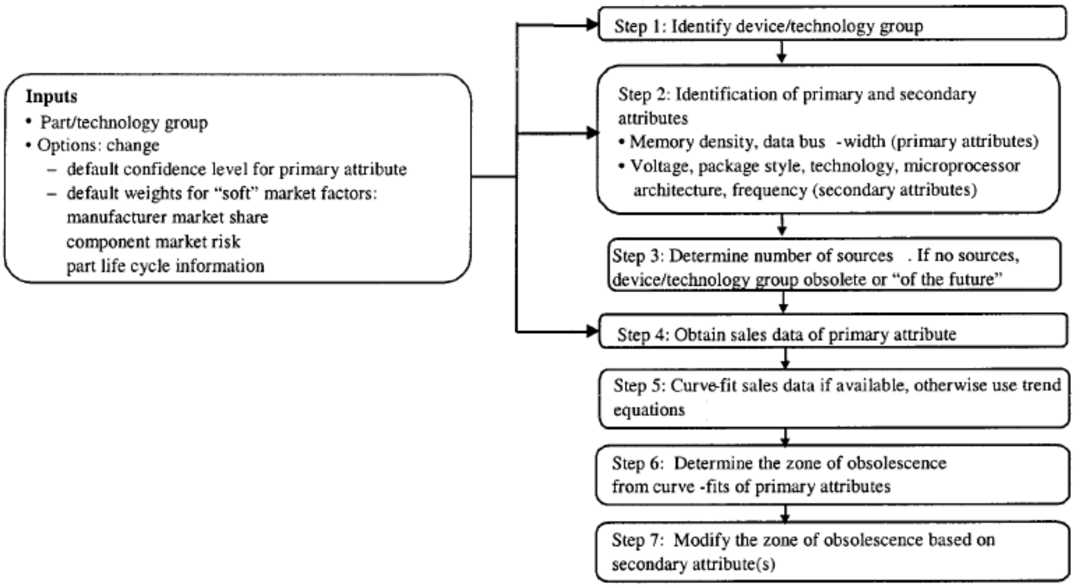


Figure 2-7 Life Cycle Forecasting Methodology (Adopted from Solomon et al., 2000)

➢ In 2004, Josias et al. (2004) developed a multiple regression model for forecasting obsolescence, applied to microprocessor for computers.

➢ The “*se-Fly Fisher*” is a technology-based obsolescence model developed by Herald et al. (2007), based on the technology curves of each part of the system. The main outputs are:

- o A forecast about how often a system baseline should synchronously change in order to minimise the system ownership costs through support.

- A resource identification, technical change management and assessment of scope impacts of the recommended changes.
- An assessment of the performance potential that is gained from each proposed system element baseline change.

None of the models described in literature addresses directly the problem of estimating the cost of obsolescence. However, the MOCA tool and R2T2 apply a set of cost estimating formulas in order to identify the most cost-effective plan for design refresh. It is argued by the developer of the MOCA tool, Peter Sandborn, that the costs calculated by this tool are “MOCA Dollars”, which are suitable for trade study comparisons only, and not for life cycle cost assessment. Moreover, the R2T2 produces a coarse cost estimate for operation and support, acquisition, spares and technology refreshments, with the purpose of enabling comparison between alternative technology refreshment frequencies. Therefore, the R2T2 is not a suitable tool for the cost estimation of obsolescence at the bidding stage. Additionally, none of the tools/models existing in the literature addresses the problem of managing materials obsolescence, and particularly estimating the costs related to these issues.

2.3 Cost Estimating

The second part of the literature review revolves around the Cost Estimating field. The main cost estimating techniques have been explored and the suitability of each of them at different stages of the life cycle has been analysed. Then, the research focuses on the cost estimating processes for the in-service phase, in which maintenance is the key activity.

According to the Association for the Advancement of Cost Engineering (AACE), cost estimating can be defined as “the determination of quantity and the predicting or forecasting, within a defined scope, of the costs required to construct and equip a facility, to manufacture goods, or to furnish a service” (AACE, 1990). These costs include assessments and an evaluation of risks and uncertainties (Stelling, 2008).

Basically, cost estimating aims to predict future costs of resources, methods, and management, based on historical data and experience. For this purpose, the cost analyst should combine concepts from multiple disciplines such as statistics, mathematics, engineering, budgeting, economics and accounting. This will provide a basis for cost and schedule control, budget preparation, business planning, and feasibility studies. (AACE, 1990; GAO, 2009)

The best practice in the cost estimating process has been identified by GAO (2009) and represented in 12 steps, as shown in Figure 2-8. Each of these steps is important to ensure reliability in the cost estimates.

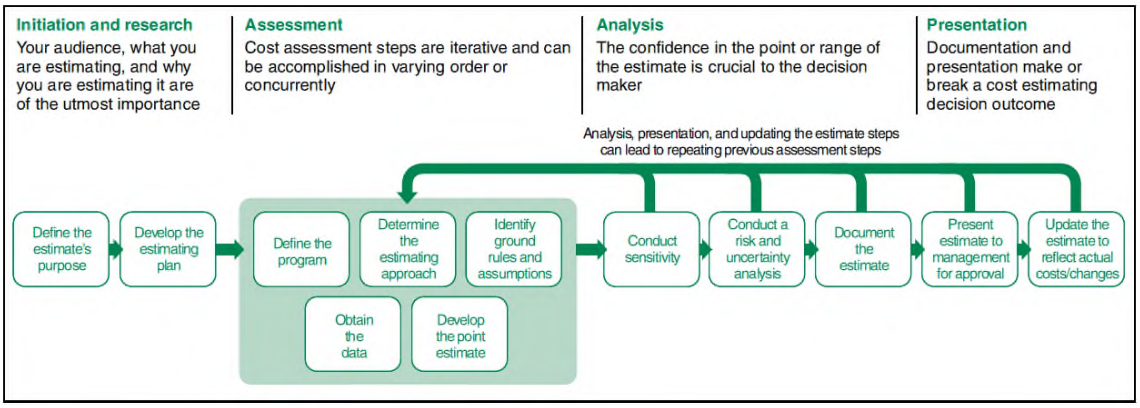


Figure 2-8 The Cost Estimating Process (Adopted from GAO, 2009)

There are many challenges to develop good cost estimates. The main obstacles identified in the literature are listed as follows (Kingsman and de Souza, 1997; Roy, 2003; GAO, 2009):

- Historical cost database not available, unreliable data or data not normalised. Lack of data available is common concerning a new product, new process or cutting edge technology.
- Lack of experience of the cost analyst.
- Overoptimism and unrealistic projected savings. Fail to recognise uncertainty and risks.
- Poorly defined or unrealistic assumptions.
- Program stability.
- Restricted time for preparing the estimates.

Several authors have identified some key activities that will help to mitigate these obstacles in any cost estimate (Romero Rojo, 2007). Roy et al. (2001) and Shehab and Abdalla (2001) have highlighted the importance of performing correctly the data collection, since the accuracy of this data is a critical factor for the success of the cost estimation. This data should be used systematically during the cost estimating process (Niazi et al., 2006). Therefore, it is suggested to develop a database updated and corrected (Stewart and Wyskida, 1987); and if possible, populated with historical cost data developed by the organisation that is doing the estimating, as this is regarded as the most valid (Boehm, 1981). Niazi et al. (2006) support this idea arguing that past manufacturing data is very helpful for the estimator in order to generate new estimates for similar products to those manufactured in the past. Additionally, Humphreys and Wellman (1995) highlight the importance of making a good judgement during the cost estimating process, focusing on the cost drivers that have a major impact on the total cost.

2.3.1 Cost Estimating Techniques

There are several cost estimating techniques. As explained by Romero Rojo (2007), they have not been consistently categorised in literature yet (Evans et al., 2006) as different authors propose different and incongruent classifications. One of the most widely accepted classifications divides the cost estimation techniques into qualitative and quantitative as shown in Figure 2-9 (Cutler T.R., 2006; Winchell, 1989; Shehab and Abdalla, 2002; Shehab and Abdalla, 2001; Niazi et al., 2006; H'mida et al., 2006; Duverlie and Castelain, 1999; Cavalieri et al., 2004; Ben-Arieh and Qian, 2003; Datta and Roy, 2010).

- **Qualitative Techniques**
  - **Intuitive** – based on the estimator’s experience (e.g. Expert Judgement).
  - **Analogical** – based on the definition and the analysis of the degree of similarity between the new product and another one which cost has been estimated in the past (e.g. Analogy-Based Costing).

- **Quantitative Techniques**
    - **Parametric** – based on an analytical function of a set of parameters characterising the product, without describing it completely (e.g. Parametric Cost Estimating).
    - **Analytical** – based on a detailed analysis of the work required into the elementary tasks that constitute the manufacturing process (e.g. Bottom-up Costing).

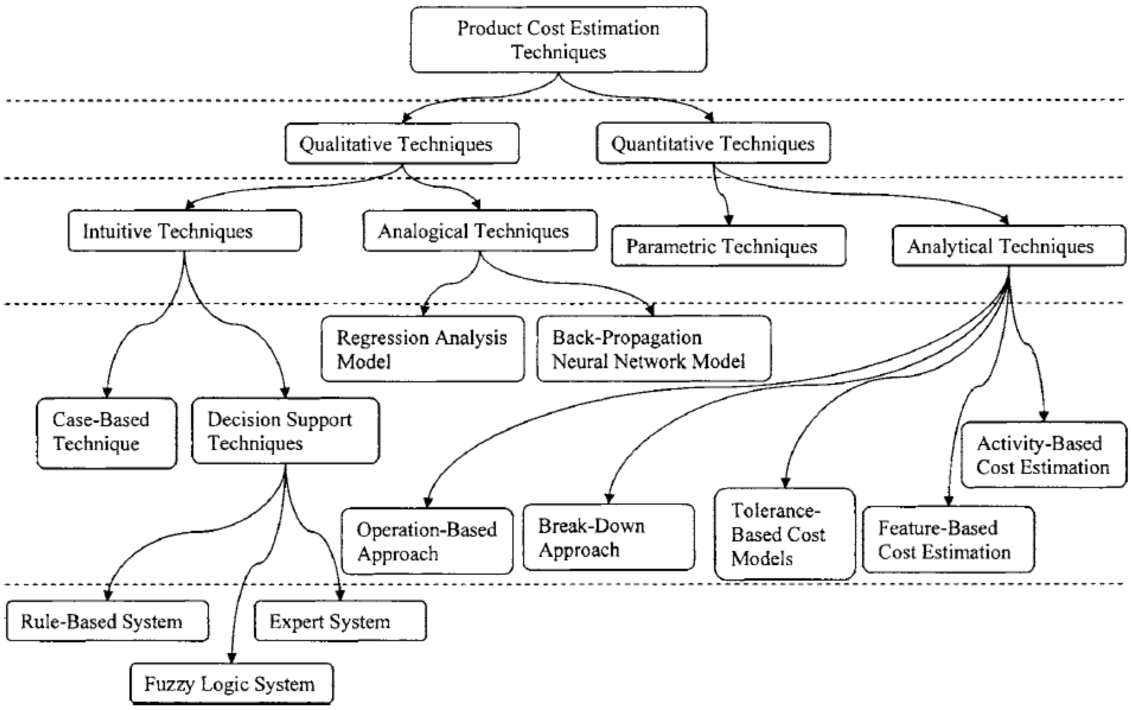


Figure 2-9 Classification of the cost estimation techniques (Niazi et al., 2006)

The four most commonly used cost estimating techniques are parametric, bottom-up, analogy and expert judgement. They are explained as follows.

- **Parametric Estimating**

Parametric Cost Estimating is defined as “the process of estimating cost by using mathematical equations that relate cost to one or more physical or performance variable associated with the item being estimated” (Stewart and Wyskida, 1987, p. 225). Historical data is processed using statistical methodologies, such as regression analysis, to derive analytical functions called Cost Estimation Relationships (CERs), which use certain parameters and characteristics, known as cost drivers, of the product such as type of material and morphologic attributes (NASA, 2004; Farineau et al., 2001; Cavalieri et al., 2004; Niazi et al., 2006). In general this technique is typically used at the early stages of a system's life-cycle, when little information is available (Palacio Madariaga, 1999; Roy, 2003; Roy and Sackett, 2003; Farineau et al., 2001; NASA, 2004). Several authors recommend this method just in those cases where the parameters, cost drivers, could be easily identified (Niazi et al., 2006; Cavalieri et al., 2004) and also the assumptions are clear and the data used is accurate (NASA, 2004; Roy, 2003; Roy and Sackett, 2003; Farineau et al., 2001). The use of this technique is only justified when it is applied to a project analogous to the ones used to generate the CERs in the first place. The main assumption of this technique is that the same factors that affected the cost in the past will continue to affect future costs (GAO, 2009; ISPA, 2008).

- **Bottom-Up Costing**

This technique is based on making detailed estimates for every activity in the work breakdown structure (WBS) and summarising them to provide a total project cost estimate (GAO, 2009). Bottom-Up Costing, and in general any analytical approach, is regarded as a slow method because a large amount of specific data is required (Duverlie and Castelain, 1999). However, this technique is widely used across industry as it ensures higher levels of accuracy than other techniques (Cavalieri et al., 2004). The unavailability of detailed data during the early stages of a project makes this method only appropriate for the cost estimation at stages when all the characteristics of the product and the WBS are well defined. (Cavalieri et al., 2004; Farineau et al., 2001; Roy and Sackett, 2003; Roy, 2003 ; Aderoba, 1997; Andrade et al., 1999; Ben-Arieh and Qian, 2003; Lere, 2001; Niazi et al., 2006; Westkamper et al., 2001).

The allocation of overheads has been identified as a key challenge for this technique by several authors (Aderoba, 1997; Ben-Arieh and Qian, 2003; Kaplan and Cooper, 1988). This issue is addressed by the Activity-Based

Costing (ABC) technique, which is probably the most widely used method of bottom-up costing (Negrini et al., 2004). The ABC technique eliminates the distortion of indirect costs allocation and takes into account all aspects of production, including non-production actions such as administration and distribution (Aderoba, 1997; Andrade et al., 1999; Ben-Arieh and Qian, 2003; Jones, 2001; Boons, 1998; Lere, 2000; Kaplan and Cooper, 1988; Koponen, 2002; Brimson, cited in Hicks, 2002, p. 273). The four basic steps involved in ABC are as follows (Stelling, 2008).

1. Identify/analyse activities
2. Assign resource costs to activities
3. Identify outputs
4. Assign activity costs to outputs

- **Analogy-Based Reasoning**

The foundation of this technique is to consider that similar products have similar costs (Roy, 2003). It assumes that no new program represents a totally new system, but it has evolved from old programs by adding new features or combining different programs (GAO, 2009). This technique requires a repository of historical information about costs and characteristics of past projects (NASA, 2004). The most similar past projects are retrieved and become the basis for the new estimate (Rush and Roy, 2001; Niazi et al., 2006; Farineau et al., 2001; Roy, 2003; Shepperd and Schofield, 1997).

This technique is more applicable for estimate costs at the initial stages of the life cycle of a project, since it does not require full details about the product, generating timely and reliable estimations (Niazi et al., 2006; Cavalieri et al., 2004; Avramenko and Kraslawski, 2006).

The number of cases stored in the database and the degree of similarity with the new case are the key drivers of the quality of the result obtained using this technique (Klinger et al., 1992; Avramenko and Kraslawski, 2006). The reason is that the more adjustments are required, the more subjectiveness is added to the estimate (NASA, 2004).

- **Expert Judgement**

Expert judgement is mainly used in situations where time, information, or other resources are insufficient to use a different cost estimation technique. The subjectivity associated with this method makes it very delicate and controversial (GAO, 2009; Zio, 1996). However, this technique is commonly used in order to get a rough estimate at the initial stages (Hughes, 1996; Roy and Sackett, 2003). In fact, despite the high level of subjectivity of this technique and the growing use of new computer-based techniques, such as neural networks, fuzzy logic and expert systems, the use of expert judgement is irreplaceable (Roy et al., 2001; Rush and Roy, 2001). The cost estimator's role is critical to generate a good estimate because is required to capture expert's knowledge and combine it with experience, logic and common sense (Rush and Roy, 2001; GAO, 2009). According to the GAO (2009), there are three main approaches to expert judgement.

- One-to-one interviews with experts
- Round-table discussions with many experts together until reaching consensus
- The Delphi Method. It is "an iterative process to collect and distil the anonymous judgments of experts using a series of data collection and analysis techniques interspersed with feedback" (Skulmoski et al., 2007).

The Delphi Method is particularly well suited to new research areas and exploratory studies (Okoli and Pawlowski, 2004; Linstone and Turoff, 1975) where there is lack of appropriate historical data (Rowe and Wright, 1999).

2.3.2 Comparative Analysis of Cost Estimating Techniques for Life Cycle Costing

The strengths and weaknesses of the techniques, and their principal applications are identified in Table 2-3 (GAO, 2009; Romero Rojo, 2007).

Table 2-3 Comparison of the Main Cost Estimating Techniques

Method	Strengths	Weaknesses	Application
Analogy	• Requires few data • Based on actual data • Reasonably quick • Good audit trail • Evolutionary method (It has the ability of learning)	• Subjective adjustments • Accuracy depends on similarity of items • Difficult to assess effect of design change • Blind to cost drivers • Requires a number of similar past cases in the database.	• When few data are available • Rough-order-of-Magnitude estimate • Cross-check
Bottom-Up	• Easily audited • Sensitive to labour rates • Tracks vendor quotes • Time-honoured	• Requires detailed data which may be unavailable • Time-consuming and laborious • Cumbersome • Costly to implement and operate	• Production estimating • Software development • Negotiations
Parametric	• Reasonably quick • Encourages discipline • Good audit trail • Objective and repeatable • Cost driver visibility • Incorporates real-world effects (risk, funding, technical)	• Lacks detail • Model investment • Cultural barriers • Need to understand model's behaviour	• Budgetary estimates • Design-to-cost trade studies • Cross-check • Baseline estimate • Cost goal allocations
Expert Judgement	• No historical data required • Easy and quick • Improves the understanding of the program • Few resources in terms of time and cost are required • Flexible	• Lack of objectivity • Susceptible to bias • Low accuracy (only valid as rough estimate) • Difficult to provide an audit trail • Inconsistent and unstructured process • Non-deterministic	• Cross-check • Baseline estimate • Cost goal allocations

The suitability of each technique depends on the stage of the programme life cycle, as represented in Figure 2-10. At early stages of the programme, Parametric and Analogy are the most suitable techniques, and their results can be cross-checked with Expert Judgement. As more data becomes available, these techniques will give way to Bottom-up (Engineering) approach and Extrapolation from actual costs. In order to improve the confidence on the estimates it is suggested to combine two or more approaches (Niazi, 2006; NATO, 2009).

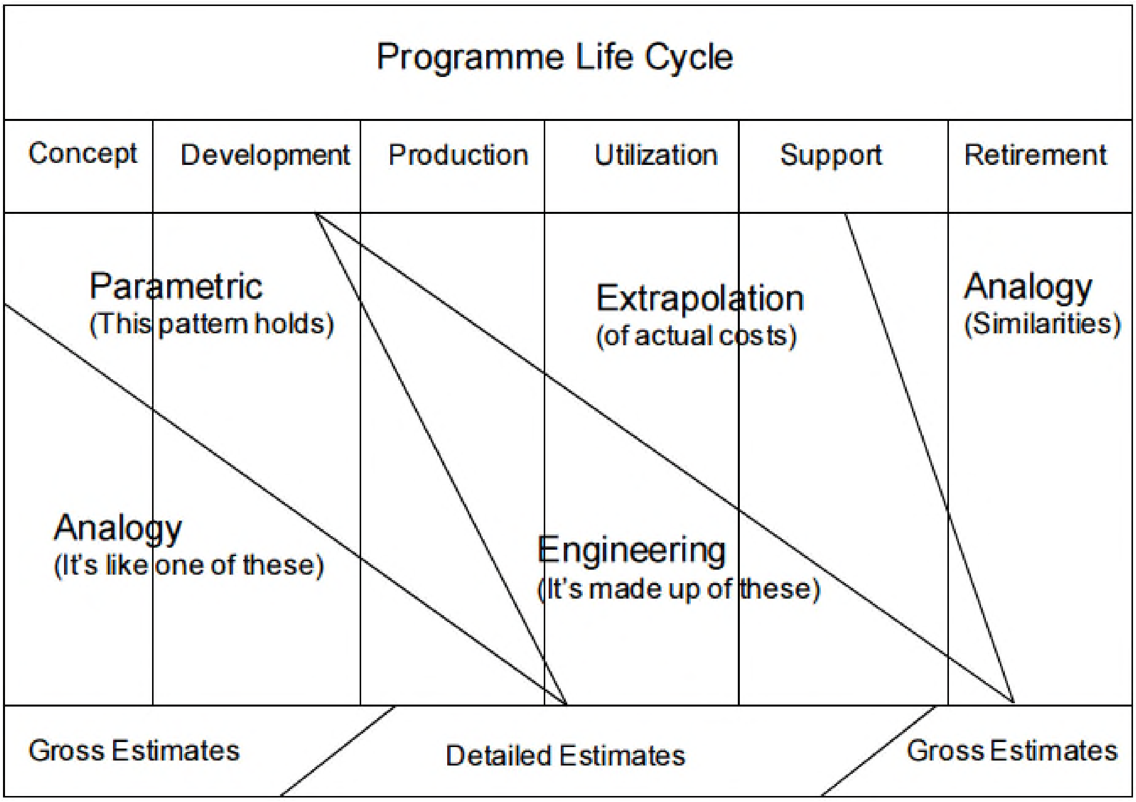


Figure 2-10 Suitability of Cost Estimating Techniques during Programme Life Cycle (Adopted from NATO, 2009)

2.3.3 Maintenance Cost Estimation

Within the Programme Life Cycle, the support (in-service) phase is where the impact of obsolescence is higher due to its long duration. Therefore, the research will focus on this stage from now on. The main activity carried out during this phase is maintenance. During the last few years, significant attention has been given to the maintenance cost estimation and a considerable amount of research has been carried out in this topic, resulting into several models for Maintenance Cost Estimation (Rahman and Chattopadhyay, 2008). The key models are briefly described in Table 2-4.

Table 2-4 Maintenance Cost Estimation Models

Year	Author	Model
1997	Steinmetz and Asmore	A model to ascertain the risks associated with each urban transport mode in terms of cost and benefits.
1999	Zoeteman and Esveld	A model to predict life cycle costs of track structures.
2001	Larsson and Gunnarsson	A model to predict maintenance costs of track when the traffic was increased from 22.5 ton to 25 ton vehicles.
2001	Bowman and Schmee	A discrete event simulation model utilizing historical cost and failure data analysis results to estimate failures and repair/replacement costs.
2002	Veit	Economic optimisation of track investment and maintenance.
2002	Vant	A model to priorities maintenance and renewal projects.
2004	Jian and Hong-fu	A model to predict the maintenance cost for civil aeroplanes based on a general cost breakdown structure (CBS) of aeroplane maintenance.
2005	Ling	A structured methodology which estimates Railway Infrastructure renewal and maintenance costs when there is a lack of quantitative cost data at the early stages of the project life cycle.
2008	Rahman and Chattopadhyay	A conceptual model for estimating cost of outsourcing maintenance of complex and critical asset/equipment taking into account both corrective and preventive maintenance as servicing strategies.

In brief, a combination of simulation models and different cost estimation techniques are employed to estimate the cost of maintenance activities (Datta and Roy, 2009). However, from the literature review carried out, it can be concluded that none of the existing Maintenance Cost Estimation Models takes into account the cost related to obsolescence.

2.4 Summary of Research Gaps

From what has been exposed throughout this chapter, it can be concluded that it is necessary to study ‘mitigation strategies’ and ‘resolution approaches’ separately. The term ‘mitigation’ refers to the measures taken to minimise the impact or likelihood of having an obsolescence problem, whereas the term ‘resolution’ refers to the measures taken to tackle an obsolescence issue once it appears. Obsolescence risk can be mitigated by taking actions in three main areas: supply chain, design and planning. Within those, collaboration within the industry; standardisation of designs and modularisation that may promote the interchangeability of components; and the implementation of proactive actions to determine accurately the cost and impact of obsolescence, are the major means to minimise obsolescence risks. The resolution approaches are classified according to the replacement used into four categories: same component, FFF replacement, emulation and redesign. Among them, same component and FFF replacement are the most commonly used.

Most of the research described in the literature makes an attempt to determine:

- how to reduce the risks of future component obsolescence;
- how to react to occurrences of component obsolescence; and,
- how to anticipate occurrences of component obsolescence.

This literature review has provided a better understanding about the state of the art in obsolescence and cost estimation research. However, it is necessary to identify as well the current practice in obsolescence management across the defence sector to gain a global understanding about the context of the research.

The research on obsolescence is growing; especially in the military and aerospace sectors because obsolescence is increasingly becoming an important issue for sustainment-dominated systems. Most of the research carried out so far in the scope of obsolescence has been focused on the EEE components. Little attention has been given to materials and software obsolescence so far. Indeed very few organisations in the defence industry are managing and costing software obsolescence. There is a lack of understanding about the concept of software obsolescence, how it can be mitigated and the key challenges to estimate its impact on the life cycle of sustainment-dominated systems.

It has been identified a need to revalidate the existing obsolescence cost metrics and identify the key cost drivers involved. This can provide the basis for the development of a systematic approach to predict, at the bidding stage, the NRE cost of resolving obsolescence issues in EEE components and materials. It should be capable of estimating the obsolescence cost even when information such as the BoM, the obsolescence predictions of a monitoring tool and the obsolescence management plan (OMP) are not in place yet.

The main research gaps identified by means of this literature review are summarised as follows:

- There is a lack of understanding about the NRE cost involved in resolving obsolescence issues for EEE components during support contracts.
- There is a lack of understanding about the NRE cost involved in resolving obsolescence issues for materials during support contracts.
- There is a lack of understanding about the concept of software obsolescence and how it can be managed and mitigated.

The following Chapter presents the objectives of this research and describes the development of the research methodology, explaining the different research strategies considered.

Chapter 3

3 RESEARCH DESIGN

3.1 Introduction

The purpose of this chapter is to state the objectives of the research and to describe how the research was designed and the research methodology followed.

In Section 3.2, the research aim and objectives are stated. In Section 3.3, the different research approaches available regarding research purpose, application strategy and enquiry mode are presented and the most suitable for this project are selected. The main methods for data collection are also described in this section, together with the key threats to validity and generalisability, and how they can be mitigated. In Section 3.4, the proposed research methodology adopted is detailed, describing the three phases of this research. Section 3.5 provides a summary of the chapter.

3.2 Research Objectives

The literature review in Chapter 2 enabled the identification of the current research trends and the challenging areas. The key objectives of this research, which relate to address the research gaps identified in the literature review (Chapter 2), are to:

- Understand current practice and state of the art in obsolescence and cost estimation.
- Clarify the concept of software obsolescence, investigate the possible mitigation strategies and determine the key challenges to estimate the cost of software obsolescence.
- Identify the key obsolescence cost drivers for resolving hardware obsolescence issues.
- Develop a systematic approach to predict Non-Recurring Engineering (NRE) cost of resolving hardware obsolescence issues, including EEE components and materials obsolescence.
- Verify and validate the systematic approach developed using detailed case studies.

In the following section, the author reviews the available research strategies, leading to the development of the research methodology for this study.

3.3 Research Methodology Development

This section presents the different research approaches that can be applied and, based on the research aim and context, a research strategy is selected. Subsequently, the issues related to the data collection techniques used are discussed.

3.3.1 Research Context

It is necessary to consider the context of the research in order to tailor the research methodology accordingly. This research is focused on cost estimating, which falls into the area of cost engineering. It is defined by the AACE (2006) as the "application of scientific principles and techniques to problems of cost estimating, cost control, business planning and management science, profitability analysis, project management, and planning and scheduling". The main factors that defined the research context are the industrial support (collaborating organisations) and the research gaps identified.

3.3.2 Research Purpose

According to Robson (2002), there are three types of research from the point of view of its purpose.

- *Exploratory*, which structures and identifies new problems. This type of research is particularly used in little-understood situations.
- *Descriptive*, which portrays systematically an accurate profile of persons, events or situations.
- *Explanatory*, which seeks an explanation of a situation or problem, clarifying how and why there is a relationship between two aspects of a phenomenon or situation.

Kumar (2005) also identified a fourth type called *correlational research*, which establishes the existence of relationships between two or more aspects of a phenomenon or situation.

Taking into account the aim, objectives, and the context of this research, a combination of *exploratory* and *explanatory* is the most suitable approach for its overall purpose. Exploratory is more predominant at the early stages of the research, as there is no much information about obsolescence, whereas explanatory becomes more relevant at the subsequent stages where the author is clarifying the relationships between obsolescence and cost estimation.

3.3.3 Research Application

From the point of view of the research application, it can be classified into two main categories: *pure research* and *applied research*. The emphasis of applied research is on practical problem solving, whereas pure research (also called basic research) is done in order to expand knowledge and investigate the unknown. As stated in the aim of this research, a framework is developed to resolve the problem of estimating the NRE cost of obsolescence at the bidding stage. Therefore, it can be regarded as applied research.

3.3.4 Types of Research Design

There are two main approaches to research design from the viewpoint of the inquiry mode: *qualitative* and *quantitative* (Gummesson, 1991; Burns, 2000; Kumar, 2005), which are also referred to as *flexible* and *fixed* designs (Johnson and Harris, 2002; Robson, 2002). The former is also known as *positivistic* or *scientific*, whereas the latter is also known as *naturalistic* or *interpretive* (Galliers, 1992; Walsh, 2001; Robson, 2002).

- **Qualitative Research**

In qualitative research, the data is collected in the form of words and observations rather than in a numerical format (Johnson and Harris, 2002). It is based on an exploratory approach, where most of the data is collected by means of surveys, interviews and observation (Robson, 2002). In this case, the researcher tends to be directly involved (Gerson and Horowitz, 2002) and the research questions can be modified as a consequence of the information gained, following an iterative process (Easterby-Smith et al., 2002). This possibility of evolving is the reason why Robson (2002) refers to this approach as flexible design. Furthermore, this type of research is more suitable for the study of dynamic processes where it is aimed to develop or discover new concepts instead of imposing preconceived ideas.

The main strengths and weaknesses of the qualitative research are shown in Table 3-1.

Table 3-1 Qualitative Research: Strengths and Weaknesses

	Strengths	Weaknesses
Qualitative Approach	Direct encounter with world	Time required in research setting
	Allows unique experiences to be taken into account	Problems with validity and reliability
	Studies objects in entirety	Problems of anonymity
	Contact with participants	Possible bias

- **Quantitative Research**

A quantitative approach is typically used when the phenomena object of the study can be quantified (Robson, 2002), and hence the data is analysed numerically (Johnson and Harris, 2002). The main characteristics of this type of research are replication, operational definition, hypothesis testing and control (Burns, 2000). Replication ensures that data resulting from experiments is reliable and repetition of the study must provide identical results. Operational definition means that the terms must be defined by the steps or operations used to measure them. Hypotheses are systematically created and subject to empirical tests. A quantitative approach provides the researcher with full control of the environment and the experimental conditions, while staying detached from it so that any influence in the results is minimised (Robson, 2002). This approach requires a 'fixed design' to provide the benefits stated hitherto, but it brings a lack of flexibility as a drawback (Robson, 2002).

The main strengths and weaknesses of the quantitative research are shown in Table 3-2.

Table 3-2 Quantitative Research: Strengths and Weaknesses

	Strengths	**Weaknesses**
Quantitative Approach	Results are replicable	Removed from everyday life
	Results are verifiable	Difficult to respond to environmental forces
	Offers control and precision	Does not account for people's unique experiences
	Illustrates causal effects	Lacks flexibility

Table 3-3 summarises the key differences between the two approaches described.

Table 3-3 Comparison of Qualitative and Quantitative Research Approaches (Burns, 2000)

	Qualitative Research	Quantitative Research
Assumptions	• Reality socially constructed	• Facts and data have an objective reality
	• Variables complex and interwoven; difficult to measure	• Variables can be measured and identified
	• Events viewed from informants' perspective	• Events viewed from outsiders' perspective
	• Dynamic quality to life	• Static reality to life
Purpose	• Interpretation	• Prediction
	• Contextualisation	• Generalisation
	• Understanding the perspectives of others	• Causal explanation
Method	• Data collection using participant observation, unstructured interviews	• Testing and measuring
	• Concludes with hypothesis and grounded theory	• Commences with hypothesis and theory
	• Emergence and portrayal	• Manipulation and control
	• Inductive and naturalistic	• Deductive and experimental
	• Data analysis by themes from informants' descriptions	• Statistical analysis
	• Data reported in language of informant	• Statistical reporting
	• Descriptive write-up	• Abstract impersonal write-up
Role of researcher	• Researcher as instrument	• Researcher applies formal instruments
	• Personal involvement	• Detachment
	• Emphatic understanding	• Objective

Both qualitative and quantitative approaches need to be considered to conduct research (Easterby-Smith et al., 2002). Although both approaches are not likely to be used at the same time, it is possible to apply each one to a different phase within a study. Taking into account the comparison made above between the qualitative and quantitative approaches, a qualitative approach is more suitable for most of the phases in this research. These phases include; understanding the current practice in the research area, iteratively developing the framework and also validating it. However, a quantitative approach is deemed more suitable for other phases of the study in which a numerical analysis of the data was required. Therefore, a combination of both types of research was required to accomplish the aim of this study. Many authors agree that a *mixed methods* *research*, resulting from combining the use of qualitative and quantitative approaches, can strengthen a study (Greene and Caracelli, 1997; Tashakkori and Teddlie, 2003).

3.3.5 Types of Research Strategy in Qualitative Research

Creswell (1998) identified five strategies that can be applied for qualitative research: biography, phenomenology, grounded theory, ethnography, and case study. From them, case study, ethnographic study and grounded theory study can be regarded as the most relevant for the context of this research (Robson, 2002).

- Case study – "a strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real life context using multiple sources of evidence" (Yin, 2009).
- Ethnographic study – aims to capture, analyse, and explain how a group, organisation or community live and experience the world.
- Grounded theory study – aims to generate theory based on the data collected from the study.

Table 3-4 Comparison of Qualitative Research Strategies (Robson, 2002)

	Grounded Theory	Ethnography	Case Study
Focus	Developing a theory grounded in data from the field	Describing and interpreting a cultural and social group	Developing an in-depth analysis of a single case or multiple cases
Discipline origin	Sociology	Cultural anthropology, sociology	Political science, sociology, evaluation, urban studies, many other social sciences
Data collection	Typically interviews with 20-30 individuals to 'saturate' categories and detail theory	Primarily observation and interviews during extended time in the field	Multiple sources ' documents, archival records, interviews, observations, physical artefacts
Data analysis	Open coding, axial coding, selective coding, conditional matrix	Description, analysis, interpretation	Description, themes, assertions
Narrative form	Theory or theoretical model	Description of the cultural behaviour of the group	In-depth study of a 'case' or 'cases'

A comparison of their characteristics is provided in Table 3-4. In the light of the characteristics and definitions, the fact that several organisations are sponsoring this research, and hence, the researcher has direct access to real-life information; makes the case study strategy the most suitable for this research.

3.3.6 Data Collection Methods

The main methods applied for data collection are literature review, surveys, interviews and focus groups. A focus group can be regarded as a particular case of interview, in which a group participates rather than one-to-one (Robson, 2002). All these methods have been applied to capture the information required to achieve the aim of this research project, together with continuous iterations for the development of a software prototype of the framework delivered.

The author’s membership to the Component Obsolescence Group (COG) set the appropriate circumstances for deploying the Delphi method as part of this study. COG is a special interest group of like-minded professionals, from all levels of the supply chain and across all industries and relevant Government agencies, concerned with addressing and mitigating the effects of obsolescence (COG, 2010). The Delphi method is “an iterative process to collect and distil the anonymous judgments of experts using a series of data collection and analysis techniques interspersed with feedback” (Skulmoski et al., 2007). This research tool is particularly well suited to new research areas and exploratory studies (Okoli and Pawlowski, 2004; Linstone and Turoff, 1975; Landeta, 2006; Grisham, 2009). The main reason for using the Delphi method is the lack of appropriate historical data about the resolution approaches used to resolve obsolescence issues, and thus expert judgment is required (Rowe and Wright, 1999).

- **Literature Review**

According to Burns (2000), the literature review is a stimulus for thinking rather than just a way to summarise the previous research done in the area, which can restrict the researcher to consider only existing concepts and categories. The qualitative approach encourages the search for new ways to look at the data, as occasionally new findings may not be fitted into existing concepts and categories. The literature review should provide the existing ideas and knowledge in the area, as well as the methodologies used (Burns, 2000).

- **Surveys**

Surveys are frequently used to collect data by asking the participants a set of relevant questions. According to the way the questionnaire is administered, the survey data collection can be divided into three main types: self-completion, where the respondents receive the questionnaire by e-mail or post and they fill it in by themselves; face-to-face interview, where the interviewer asks the questions and completes the questionnaire in the presence of the respondent; and telephone interview, where the respondent is contacted by phone and the responses are recorded (Robson, 2002). Although surveys can be applied to any type of research, its use is not advisable to carry out pure exploratory research. The reason is that standardising the questions to reduce ambiguity is a requirement to ensure reliable data but it clashes with the nature of an exploratory research. This is why surveys are typically used for descriptive purposes (Robson, 2002).

A list of the advantages and disadvantages of the survey approach is presented as follows (Table 3-5).

Table 3-5 Surveys: Strengths and Weaknesses (Robson, 2002)

	Strengths	Weaknesses
General to all types of survey	• A simple and straightforward approach to study of attitudes, beliefs, values, motives etc. • Adaptable – can collect information from almost any human population • High amounts of data standardisation	• Data affected by respondents' characteristics • Respondents may not report beliefs, attitudes etc. accurately – trying to create good impression
Postal and other self-administered surveys	• Can be very efficient – large amounts of data at low cost in short time • Often only or easiest way • Allow anonymity – can therefore encourage honest answers, particularly regarding sensitive areas	• Low response rate. Sample may not be representative as don't know characteristics of non-respondents • Ambiguities and misunderstandings in survey questions may not be detected • Survey may not be treated seriously – may not be able to detect this
Interview surveys	• Interviewer can ensure questions are clearly understood • Presence of interviewer can encourage participation and involvement	• May be affected by interviewer's characteristics – could influence responses • May be affected by interactions of the interviewer and respondent • Respondents may consider they are not anonymous and so be less honest and open

- **Interviews**

There are mainly three types of interview according to their level of standardisation and structure: fully-structured, semi-structured and unstructured (Robson, 2002).

Fully-structured interviews have predetermined questions, usually in a preset order, using fixed wording (Denzin and Lincoln, 1998; Fontana and Frey, 1998; Robson, 2002). The characteristics of this type of interview are very similar to those aforementioned for surveys. Therefore, this approach is mainly suggested for surveys and opinion polls rather than qualitative research (Robson, 2002).

Semi-structured interviews have predetermined questions, but the interviewer has the freedom to choose the wording of the questions, their sequence and how long is spent with each one. This gives more flexibility than the fully-structured interviews and facilitates building rapport between interviewer and interviewee (Burns, 2000). However, it could be difficult and time-consuming to compare and analyse data provided by various respondents.

Unstructured interviews have open-ended questions that enable the interviewer to go in-depth, clear up any misunderstanding, establish good rapport between interviewer and interviewee and usually lead to unexpected answers (Robson, 2002). The drawback of this approach is that there is a significant chance for the interviewer to lose control of the interview and also the analysis of the responses is difficult.

The suitability of using interviews as a data collection method depends upon the particular research project (Marshall and Rossman, 1989), in the light of the strengths and weaknesses shown in Table 3-6.

Table 3-6 Interviewing: Strengths and Weaknesses

Strengths	Weaknesses
Co-operation between interviewer and interviewee	Limited time period available with interviewee
Allows knowledge construction	Difficulties with establishing reliability
Provides in-depth understanding of informant's experiences	Time consuming to prepare questions and analyse data
Flexible/adaptable	Possible bias

3.3.7 Research Evaluation

In order to make a research trustworthy and believable, it needs to be evaluated in terms of its validity and generalisability. Validity is concerned with identifying if a piece of qualitative (flexible) research is true, accurate, or correct (Robson, 2002). There are three main threats to validity, which can be mitigated by the researcher if they are treated in advance (Robson, 2002):

- **Reactivity** – it refers to the way in which the researcher's presence may interfere somehow with the setting, and with the behaviour of the people involved.
- **Respondent bias** – it can refer to cases where the respondent tries to give the answers or impressions which they judge that the researcher wants; or when the researcher is seen as a threat, so the respondent may withhold information.
- **Researcher bias** – it refers to the assumptions and preconceptions that the researcher brings to the situation, which may affect the way in which they behave in the research setting. As a consequence, the researcher may: see a relationship where they are not correct; reject them where they are correct; and ask the wrong questions (Kirk and Miller, 1986).

There are several strategies that can be applied to minimise those threats (Robson, 2002; Creswell, 1998; Flick, 2002):

- **Prolonged involvement** – the researcher spends time within the research setting, developing relationships with the participants and understanding the culture of the setting studied. However, prolonged involvement could potentially increase the researcher bias.
- **Triangulation** – the use of alternative sources and methods to cross-check results and enhance the research rigour (Jankowicz, 1995).
- **Peer debriefing and support** – researcher bias can be reduced by means of debriefing sessions after long periods within the research setting.
- **Member checking** – it involves receiving feedback from respondents after showing them the collected material. Creswell (1998) regards this as a crucial approach to establish credibility of the research.
- **Negative case analysis** – applying the working hypothesis/theory under negative or disconfirming evidence. This usually allows refining the theory (Creswell, 1998; Robson, 2002).
- **Audit trail** – keeping track of all activities taking place during the research.

A summary of the effect that these strategies may have on each threat is provide as follows in Table 3-7.

Table 3-7 Impact of Mitigating Strategies on Threats to Validity (Robson, 2002)

	Threats to Validity		
Strategy	**Reactivity**	**Researcher bias**	**Respondent bias**
Prolonged involvement	Reduces threat	Increases threat	Reduces threat
Triangulation	Reduces threat	Reduces threat	Reduces threat
Peer debriefing and support	No effect	Reduces threat	No effect
Member checking	Reduces threat	Reduces threat	Reduces threat
Negative case analysis	No effect	Reduces threat	No effect
Audit trail	No effect	Reduces threat	No effect

Generalisability is related to stating whether the results may be generally applicable to different persons, context, situations and times. There are two types of generalisability: internal and external (Maxwell, 2002; Robson, 2002). The internal generalisability is related to whether the findings can be extended within the setting studied to those who were not directly involved in the initial study. The external generalisability is related to whether the conclusions can be extended to other institutions or research groups beyond the setting studied.

The fact that a case study strategy was chosen for this research increased the risk of bias from both sides; the respondent and the researcher. Therefore, the researcher has adopted all the mitigation strategies above to prevent jeopardising the validity and generalisability of the results of this research.

3.4 Research Methodology Adopted

3.4.1 Research Approach Selection

The reasoning provided above justifies the selection of the research approaches for this study. A summary of this selection is represented in Figure 3-1.

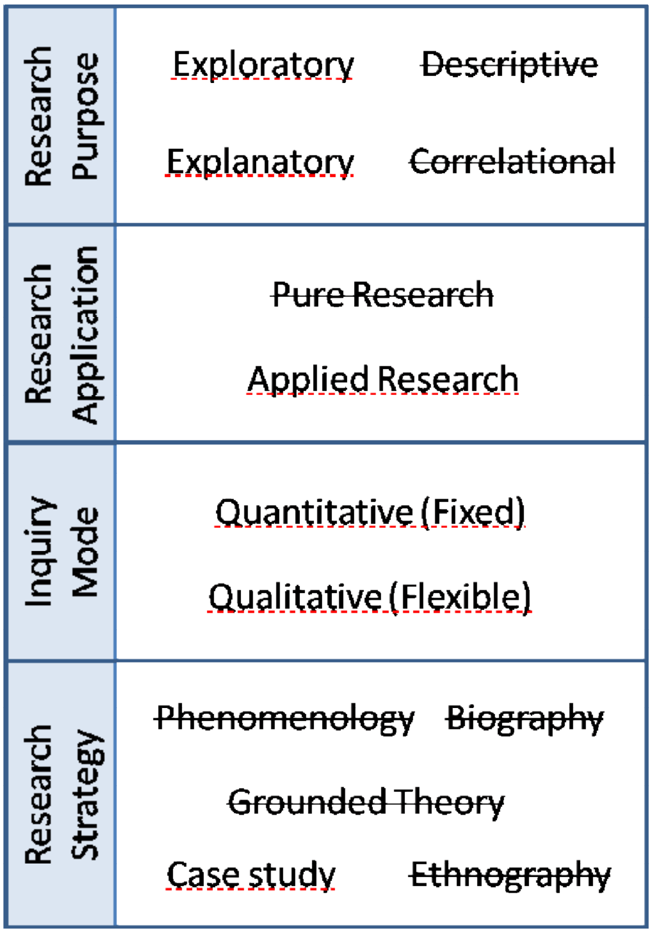


Figure 3-1 Research Approaches Selection

Typically, the case study strategy requires the use of multiple methods of data collection (Yin, 2009; Robson, 2002; Creswell, 1998; Eisenhardt, 1989). The main methods applied for data collection are explained as follows.

3.4.2 Research Methodology Adopted

The author presented his rationale regarding the decisions made to define the research methodology to be applied to this project. Due to the type of information expected to be gathered along the research process, an inductive approach has been applied. A cross-case-study-based research strategy was used to gain the contextual understanding and develop a framework for the cost estimation of obsolescence. This approach will enable the generalisation of the framework developed to the defence and aerospace environment. The proposed research methodology, which is represented in Figure 3-2, is divided into 3 main phases: 1) understanding context and current practice, 2) framework and prototype software development, and 3) framework and prototype software validation.

- **Phase 1: Understanding Context and Current Practice**

The first phase is related to gaining a contextual understanding, defining the research protocol and capturing the current practice on obsolescence cost estimation in the defence sector. An extensive literature review on the concept of obsolescence, obsolescence management and obsolescence costing; the participation on a spring school on PSS; the study of the methodology and conclusions resulting from a Cranfield PSS-focused project called “Stage 00”; and interaction with obsolescence experts members of the Component Obsolescence Group (COG), allowed gaining a better understanding about the context of this project. Once a questionnaire was developed by means of a brainstorming within the PSS-Cost team; it was piloted and validated with an industrial partner, so it could be used in a set of introductory visits with four industrial partners. In each of the introductory meetings carried out, semi-structured questionnaires were utilised. The aim was to identify the major issues, identify stakeholders and check the availability of employees. The analysis of the information collected, by means of MindMaps, allowed the development of the research protocol for the next stage of the project. Once it was developed, it was piloted with an industrial partner.

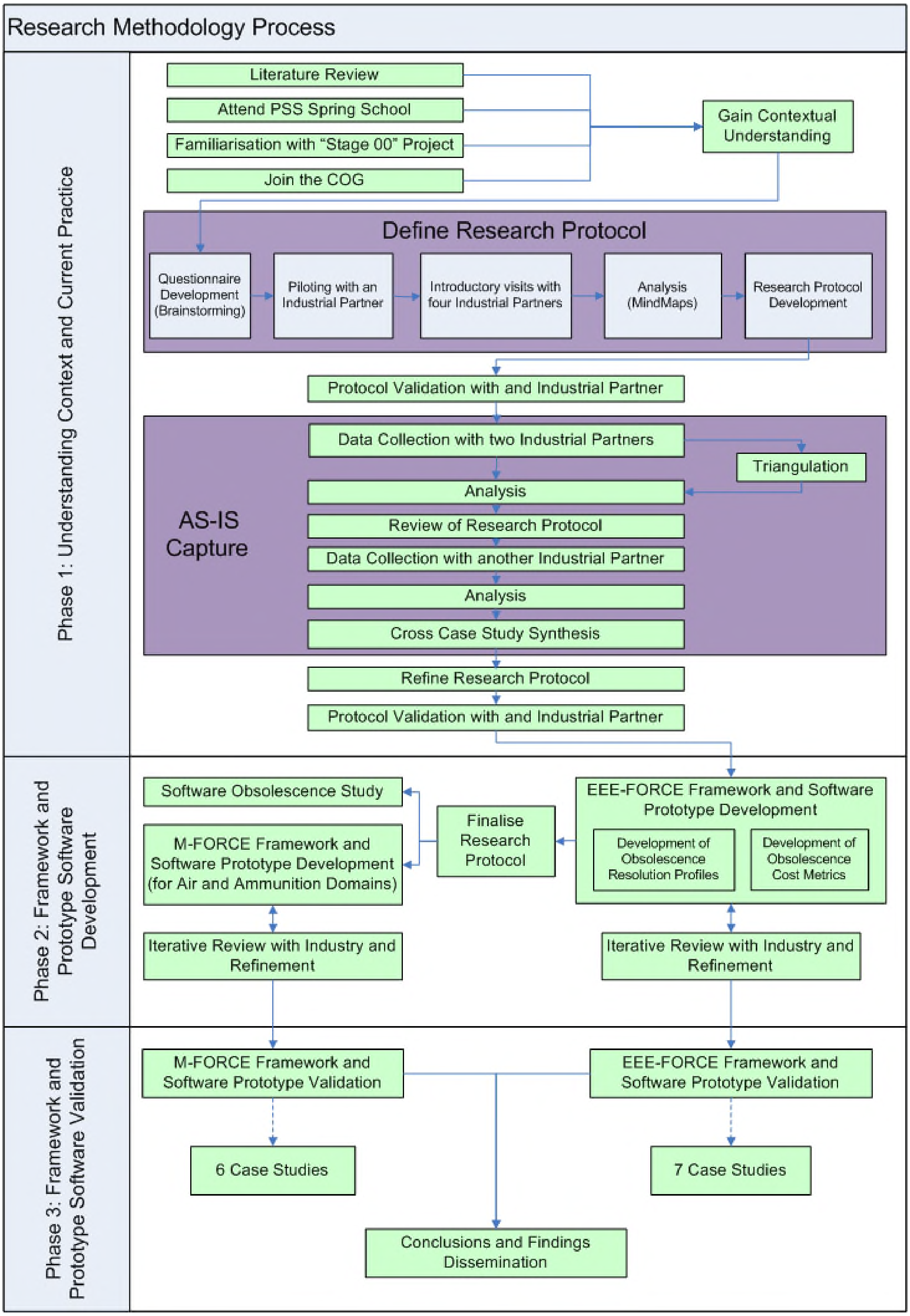


Figure 3-2 Research Methodology Adopted

The enrolment in the Component Obsolescence Group (COG) allowed not only to gain access to the latest information about the obsolescence issues in the industry and possible solutions, but also to come into contact with the main experts in obsolescence management from many organisations across the UK and abroad. The research protocol developed was used to capture the current practice by means of semi-structured interviews and workshops with relevant stakeholders such as bidding team members, whole life costing and obsolescence experts from the different organisations that participated in the study. Additional methods of data collection (e.g. analysis of publicly available information such as marketing documents and company information such as obsolescence management plans (OMP), previous bids and commercial agreements) were used to triangulate the data obtained from the interviews and workshops. The data gathered was transcribed and codified into mind maps using appropriate protocol analysis software (MindManager). Once the data gathering and analysis were completed, a cross case synthesis was performed by means of an exhaustive comparison between the data collected from different organisations and the literature review. A set of reports were drawn up highlighting the conclusion from the AS-IS study and were validated by the industrial partners. Finally, the research protocol was refined and it was validated with an industrial partner.

- **Phase 2: Framework and Prototype Software Development**

This phase of the research is focused on the development of a framework for the estimation of NRE costs of hardware (EEE components and materials) obsolescence that can be used during the CADMID cycle of support contracts in the defence sector. A study on the concept of software obsolescence, how it can be mitigated and the key challenges related to it, is also carried out in this phase.

The study started focusing on the development of the NRE cost estimating framework for EEE components obsolescence. The research protocol was employed to collect data about the contract from existing cost related documents, cost estimating tools (excel spreadsheets) and systems within the company, annual report, board papers and expert interviews. The data was then analysed together with the literature review to develop methodologies to model the different types of NRE costs incurred due to obsolescence. Different types of cost modelling techniques were explored, such as analogy based, expert judgement based, parametric and fuzzy rule based cost estimating. Based on the results of the analyses carried out so far, it was decided the rationale behind this framework. The two main pillars required for the use of this rationale are a set of reliable obsolescence cost metrics and the probability of using each resolution approach to resolve an obsolescence issue (this is called “obsolescence resolution profiles” (ORP) henceforth).

A cost metrics study was carried out during an obsolescence workshop organised at Cranfield University in which 21 obsolescence experts from different organisations participated. The experts were arranged into groups of four, following a careful selection based on their backgrounds, areas of expertise and the organisations they belong to. The intention was to make heterogeneous groups whose members may have expertise in different fields (e.g. EEE components obsolescence, materials, software, systems support) from different organisations. The interaction and discussion among them about the proposed topics for discussion led to reach consensus. This approach reduces the subjectivity and bias that can be expected from expert opinion. A further analysis of the outcomes of each group lead to collating them, by identifying communalities, and deriving a set of obsolescence cost metrics. These results were validated and refined by means of one-to-one interviews with three key obsolescence experts.

The membership of the Component Obsolescence Group (COG) set the appropriate circumstances for deploying the Delphi method to estimate the probability of using each resolution approach to tackle an obsolescence issue, taking into account the complexity level of the EEE component and the obsolescence management level. Firstly, a questionnaire was developed to be used in the first round with the COG panel. Prior to this, it was piloted with an obsolescence expert to make sure it was clear, unambiguous, easy to fill in and precise. A total of 38 experts in obsolescence participated in the first round and subsequently the responses were analysed. The outcomes of this analysis were presented at a second round to 33 experts in obsolescence, who took the opportunity to discuss about the results and fill in a new questionnaire either corroborating the results or correcting them. A final analysis of these responses allowed refining the outcomes of the first round, providing as a result the obsolescence resolution profiles. A “definition refining” session and a “trends refinement” session allowed validating and refining the ORP resulting in collaboration with six key obsolescence experts.

A prototype software system was designed and developed to embody the framework rationale, so it can be used and tested. It was presented to obsolescence experts and a few enhancements were suggested. Once the changes were implemented, this enhancement process was carried out in an iterative way, getting feedback from experts across different organisations.

The protocol was reviewed and adapted to be applied to the development of the NRE cost estimating framework for materials obsolescence in the air and ammunition domains. Four materials obsolescence experts participated in a workshop that aimed to identify the major factors that influence materials obsolescence, and hence, the cost related to it. Once the framework and the software prototype were developed, it was presented to experts in materials obsolescence to identify possible enhancements. This process was repeated iteratively, until the experts were satisfied with the resulting framework.

Additionally, software obsolescence has been explored. Five one-to-one interviews (4 to 5 hours each) with four software obsolescence experts from different companies, using semi-structured questionnaires, allowed capturing the key challenges to estimate the software obsolescence cost and best practice for managing it and mitigating the risk.

- **Phase 3: Framework and Prototype Software Validation**

The third phase is concerned with the validation of the frameworks and the respective prototypes developed. This was done by means of qualitative and quantitative assessment. The validation started with planning meetings with the key stakeholders. The meetings identified the relevant experts in the organisations who could critically appreciate the effectiveness of the methodologies and at least one support contract within each organisation. The methodologies were demonstrated to the experts, and their feedback was captured using a semi-structured questionnaire. Any additional feedback was noted and transcribed. Once the data was collected from the workshops, it was analysed. The observations were triangulated with literature review and previous estimates from the companies, so the bias for the cost modelling can be reduced. A total of six organizations from the defence sector participated in the validation of the EEE-FORCE framework providing qualitative and quantitative validation, by means of a total of seven case studies, where real data from current or past projects was input to the prototypes and the outputs were analysed. Predicted costs were compared to available actual cost data. Any gap in actual data was covered by expert evaluation within a workshop environment. Two other companies from the nuclear and railway sectors validated the generalisability of this framework. Additionally, a total of three organizations from the defence sector, including the aerospace and ammunition domains, participated in the validation of the M-FORCE framework providing a total of six case studies.

3.5 Summary

In this Chapter the research objectives were presented. Subsequently, the different research methods were reviewed and the rationale for selecting the most suitable one for this research was provided. The different data collection methods were presented, together with the research design issues and techniques to minimise threats to the validity and generalisability of the study.

The following Chapter presents the current practice in the UK defence sector in contracting for support and in obsolescence management for EEE components. It also provides an understanding about software obsolescence and how it can be managed.

THIS PAGE IS INTENTIONALLY LEFT BLANK

Chapter 4

4 CURRENT PRACTICE IN OBSOLESCENCE MANAGEMENT AND COST ESTIMATION

4.1 Introduction

This Chapter presents the current practice in the UK defence sector for contracting (bidding process) and whole life cycle cost estimation at the bidding stage (Phase 1) and the current practice in obsolescence management for EEE components and obsolescence cost estimation (Phase 2). It also provides an understanding about software obsolescence, mainly based on industrial input due to the lack of existing research into this area in the literature (Phase 3).

Most of the existing literature related to obsolescence is solely focused on the obsolescence of electronic components, disregarding the software obsolescence problem. Recently, a few authors (Sandborn, 2007b; Sandborn Sandborn and Plunkett, 2006; Merola, 2006) have recognised the importance of software obsolescence – especially related to Commercial off-the-shelf (COTS) Software – and hence there is a need for further research in this area to be able to manage and mitigate it properly. The Component Obsolescence Group (COG) at UK has also identified recently this necessity, and they have published a guide that gives an overview about the software obsolescence problem and provides a starting point for managing it (Rumney, 2007).

Phase 1 was carried out in collaboration with two other PhD researchers to gain an overall understanding on contracting in the defence environment and the bidding stage, whereas Phases 2 and 3 were carried out individually focusing on obsolescence in more depth than during the previous phase.

In Section 4.2, the research methodology that the author followed in each of the three phases is presented. Section 4.3 provides a description of the outcomes of Phases 1 and 2, including the current practice in cost estimation at bidding stage for defence contracts and obsolescence management for EEE components. In Section 4.4, the author presents the outcomes of Phase 3, clarifying the meaning of software obsolescence and explaining the key challenges to manage it and the main strategies that can be applied to mitigate this risk.

4.2 Detailed Research Methodology

4.2.1 Phase 1: Current Practice in Contracting and Whole Life Cycle Cost Estimation at the Bidding Stage in the UK Defence Sector

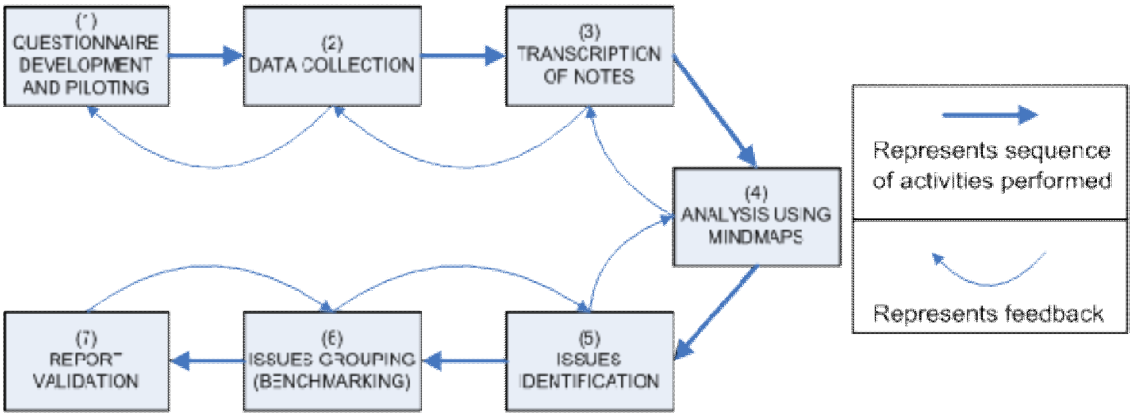


Figure 4-1 Research Methodology in Phase 1

The research method followed in Phase 1 is based on the sequence of activities shown in Figure 4-1. Activity ❶ involved the development of a semi-structured questionnaire based on the results of a brainstorming session carried out in collaboration with two other PhD researchers. Due to the exploratory purpose of these interviews, it is justified the usage of a semi-structured questionnaire because it combines open questions, to gain an overall understanding about the current practice in the defence sector, with others more specific that each researcher designed to focus on their own specific research area. That questionnaire was piloted with an engineering manager from industry (31 years experience) to ensure the quality for the interviews. Appendix A.1 shows the questionnaire used during the interviews. The questionnaire was used during interviews and focus groups with experts from BAE Systems, GE Aviation, Lockheed Martin and MoD (activity ❷). These organisations were selected for this study because they provide a good representation of the defence sector. The responses were transcribed (activity ❸) and Mind Map techniques, using a software called MindJet MindManager 8, were used to summarise and analyse the responses (See Appendix B.2) (activity ❹). As a result, the major issues were identified (activity ❺) and they were grouped by means of a cross-case study analysis (benchmarking exercise) (activity ❻), showing the current practice in contracting and Whole Life Cycle Cost estimation at the bidding stage in the UK defence sector. Finally, the outcomes of this study were validated in collaboration with Rolls-Royce (activity ❼) to ensure the generalisability and validity of the results. The details of the experts from industry involved in this study are provided in Table 4-1. The experts selected were mainly project managers, Integrated Logistics Support (ILS) managers and cost estimators, as they have a good understanding about the bidding stage, defence contracting and the current practice for whole life cycle cost estimation.

Table 4-1 Experts Involved in AS-IS Capture

Organisation	Role	Years of Relevant Experience
ORG_A	SET Assurance Team Leader (Pricing and Forecasting)	20
ORG_A	Strategic Forecasting Team Leader I	23
ORG_A	Strategic Forecasting Team Leader II	26
ORG_A	Project Manager (Availability Contracts expert)	14
ORG_B	Engineering Manager	31
ORG_B	Project Manager	9
ORG_B	Assistant Project Manager	4
ORG_B	Whole Life Cycle Cost Estimator	6
ORG_B	Design Analysis Diagnostics Engineer	13
ORG_B	ILS Engineer	15
ORG_B	Project Manager	30
ORG_B	Support Solutions Manager	23
ORG_B	Integrated Logistics Support Manager	12
ORG_B	ILS Supportability Engineer	10
ORG_B	Supportability Specialist	17
ORG_B	Business Development Manager	7
ORG_B	Systems Engineer	11
ORG_B	Risk assessment Expert	28
ORG_B	Finance	11
ORG_C	Operations Management	6
ORG_C	Project Manager	15
ORG_D	Programme Manager	12
ORG_D	Business Development Manager	8
ORG_D	Field Support Engineer	7
ORG_E	LCC Analyst	3

The data collection activity involved nine semi-structured interviews with groups of experts from four organisations, to gain an overall understanding. In addition, three one-to-one interviews and four phone interviews were carried out to clarify concepts and discuss them in greater detail. The usual duration of each group-focus interview was four hours, where two to four experts from industry participated. The structure designed for each session is described as follows. The three PhD researchers presented the aim and objectives of their research so that the participants were aware of the type of information required. Subsequently, the first half of the session was spent on discussion about general topics such as defence contracting, with special interest on availability and capability contracts, and whole life cycle cost estimation. An excerpt of the questionnaire used for this purpose is as follows.

- Describe the Cost Breakdown Structure (CBS) that you employ in availability/capability contracts?
- What rationale was used to select the estimating method(s) for the programme (e.g. by analogy, expert opinion, extrapolation, parametric, or bottom-up)?
- Is there an agreed master data and assumptions list (MDAL) e.g. that supports translation of programme requirements into a defendable cost estimate?
- What is the scope of the estimate in programme terms, e.g. for United Kingdom MoD contracts what stages of the CADMID/CADMIT cycle are included?

These questions lead to gain a better understanding about the defence contracting context and the current practice for cost estimation in this environment.

The second half of the session concentrated on the individual topics of each PhD researcher. The questions about obsolescence were focused on gaining an overall understanding about the current practice in obsolescence management and obsolescence cost estimation, and also on identifying any obsolescence expert in the organisation, as shown below.

- What methods are used to predict and mitigate obsolescence?
- How do you incorporate obsolescence into cost models?
- Is there any expert or department within your organisation focused on obsolescence management?

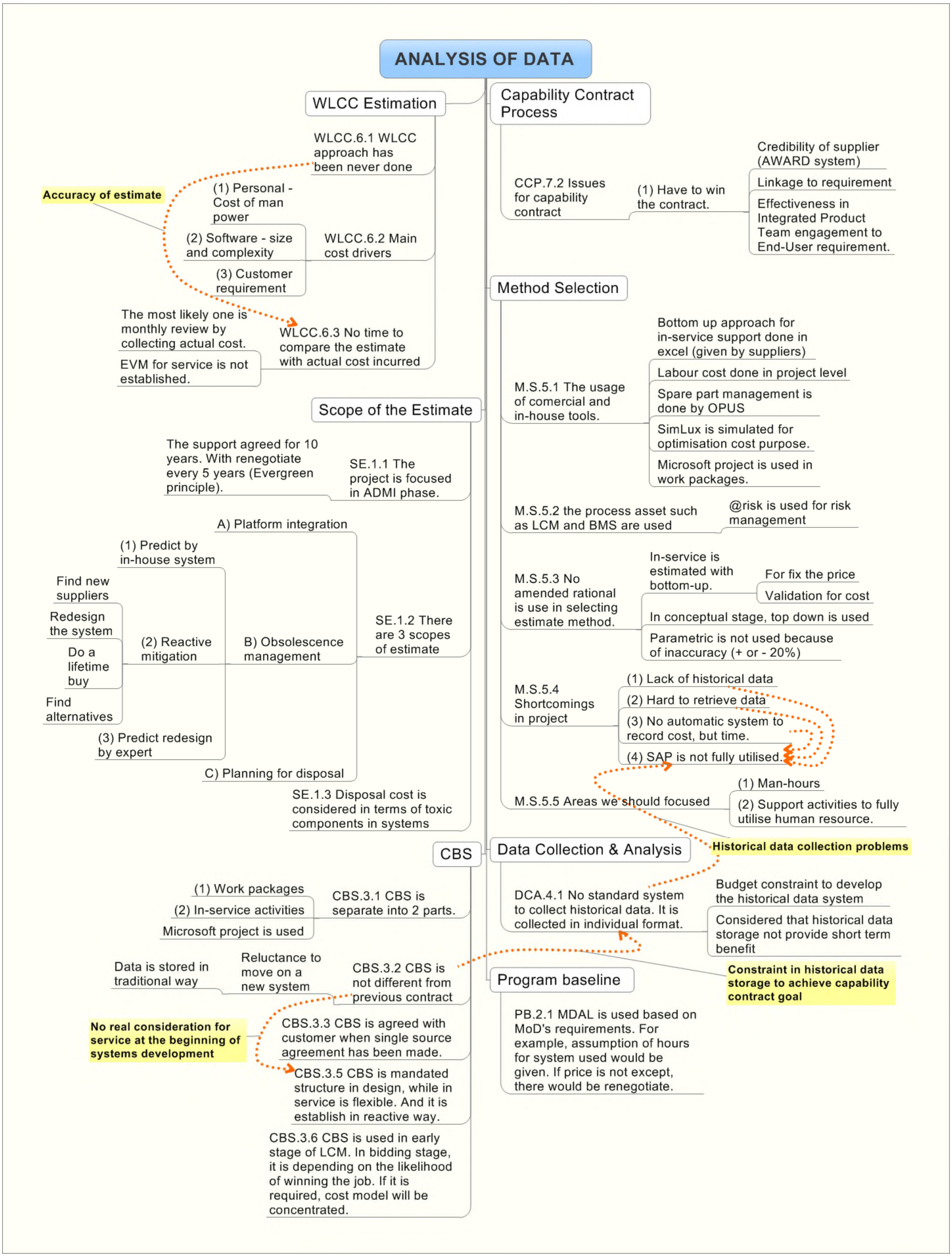


Figure 4-2 Example of a MindMap Used for Analysis of Responses

The analysis of the responses was done using MindMaps (an example is shown in Figure 4-2) and they were classified into different areas:

- Scope of the estimate
- Programme baseline
- Cost breakdown structure (CBS)
- Data collection and analysis
- Method selection
- Obsolescence – technology refresh
- Whole life cycle cost estimation
- Availability/Capability contract process

For each area, similarities, differences and unique responses were grouped as part of the analysis. The following section summarises the outcomes from the analysis and comparison across the four organisations that participated.

A key activity during Phase 1 was the identification of the experts on obsolescence for each organisation, so that the current practice on obsolescence management could be captured in detail during Phase 2.

4.2.2 Phase 2: Current Practice in Obsolescence Management for EEE Components in the UK Defence Sector

The current practice in obsolescence management for EEE components in the UK aerospace and defence sector has been captured in more detail than in the previous phase. A total of 20 interviewees from across five organisations have participated in workshops or one-to-one interviews. They are mainly Obsolescence Managers, Obsolescence Specialists and Support Managers, with experience in the area ranging from 4 to 45 years, as shown in Table 4-2.

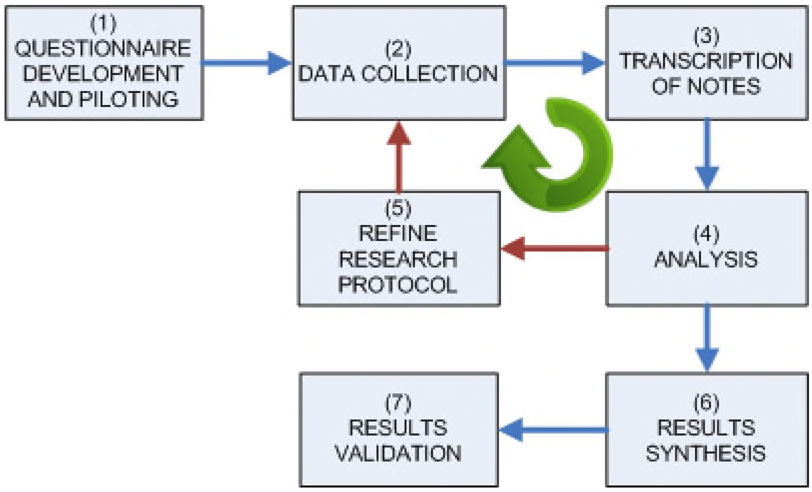


Figure 4-3 Research Methodology in Phase 2

The research methodology followed in Phase 2 is outlined in Figure 4-3. Activity ❶ involved the development of a semi-structured questionnaire based on the information collected during Phase 1 and the literature review. Due to the exploratory purpose of these interviews, it was decided to use a semi-structured questionnaire. The questionnaire was piloted with an obsolescence manager from industry (9 years experience) and an engineering manager (31 years experience) to ensure the quality for the interviews. Appendix A.2 lists the questionnaires used during the interviews. The interviews had an average duration of three to five hours. During the first 20 minutes the researcher presented the aim and objectives and the purpose of the interview. Subsequently, the first half of the session was spent on discussion about the current practice on managing obsolescence and the second half was focused on capturing the current practice on obsolescence cost estimation (activity ❷). The Obsolescence Managers, Obsolescence Specialists and Support Managers from the industrial collaborator were chosen to participate in these interviews due to their experience in the area. The responses were transcribed (activity ❸) and analysed (activity ❹). Another source of information is the documentation provided by these organisations, such as logistics and support plans, obsolescence management plans (OMPs) and obsolescence management reports. They were used to triangulate with the information collected during the interviews. As a result of the analysis of the responses from each interview, the research protocol was refined and applied to subsequent interviews, following an iterative process (activity ❺). Finally, all the results of the analysis were synthesised, identifying similarities and differences between the information provided by the different experts (activity ❻). The outcomes of this study were validated in collaboration with Rolls-Royce (activity ❼) to ensure generalisability and validity of the results.

Table 4-2 Experts Involved in Capture of Current Practice for Obsolescence Management and Cost Estimation

Organisation	Role	Years of Relevant Experience
ORG_A	Strategic Forecasting Team Leader II	26
ORG_A	Obsolescence Management Policy A&G Lead	5
ORG_A	Obsolescence Management I	5
ORG_A	Obsolescence Management II	5
ORG_A	Typhoon Obsolescence Manager	12
ORG_B	Component Obsolescence Specialist	9
ORG_J	Team Leader-Materials, Standards and Obsolescence	25
ORG_J	Product Qualification	35
ORG_J	Materials Engineer	45
ORG_J	Materials Engineer	25
ORG_D	Obsolescence & Spares Engineering Manager	4
ORG_D	Programme Manager	12
ORG_I	Chief Systems Engineer – Customer Support and Services	17
ORG_I	In-Service Support Manager	18
ORG_I	Support Solutions Manager	25
ORG_I	Team Leader Logistics Modelling and Simulation	7
ORG_I	Modelling and Simulation Engineer	9
ORG_I	Business Cost Forecasting & Pricing Future Projects	12

An example of the questions used during the interviews is provided as follows.

- Do you forecast obsolescence issues? How?
- How is the risk assessment of the BoM done?
- Do you take into account the cost related to obsolescence issues at the bidding stage? What types of obsolescence are taken into account?
- How do you estimate the cost of obsolescence? What kind of technique do you use? (e.g. expert opinion, parametric, analogy-based, detailed,…)
- What do you regard as the key cost drivers for obsolescence?

The responses were analysed by identifying similarities, differences and unique responses across the different participants. The outcomes from this analysis are summarised as follows.

4.2.2.1 Obsolescence Management for EEE Components

The main challenge identified in the four participating organisations is a difficulty in performing the risk assessment for the obsolescence impact of each component or Line Replaceable Unit (LRU) of the system. The accuracy of this assessment is crucial to develop a suitable obsolescence management plan as it provides the basis of selecting the appropriate mitigation strategies.

There is a lack of reliable obsolescence cost metrics. In 2004, the Ministry of Defence (MoD) in the UK commissioned ARINC the development of a set of cost metrics that may be used for the estimation of costs related to obsolescence. However, many organisations are very sceptical about the reliability of the results of that study. For example, it is questioned the validity of ignoring part of the raw data, regarding it as “outliers” (data outside of 3 standard deviations from mean was not considered). This approach is suitable in difficult observational experiments, where a volatile observation cannot be repeated and there is the possibility that the observer got it wrong. However, the information collected for the cost metrics study is not volatile data and can be verified. Additionally, the LTB approach was not considered for this study, although it is a common obsolescence resolution approach. A major limitation of these cost metrics is that a single figure is allocated to each resolution approach, disregarding any other factors that may have an impact on the cost. The obsolescence cost metrics would allow the selection of the most cost effective solution, a cost avoidance assessment and the estimation of the impact of obsolescence on the Whole Life Costs. The lack of reliable obsolescence cost metrics impairs the selection process of the most suitable mitigation strategy to tackle obsolescence issues.

Although most of the industrial collaborators (3 out of 4) have access to monitoring/forecasting commercial tools based on technology roadmapping, they struggle to combine this information with the information about the "health" of the suppliers, regulation changes and the market trends in order to forecast accurately the obsolescence events. This is necessary to plan ahead the mitigation and resolution strategies that should be put in place.

In one of the organisations it has been identified a problem that prevents the contractor from managing obsolescence in the most cost effective way for the customer. The main reason is the current contractual procedure. The obsolescence risk for the contractor is immediate and persists throughout the availability contract period, whereas the risk for the customer begins at the end of the contract period. The majority of support contracts do not cover the whole in-service phase but smaller period initially, and subsequently they are extended for small periods (e.g. 5 or 10 years). This contractual style usually encourages the contractor to optimise the obsolescence solutions to cover just the contracted period, which is different from the optimal solutions to cover the whole in-service period.

The skills, processes, software, test equipment and tools obsolescence are barely considered in the obsolescence costing at the bidding stage in the participating organisations. The consequences of ignoring these types of obsolescence, which eventually will impact on the project, are unexpected costs that may jeopardise the sustainability of the project.

4.2.3 Phase 3: Understanding Obsolescence in Software

The fact that this topic is very recent and has not been explored enough yet has been the reason why, apart from the information collected through an exhaustive literature review, it was necessary to capture information directly from industry. The research methodology followed in this study is outlined in Figure 4-4. After analysing the existing literature, a semi-structured questionnaire was developed (shown in Appendix A.3) in order to capture general understanding of the software obsolescence concept and then analyse in depth the key triggers of software obsolescence, the mitigation strategies that can be applied and the current practice to manage it. Examples of the questions contained in that questionnaire are provided as follows.

- What is the difference between Software Support and Software Obsolescence?
- What are the main reasons for Software Obsolescence?
- Do you forecast obsolescence issues? How? (Technology roadmap)
- Is there any mitigation strategy that can be applied to minimise the impact or probability of having a software obsolescence issue?

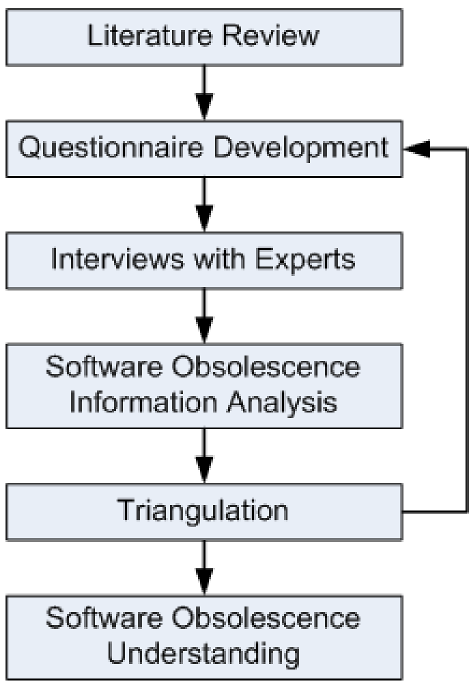


Figure 4-4 Research Methodology in Phase 3

A total of eleven interviews with eight experts from different industrial organisations in the defence, aerospace and nuclear sectors were carried out (the roles and years of experience of the participants are shown in Table 4-3). After each interview, the information captured enabled refining the questionnaire to gain more in-depth information in subsequent interviews.

Table 4-3 Software Obsolescence Experts Interviewed

Expert Number	Organisation	Role	Years of Relevant Experience
1	ORG_B	Software cost estimator	23
2	ORG_B	Technology Change Forecast	14
3	ORG_B	Engineering Manager	11
4	ORG_F	Software process improvement manager	16
5	ORG_M	Asset Management	21
6	ORG_I	Principal Engineer on Software	20
7	ORG_L (Academic)	IT Director	29
8	ORG_B	Project Manager	25

The information collected through the interviews was systematically analysed and summarised identifying the key ideas. This summary was presented and validated at the final interview with a key expert from industry. By means of gathering information related to software obsolescence from different experts across different organisation and sectors dealing with long-term sustainment systems, it was possible to triangulate responses between them and existing literature. This enabled developing a better and unbiased understanding about all the aspects of software obsolescence. Altogether, despite the fact that the experts have different roles and belong to different organisations, their views were congruous. Their responses were either similar or complementing each other. The main ideas captured are explained in the next section.

4.3 Current Practice

The current practice captured during the interviews, and triangulated with official documents, is presented as follows.

4.3.1 Contracting in the Defence Sector

Major defence programmes frequently have similar characteristics to the civil aerospace and other technology-intensive sectors (DIS, 2005):

- high cost and high risk projects;
- high value, low volume products;
- international collaboration in design and development;
- high barriers to entry;
- issues around safety critically, long-service lives and hence obsolescence.

Defence contracts can be extremely high value and the risks involved must be assessed carefully. Projects may extend over many years and involve a whole range of legal disciplines.

4.3.1.1 CADMID Cycle

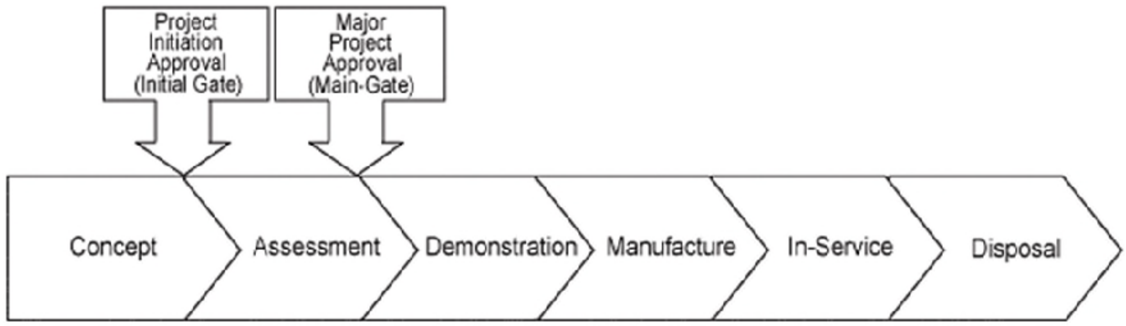


Figure 4-5 CADMID Cycle

The UK Ministry of Defence (MoD) has been using the CADMID cycle to represent the project life cycle since 1999 (Figure 4-5). It was devised as part of the Smart Procurement initiative to deliver equipment capability within agreed performance, cost and time parameters. It is divided into six phases: Concept, Assessment, Demonstration, Manufacture, In-Service and Disposal, with formal approvals at Initial Gate and Main Gate, as shown in Figure 4-5. Each phase is described as follows (MoD, 2006):

1. **Concept:** A statement of the military customer's requirement.
2. **Assessment:** Identification of an acceptable balance of time, cost and performance (including commercial and technical factors); risk defined and quantified to a level consistent with delivering an acceptable level of system performance to tightly controlled time and cost parameters, and selection of the most appropriate procurement strategy.
3. **Demonstration:** Progressive reduction of development risk; performance targets fixed for manufacture.
4. **Manufacture:** Delivery and acceptance of the solution to meet the military requirement.
5. **In-service:** Provision of effective support to the Front Line; delivery of any agreed upgrades.
6. **Disposal:** Efficient, effective and safe disposal of the equipment.

It is important to highlight that a project does not necessarily cover the whole life cycle of a system. Therefore, if the system's life cycle is represented as well by means of the CADMID cycle, there will be nested CADMID cycles as represented in Figure 4-6, where Project 1 represents "procurement management" and Project 1 represents "logistics support".

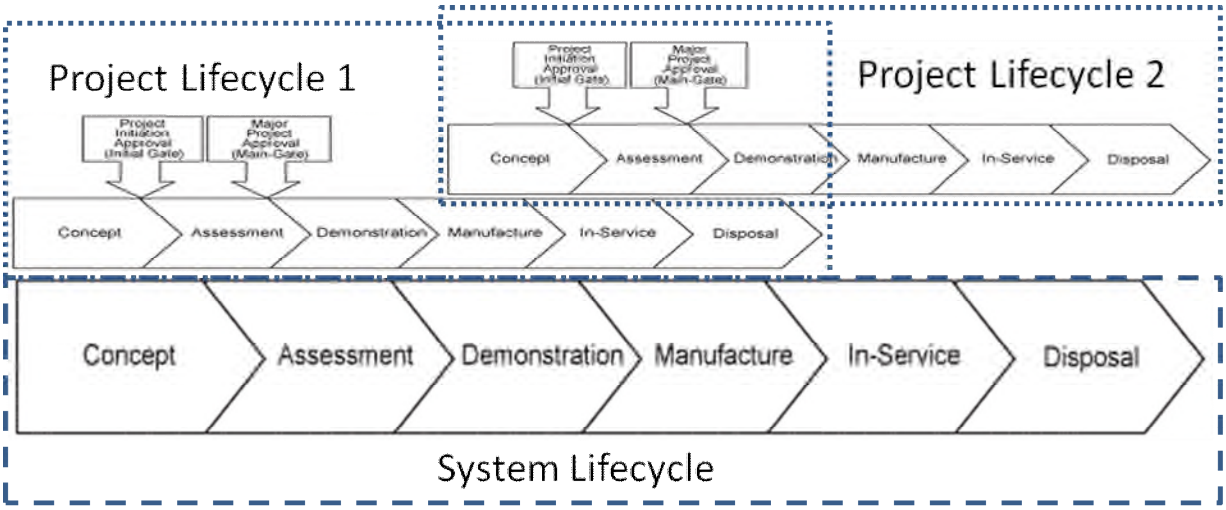


Figure 4-6 Nested CADMID Cycles

4.3.1.2 Whole Life Cycle Cost Estimation

Whole Life Costing (WLC) is defined by the British Standard Institute (BS5760) as “the cumulative cost of a product over its life cycle” (Bradley and Dawson, 1999). Within the context of this research, WLC is defined as “the cumulative cost of a capability or service over its contract duration”. This could include the non-recurring costs of developing the product, the unit production cost of manufacture, the ongoing cost of maintaining the product (e.g. spares and repairs), and the ongoing cost of delivering and operating the service (e.g. staff training, commodities, consumables), as well as the end-of-life treatment cost with an intention of reducing the total cost. The exact composition of a WLC calculation will depend on the nature of the contract. Predicting the whole life cost of availability/capability contracts at the bidding stage is even more challenging due to the growing level of responsibility that is given to the contractor.

In all organisations analysed, a lack of historical data repository has been identified. The implementation of an ERP system is necessary to manage the historical data properly, so the retrieval and analysis of it may allow the improvement of the cost estimation at the bidding stage. All organisations that were interviewed develop bespoke cost breakdown structure or work breakdown structure for every project. This means that, in general, knowledge from previous projects is not fully considered and there is high dependence on individuals’ own knowledge.

Whole life cycle cost estimation is still limited in industry, as projects tend to be contracted for particular phases within the life cycle. The major challenge relates to the fact that there is not enough historical data storage, especially on support costs. Also, with the growth in the scope of services offered, new responsibilities have arisen for contractors. Nevertheless, three out of four organisations recognise the benefits of developing such estimates, especially for the support phase, in which risk experts from a range of organisations highlighted the great difficulty that they were facing to estimate costs. Two out of the four organisations that were interviewed also mentioned that the strategy of disposal needs to become clearer early on at the design, due to developments in legislation.

Three out of four organisations highlighted that there was lack of common terminology across departments. For instance, terms such as risk and uncertainty are commonly interpreted differently.

Two out of four organisations defined a challenge derived from employees changing the template that has been delivered to them. The template refers to the standard cost estimating guidelines that are specified at a corporate level. This causes unsystematic applications and makes it harder to retrieve data.

In one out of the four organisations that were interviewed, lack of coordination among departments was mentioned to be the cause of holes or double counting. This reflects the influence of organisational structure and governance on cost estimating.

Inputs

The inputs needed to enhance accuracy in whole life cost estimation include:

- **Work/Cost Breakdown Structure (WBS/CBS)**

A well designed Work/Cost Breakdown Structure (WBS/CBS) should contain data relating to the various activities involved in the contract; for example, a support contract would involve activities relating to operations, maintenance, and support. Other examples of costs that are incurred through these activities include:

a) Management costs
b) Support costs
c) Repairs costs
d) Manufacturing costs
e) Training costs

f) Cost of Raw materials
g) Labour costs
h) Bidding costs
i) Acquisition costs
j) Design costs
k) Post design costs
l) Procurement costs
m) Obsolescence costs
n) Disposal Costs

These costs are classified into different activities and tasks. Furthermore, each class carries different weights of cost; for instance, it is commonly regarded that design costs are usually higher than other costs (e.g. 60% of development cost). Furthermore, each company has its own generic WBS/CBS which could be adapted to specific contracts or projects.

- **Assumptions List (MDAL)**

A document called the Master Data Assumptions List (MDAL) contains the details of assumptions made concerning a contract. This document, which is the main supporting document for the cost model, describes the origin of each input and the adjustments made to them. It is usually updated as the contract progresses and amendments are made with the agreement of both the customer and contractor. The customer could be allowed visibility of the assumptions made in the vendor’s costing if an open book policy is agreed between both parties. At other times, the contractor’s overhead rates could be agreed with the customer without allowing the customer full disclosure of cost estimates.

- **Customer requirements**

The customer requirements are contained in a document called the User Requirement Document (URD). These requirements go through a process in which they are transformed into a system requirement by the supplier. This system requirement is contained in a document called the System Requirement Document (SRD), which is a solution offered by the designer to the customer.

While the URD takes the customer/user perspective, all stakeholders on the customer side and the manufacturer side work together to develop both the URD and the SRD.

- **Customer Budget**

All projects are part of a program for which a budget is set by the customer. The budget affects customer affordability because the cost of a manufacturer's solution is usually weighted against the customer budget to decide whether or not to invest in the solution. The delivery of customer requirement in fixed-price projects could be affected by changes in the cost of resources e.g. labour rates, fuel price, cost of raw materials as well as factors affecting the supply chain. Therefore, fixed-price contracts could also exceed budgets, so any change in contracts will require re-negotiation between the supplier and customer.

- **Historical data and Expert judgment**

The accuracy of cost estimates could be improved with the availability of historic data from previous projects as this can be reviewed in order to forecast future costs. On some projects the customer holds historical data; therefore, it would be beneficial to share this data with the contractor to improve the reliability of the cost estimation. Additionally, it is important to ensure that historical data is stored in a way that can be easily retrieved and in a form that other employees can understand without the need to consult employees previously involved in projects. Furthermore, the availability of historic data helps the customer to set a more realistic budget because there is transparency of cost data. While expert judgment is useful in cost estimation, a higher degree of accuracy can be achieved when this judgment is informed by the provision of historic data.

4.3.1.3 Generic Bidding Process for Defence Contracts

The bidding process contains a number of phases before an agreement is reached (Figure 4-7).

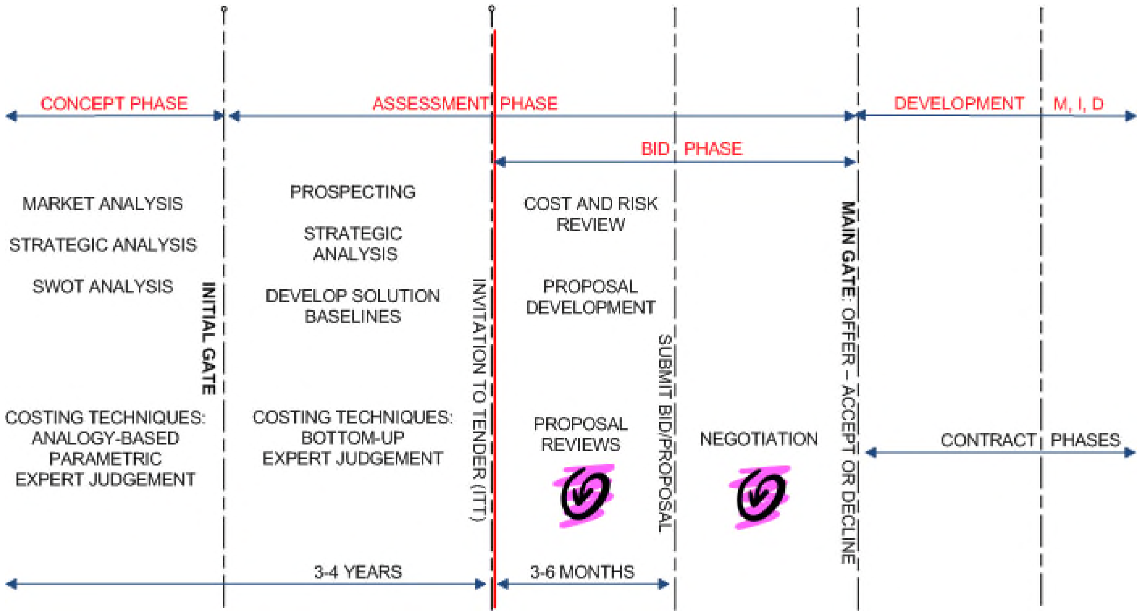


Figure 4-7 Bidding Process

The conceptual foundations of a bid may begin several years prior to an offer. During this process the nature of reviews, based on profitability and sustainability, advances as new information becomes available. Reviews take place to examine the potential of projects in terms of risk, uncertainty, cost, price, winning probability, and the detail of the proposal. Though, the length of reviews is constrained within allocated budgets, the rising costs of contract acceptance is covered from the overheads budget. Also, no commitments are formulated until a contract is agreed with the customer. At the concept stage, estimates are a rough order of magnitude (ROM), with a wide margin of error. These are usually reached based on information from previous projects (analogy-based) or parametric tools, either commercial or developed in-house, and expert judgement.

After the Invitation to Tender (ITT) is formally released by the customer, the submission of the bid/proposal yields a negotiation phase which results in an offer accepted or declined. In negotiation, the customer requires explanations to price, while the degree varies depending on the type of bid. At this point, progression to the contract enhances the detail of design. The level of design maturity is governed by customers' satisfaction. During the bidding process, the estimating techniques used may vary depending on available information, which tends to evolve from a parametric approach towards detailed estimating (bottom-up).

4.3.2 Obsolescence Management for EEE Components

The obsolescence management process can be divided into 3 main stages (Figure 4-8): the obsolescence risk assessment, the mitigation strategy selection and the resolution approaches implemented to resolve the obsolescence issues. Each stage is explained as follows.

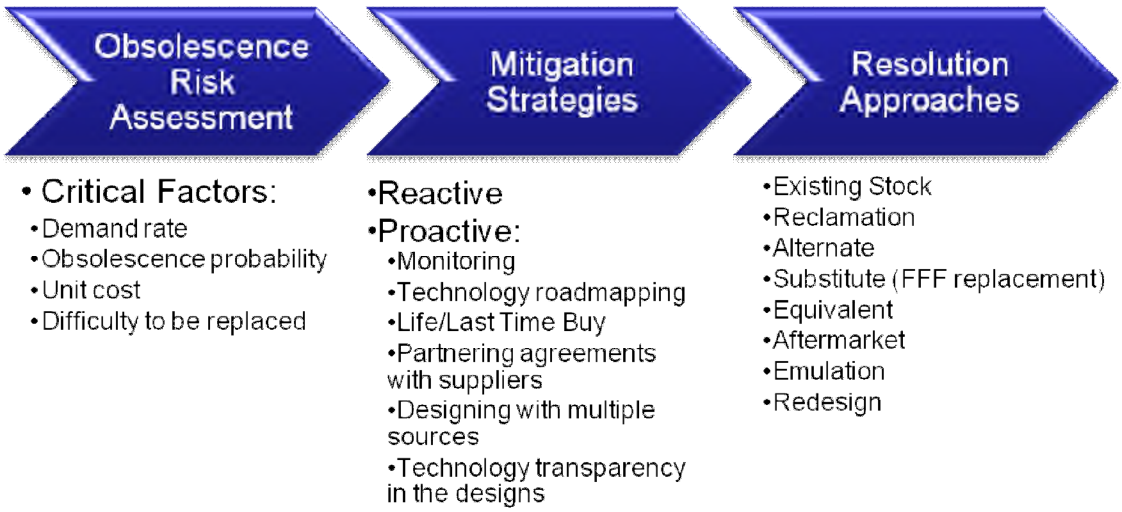


Figure 4-8 Obsolescence Management Process

Obsolescence Risk Assessment

Generally, the critical factors considered for each component in the obsolescence pricing process are:

- **Demand rate**. It mainly depends on the utilisation rate, reliability and quantity fitted.
- **Obsolescence probability**. It is based on organisational experience (e.g. the obsolescence probability for resistors is lower that for graphics chips due to the changes in technology).
- **Unit Cost**.

- **Difficulty to be replaced**. The more difficult it is to find a replacement or a solution to the obsolescence issue, the higher will be the impact of shortage.

All the organisations interviewed make an initial risk assessment about the impact of obsolescence of any component or Line Replaceable Unit (LRU) used in the system, based on the obsolescence probability and the impact of shortage. In these organisations, the risk associated with the obsolescence of software, test equipment, tools, techniques (e.g. particular manufacturing processes) and skills is not considered, or roughly quantified based on expert judgement. The risk assessment for components and LRUs is generally based on experience and expert opinion. One of the organisations has developed formulae for this purpose, based on their experience. Based on the results of this assessment, it is decided which components (the critical ones) will be monitored in order to proactively tackle any possible obsolescence issue and which components (non-critical ones) can be managed in a reactive way. The basis of this process is to determine which components are worthwhile to be managed proactively.

Mitigation Strategies

Usually the project manager defines the mitigation strategy to deal with obsolescence. The mitigation strategy depends on the risk of obsolescence. It is usually one or a combination of some of the following ones:

- Deliberately deal with obsolescence issues in a reactive way.
- Monitoring.
- Technology roadmapping.
- Risk Mitigation Buy - The procurement of items sufficient to support the product throughout its life cycle, or until the next planned technology upgrade.
- Partnering agreements with suppliers.
- Designing with multiple sources (avoiding critical components).
- Technology transparency in the designs.

Most of the organisations are using an Obsolescence Management Plan (OMP) that defines the policy to deal with obsolescence for each project. The OMP is developed by the department/expert in obsolescence management in each organisation. The OMP gives guidelines to the project managers to manage obsolescence in the same manner as the rest of the organisation. The OMP typically calls for a two-stage response: first, to identify obsolescence risks where economically viable; second, to mitigate the impact of residual risks should they arise. The typical contents of the OMP are:

- Description of the obsolescence management process
- Description of the standard process to resolve obsolescence issues
- List of possible obsolescence resolution approaches
- Description of the contract requirements for obsolescence management

In order to decide the most appropriate mitigation strategy, it is necessary to assess the cost avoidance by comparing the estimate of the resolution costs with the managing cost. This is a major gap in all the organisations interviewed. A revalidation of the obsolescence cost metrics study done in 2004 is required for this purpose, according to the MoD obsolescence policy manager.

Three out of four organisations interviewed are carrying out monitoring by means of commercial tools such as Q-Star or IHS. For those components that are not included in those databases, it is necessary to perform a manual monitoring. One of the participating organisations has developed an in-house tool that facilitates this manual monitoring process. It is widely accepted that technology roadmapping and the management of the supply chain are the key factors in predicting and monitoring obsolescence issues.

Obsolescence prediction is mainly based on expert opinion, engineers experience and the algorithms that commercial monitoring tools incorporate. Two organisations highlighted that they have no methods to forecast system level obsolescence. Therefore, it is very difficult for them to estimate the cost related to obsolescence at the early stages of a project. None of the industrial collaborators is using standards for the cost estimation related to obsolescence at the bidding stage. This estimate is in general very rough and is frequently a percentage of the acquisition cost of the LRUs. In fact, one of the experts interviewed claims that "it is impractical to perform obsolescence analysis until there is a BoM available. Prior to that, expert judgement and analogy-based methods might be used for high level analysis only".

Resolution Approaches

There are many different resolution approaches and their impact on costs varies substantively from one to another. A description of the different resolution approaches is included in Chapter 2. The resolution approach for each obsolescence issue is decided by the project manager, but it has to be agreed with the customer.

Depending on the contract, the allocation of responsibilities between the customer and the supplier varies.

4.3.3 Contractual Agreements for Obsolescence Management

As explained in previous chapter, the continuous evolution of contracting in the defence procurement in the UK, which has been motivated by the MoD's aim to deliver military capability at optimised cost of ownership, is bringing with it new challenges for ensuring both the affordability of military operations and the profitability of suppliers. Acquisition strategies now include a range of initiatives including spares inclusive, availability based contracting and ultimately, contracting for capability (Figure 4-9). These system-support contracting strategies can range from the provision of traditional fourth line repair and overhaul to usage based service level agreements. This range gives evidence of the recent expansion in the strategic degrees of freedom available to organisations operating in the defence sector. However this business evolution brings with it the potential of increased operational risks for military customers, and issues arising from the commitment to future expenditure over long period of time.

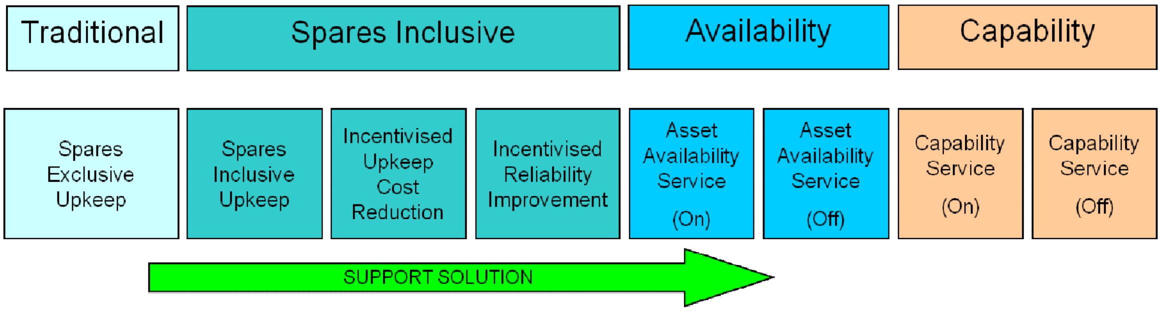


Figure 4-9 Evolution in Defence Contracting

There is an increasing trend towards contracting for availability. The essence of availability contracts is that the suppliers are paid for achieving an availability target for the system (typically expressed as a percentage, e.g. "available 99.95% of the time") and not just for the delivery of the product and spares/repairs. This helps to ensure value for money for the customer. However, this transition implies the transfer of risks, such as obsolescence, from the customer to the contractor. It is critical to agree in the contract the allocation of responsibilities for managing obsolescence, resolving obsolescence issues and defraying the cost of them. The resolution strategy for each obsolescence issue is decided by the contractor's project manager. The strategy may also have to be agreed with the customer but this depends on the contract; the allocation of responsibilities between the supplier and the customer varies. The most common strategies are described as follows:

1. The customer is responsible for the cost of resolving any obsolescence issue, whereas the contractor is in charge of monitoring, identifying obsolescence issues, reporting them to the customer and making recommendation to resolve them. This has been the traditional way of contracting in the military sector. Customers would like to move away from this contracting style because, from their point of view, the supplier is not encouraged to find the most cost-effective resolution strategy.
2. The supplier is responsible for the management and cost of resolving any obsolescence issue. Some availability contracts are implementing

this strategy in order to agree a fix price. In principle the solution will be cheaper than option (1) because the supplier is better placed to manage the issues. However, the risk has transferred from customer to supplier and the supplier price will be driven up to cover the risk budget.

3. Contractor pays for any form fit and function (FFF) replacement while the customer pays for any other obsolescence resolution.
4. Financial threshold. A cost limit is set and the contractor will cover the costs related to resolving obsolescence issues up to that limit. From that point onwards, the customer will be in charge of covering the costs.
5. Target cost incentive fee. A target cost is set and if the final cost is lower than it, the contractor will receive a percentage of the cost avoided. This encourages the contractor to manage obsolescence in the most cost effective way.
6. The supplier is responsible for the management and resolution of any obsolescence issue and the cost related to it is shared between the supplier and the customer. All resolution costs are split by a percentage factor between the customer and the contractor (e.g. 70/30, 50/50, 60/40). This is regarded as the best solution as it provides incentives to the supplier to search for the most cost-effective resolution strategy. It aligns the interests of both parties. The resolution strategies are defined by the supplier and approved by the customer.

4.3.4 Obsolescence Cost Estimation in Industry

A general lack of standard procedures has been identified for the cost estimation of obsolescence across all the industrial collaborators. In two of the organisations interviewed, the obsolescence cost estimation at the bidding stage is regarded as a percentage of the cost of development of the equipment. The other two organisations base the obsolescence cost estimating at the bidding stage on experience and expert judgement. These rough estimates are in general inadequate to set the basis for the negotiation of the contract.

Discussion with obsolescence managers from different companies, at the COG quarterly meetings, showed that some companies have developed in-house obsolescence cost estimating tools. However, they are not publicly available.

4.4 Understanding Obsolescence in Software

The general perception from industry is that software obsolescence is becoming an important problem mainly because it is ignored in general. Both in US and in UK, the software obsolescence is neither been consistently managed nor mitigated proactively (Merola, 2006).

4.4.1 Software Obsolescence: An Overview

IEC 62402 (2007) defines software as “programs, procedures, rules, data, and documentation associated with programmable aspects of systems hardware and infrastructure”. Some people argue that software cannot become obsolete because it is not affected by degradation (and hence does not require replacement) and can be easily replicated. Their misconception is to try to apply the same reasoning to software obsolescence as to mechanical or EEE components obsolescence. It is necessary to acknowledge the different nature of the software obsolescence problem. The essence of obsolescence is that it prevents from maintaining and supporting the system. Taking this into account it is possible to identify the commonalities between hardware and software obsolescence. When an EEE or mechanical component becomes obsolete and there is no more stock available, the system cannot be maintained according to the original planning. Analogously, the software obsolescence prevents the software from being maintained accordingly.

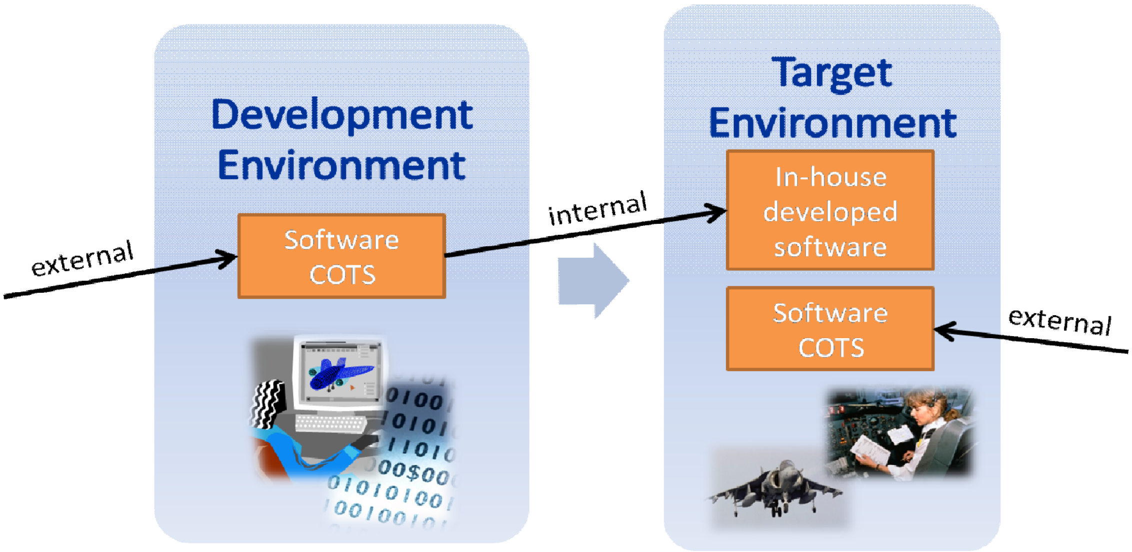


Figure 4-10 Software Environments

In the area of computer science, the software development environment (SDE) is the “entire environment (applications, servers, network) that provides comprehensive facilities to computer programmers for software development” (Wikipedia, 2009) and also for software testing. The software target environment (STE) represents the final system in which the software developed in the SDE will be ultimately run. Software obsolescence can happen in both, the development environment and the target environment, as shown in Figure 4-10, due to external factors (e.g. loss of support from COTS supplier) or internal factors (e.g. loss of skills). From the business model point of view, it is important to make this distinction between environments. The reason is that an organisation may be in charge of supporting different systems. Therefore the organisation will have to manage obsolescence independently for each STE, at the project level, according to the terms agreed in each support contract. However, the obsolescence issues that happen in the SDE have to be managed at the organisation level, and they can have an impact on the supportability of the STE as shown in Figure 4-10, so this strategy to manage obsolescence needs to be aligned with the support contracts.

4.4.2 Types of Software Obsolescence

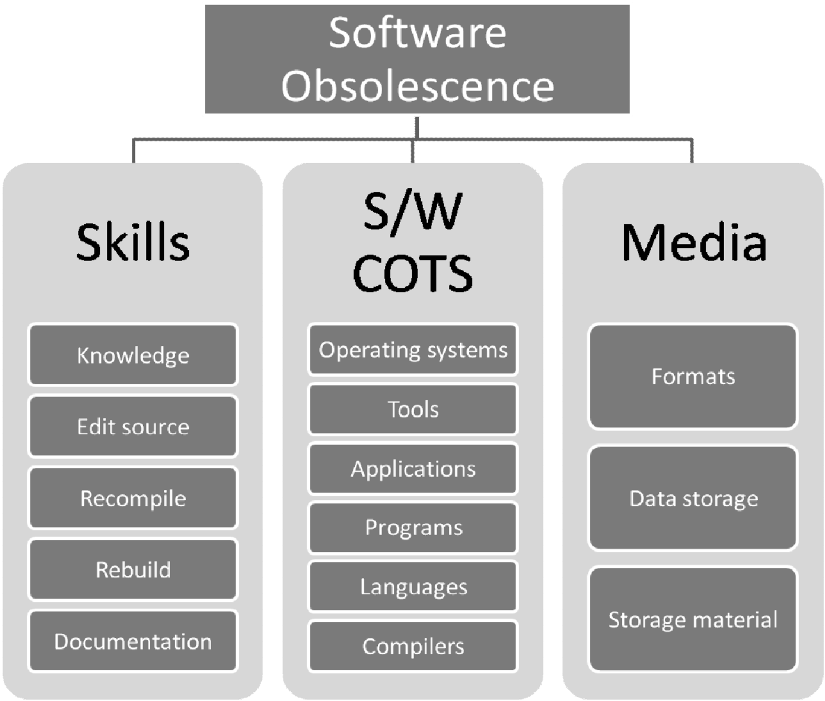


Figure 4-11 Types of Software Obsolescence

Software obsolescence can happen in three different areas as shown in Figure 4-11: skills, COTS software and media.

- **Skills**

It refers to the skills and information necessary to develop, support or modify software developed in-house or by a third party. The loss of required skills is regarded as skills obsolescence and inhibits the maintenance of the software. A common example of this is the difficulty to maintain legacy software (written using legacy programming languages) because the original programmers get retired and the new generations are only trained in new programming languages.

Skills obsolescence hinders the usage of the SDE to support in-house developed software hosted in the target environment.

- **COTS Software**

Commercial off-the-shelf (COTS) Software is regarded as any commercial operating system, program, application, tool, compiler or programming language that is used in the development environment to produce in-house software or that is used directly in the target environment. COTS Software becomes obsolete when its supplier stops supporting it. This is the most common and risky software obsolescence problem because it is difficult to predict when it is going to happen and is usually beyond the control of the customer.

COTS Software can be found in the SDE in the form of tools for software development and in the STE in the form of software components or tools used for configuration at the end-user level.

- **Media**

It represents the data storage materials and formats used to keep the software information. If they are not properly managed and maintained, there is a risk of losing data and information because they can no longer be accessed from legacy media or legacy formats. Moreover, some forms of media have proved to be less stable and robust than expected.

4.4.3 Key Challenges to Manage Software Obsolescence

The technology has been evolving rapidly over the last few decades. This has become a major issue for the support of sustainment-dominated systems in the defence and aerospace sector. Moreover, the fact that most of the EEE and software components suppliers have moved from the defence sector to a more profitable commercial market with higher volumes has exacerbated this problem (Shuman, 2002). In the present market, the use of COTS software is widely extended across the defence sector although they have little control over this supply chain (Sandborn, 2007b). This fact increases the risk of facing obsolescence problems because the defence interest of maintaining long-life systems over several decades clashes with the interest of COTS software providers, which is to reduce the life-cycle of their products, making the COTS software obsolete as a market strategy (Sandborn, 2007b; Merola, 2006).

The main problem related to software obsolescence is that it is generally ignored within the defence and aerospace sector and usually it is not included in the Obsolescence Management Plan (OMP) or just briefly mentioned without providing a detailed strategy to manage it. The current efforts in dealing with obsolescence are mainly focused on EEE components while software obsolescence is disregarded and not managed at all (Merola, 2006). Apart from the lack of awareness, there is a lack of tools to assist in the software obsolescence management such as obsolescence monitoring tools (analogous to those used for EEE components such as those supplied by QinetiQ and IHS) which makes difficult the forecast of software obsolescence issues.

It is important to raise awareness of the software obsolescence problem as in most complex systems the cost of dealing with it during the life cycle is comparable to the cost of dealing with hardware obsolescence problems, or even higher (Sandborn, 2007b; Merola, 2006).

The move towards availability contracts in the defence sector is triggering a shift in obsolescence risk, which will eventually make the prime contractors more responsible to manage software obsolescence to guarantee the availability of the system at an affordable price.

4.4.4 Mitigation Strategies

By means of interviews with experts in software and obsolescence across different sectors, where they have to support complex systems for long periods, it has been identified a set of mitigation strategies to reduce the risk of software obsolescence in both the probability and the impact of having an obsolescence issue. The main mitigation strategies for software obsolescence are as follows.

- Loose coupling (Decoupling). The dependencies between hardware and software can be reduced by using standard interfaces and a middleware in the system architecture design. This means that an obsolescence issue in a component will be less likely to impact the rest of the system, and hence can be easily replaced. This mitigation strategy is especially useful to reduce the interactions between obsolescence issues in EEE components and software.

- Make the development environment flexible enough to support changes in the target environment. This is particularly important for the support of sustainment-dominated systems, as it contributes to its adaptability during the life cycle (Roy and Cheruvu, 2009).

- Use of Technology Roadmaps that take into account:
  - Evolution of technology
    - Maturity of technology used
    - Technology stability assessment (identify potential changes in the future)
  - Evolution of suppliers (market)
  - Evolution of customer requirements

- Proactive analysis. To carry out a risk assessment for software obsolescence based on:
  - Impact of the obsolescence issue
  - Probability of becoming obsolete

There are other mitigation strategies that can be applied specifically for each software obsolescence type.

Mitigation Strategies for COTS Software Obsolescence

- Escrow agreements. It is a legal arrangement in which the software source code and the software development environment are placed by the supplier with a third party to be held in trust pending some event, upon which the software will be delivered to the user (Rumney, 2007). This mitigates the obsolescence issue that may happen if the software supplier goes out of business.

- Develop contract clauses to ensure lifetime support (or at least until the next midlife upgrade).
- Keep good relationships with key vendors.

Mitigation Strategies for In-house Developed Software Obsolescence

- Maintain the supporting infrastructure (Rumney, 2007).
- Collaboration across different departments to minimise problems of integration/interactions.
- Consider the use of COTS software instead.
- Ensure skills do not become obsolete (apply mitigation strategies for skills obsolescence listed as follows).

Mitigation Strategies for Skills Obsolescence

- Standardisation (Use of “Preferred Technology”) (Rumney, 2007). Minimise the number of programming languages/compilers/software components used across the organisation.
- Maintain people with skills and knowledge required (even after retiring) (Rumney, 2007). So they can continue supporting the system as consultants or they can transfer their skills and knowledge by training other people.
- Use a “skill register” database to monitor experts and their skills.
- Develop training schemes to preserve skills and knowledge required, proactively identifying potential skills shortages.
- Implement knowledge management systems within the organisation.
- Make sure that the human resources department is aware of potential skills shortages, so new experts can be hired promptly.

- Consider outsourcing the maintenance or development of software. This may be a more cost effective solution than trying to keep the skills in-house for the maintenance or development of software. However, this decision may increase the uncertainty of having an obsolescence issue due to the loss of control over the supplier.

Mitigation Strategies for Media Obsolescence

- Keep structured documentation, formats and data storage systematically, and up to date.
- Plan the upgrades of media, formats and data storage.
- Outsource the media management.

4.4.5 Cost Estimation of Software Obsolescence

The risk of obsolescence in EEE components is progressively being included in availability-type support contracts. Eventually, the risk of software obsolescence will need to be included explicitly as well. The challenge is to be able to assess this risk at the bidding stage and to estimate the cost related to it for the duration of the contract. At the moment, no organisation is able to make robust cost estimations for software obsolescence.

It is acknowledged that the development of a validated cost model would facilitate the negotiation process for contracting; giving a common understanding to both parties about the risks and cost implications that software obsolescence will have on the system during its life-cycle. It would also increase the level of confidence on the software obsolescence planning through an analysis of Return on Investment (ROI) (Merola, 2006). It is important that this cost model is developed at system level, so both the software and hardware obsolescence are concurrently considered, since they are so closely linked (Merola, 2006). However, there are several reasons that make the development of the cost model very challenging at this stage:

- The data related to software obsolescence problems is frequently spread over different areas such as hardware obsolescence, software defect maintenance, or program schedule slips and additional resource requirements (Merola, 2006). In most of the organisations there is not a common understanding about the concept of software obsolescence and what falls in and out its scope.

- In general, there is no map of interactions across the system between hardware and software, except for high reliability applications. Typically this is due to inadequate design documentation and configuration management. The lack of this information makes very difficult the prediction of the impact that an obsolescence issue in a component will have on the rest of the system, as this will depend upon the level of interactions and dependencies.

- The organisations are not keeping systematically record of the costs associated with obsolescence events. Historical data is essential to develop cost metric that can be applied to estimate the cost of software obsolescence and include this risk in the contract. It also allows measuring the overall consequences of using different software obsolescence management strategies (Merola, 2006).

- The strategies deployed to manage software obsolescence are usually very limited or not included at all in the OMP. Nevertheless, the software obsolescence management strategy will have a critical impact on the cost.

- Unlike the EEE obsolescence area, there are no monitoring tools available in the market that can assist with the monitoring and forecasting of software obsolescence. It makes it more difficult to develop a management planning and to estimate the number and nature of the obsolescence issues expected during the contracted period.

The challenges exposed above show the lack of maturity of this subject, which makes unfeasible at this point the development of a framework for the cost estimation of software obsolescence at the bidding stage for support contracts.

Along these lines, the current interest of the sponsoring organisations was solely focused on the cost estimation of hardware obsolescence, though they acknowledge that software obsolescence will require more attention in the future.

4.5 Summary and Key Observations

This Chapter has presented the current practice in the UK defence sector for contracting (bidding process) and whole life cycle cost estimation at the bidding stage (Phase 1) and the current practice in obsolescence management for EEE components and obsolescence cost estimation (Phase 2). It has also developed an understanding about software obsolescence and how it can be managed (Phase 3). Nowadays, industrial organisations are focusing their efforts on dealing with EEE components obsolescence, while disregarding software obsolescence. This lack of awareness and its consequent lack of supporting tools (i.e. obsolescence monitoring tools) for the prediction of obsolescence issues are the main challenges to manage software obsolescence.

In Section 4.2, the research methodology followed to capture the information required in each of the three phases was presented. Phase 1 was carried out in collaboration with two other PhD researchers to gain an overall understanding on contracting in the defence environment and the bidding stage, whereas Phases 2 and 3 were carried out individually focusing on obsolescence in more depth than during the first phase.

Section 4.3 described the outcomes of Phases 1 and 2, and is structured as follows. In Section 4.3.1, the current practice in cost estimation at the bidding stage for defence contracts has been presented; explaining the CADMID cycle, the bidding process and the inputs required for the whole life cycle cost estimation. In Section 4.3.2, the current practice in obsolescence management for EEE components was explained, including activities for obsolescence risk assessment, mitigation strategies and resolution approaches. The different contractual agreements for obsolescence management are described in Section

4.3.3, and finally, the current practice in industry for the cost estimation of obsolescence is presented in Section 4.3.4.

Section 4.4 described the outcomes of Phase 3, and is structured as follows. Section 4.4.1 provided an overview about the meaning of software obsolescence, explaining how software obsolescence issues can arise in both the software development environment (SDE) and the software target environment (STE). In Section 4.4.2, software obsolescence is classified into three types: skills, COTS software and media. In Section 4.4.3, a set of general software obsolescence mitigation strategies have been suggested, such as: decoupling, make the development environment more flexible, use of technology roadmaps that take into account the evolution of technology, the suppliers and the customer requirements, and risk assessment for software obsolescence. Additionally, a set of mitigation strategies have been suggested to deal with obsolescence in each of the following areas: COTS software, in-house developed software, skills, and media. Section 4.4.3 described the key challenges that the author has identified to manage software obsolescence and to estimate its cost. It has been identified that currently there are no models for the cost estimation of software obsolescence. The main reasons that make this development very challenging are mainly related to the lack of understanding of the problem, the lack of historical information about software obsolescence issues, the lack of software obsolescence management tools and the lack of information about the interactions between hardware and software. Future research on this area should be focused on the development of a model for the cost estimation of software obsolescence, tools for the monitoring, managing and predicting software obsolescence issues. Additionally, it is required to explore the correlation between hardware and software obsolescence due to the high level of interdependencies between them.

After developing an understanding about software and hardware obsolescence, the current lack of maturity in the software obsolescence area and the lack of interest from the sponsoring organisations on this topic have induced the author to focus his research on the development of cost estimating frameworks for hardware obsolescence.

The next Chapter presents the development of the “Electronic, Electrical and Electromechanical - Framework for Obsolescence Robust Cost Estimation” (EEE-FORCE) that can be used at the bidding stage of a support contract to estimate the NRE costs incurred during the contracted period in resolving EEE components obsolescence issues.

Chapter 5

5 COST PREDICTION FOR EEE COMPONENTS OBSOLESCENCE RESOLUTION

5.1 Introduction

The review of the literature, presented in Chapter 2, has brought to light a lack of understanding about the NRE cost involved in resolving obsolescence issues for EEE components during support contracts. Additionally, the capture of the current practice in the UK defence sector for contracting, explained in Chapter 4, has revealed that the responsibilities for managing and solving obsolescence issues are shifting from the customer to the prime contractor and industry work share partners. This new scenario has triggered the need to estimate the cost of obsolescence at the bidding stage, so it can be included in the support contract. In this Chapter, the author presents the development of the "Electronic, Electrical and Electromechanical - Framework for Obsolescence Robust Cost Estimation" (EEE-FORCE) that can be used at the bidding stage of a support contract to estimate the obsolescence NRE costs incurred during the contracted period.

One of the main challenges of estimating the obsolescence cost is that, in most cases, the resolution approach to tackle a particular obsolescence issue cannot be specified in advance. Therefore, the "obsolescence resolution profiles"

(ORP) study has been carried out to determine the probability of using each resolution approach to tackle an obsolescence issue, based on the experience of more than 40 industrial experts in obsolescence. Also, a key element in the estimation process is a good understanding of obsolescence cost drivers and the cost metrics. As it was explained in Chapters 2 and 4, the existing obsolescence cost metrics require to be revalidated. In order to address this issue, the “obsolescence cost metrics” (OCM) study was undertaken.

In this Chapter, the research methodology followed in the development of this framework, together with the specific methodology followed in the ORP and OCM studies are detailed. Subsequently, the results of the studies and a description of the structure, methodology and rationale that the EEE-FORCE follows are presented. Finally, the iterative process followed to develop the framework is described.

5.2 Detailed Research Methodology

The research methodology followed for the development of the EEE-FORCE framework is shown in Figure 5-1. The first step was to identify the requirements for the framework, followed by a preliminary study that provided the basis for undertaking the ORP and OCM studies. Based on them, the EEE-FORCE framework was developed following an iterative process in which the experts from industry reviewed it and suggested enhancements that were implemented accordingly.

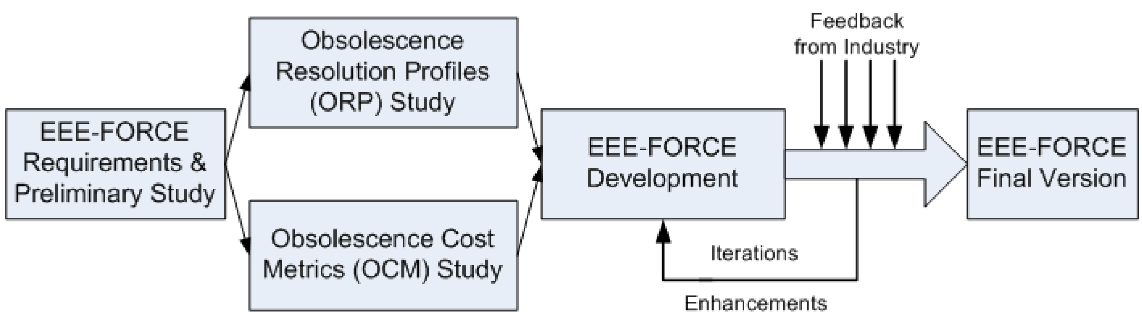


Figure 5-1 Research Methodology for EEE-FORCE Development

5.2.1 Detailed Research Methodology for Capture of EEE-FORCE Requirements

The initial requirements for the EEE-FORCE framework were captured during the interviews and workshops with obsolescence experts from different companies, as described in Chapter 4. Based on those requirements, a draft version of the framework was developed and presented in a workshop with seven practitioners from four organisations from the defence and aerospace sectors. Four of which are experts on obsolescence, as shown in Table 5-1. The purpose of this workshop was to refine the initial requirements, identify other requirements and validate the rationale proposed for the framework. The workshop duration was five hours, during which the draft version of the framework was presented, and, after discussion among the experts, they filled in a questionnaire to assess it and propose further enhancements (shown in Appendix A.5). An example of the questions contained in that questionnaire is provided as follows.

- Would an obsolescence costing framework be beneficial for the defence and aerospace industries at the bidding stage?
- Assess the relevance of the presented framework to your business.
- Assess the benefits of the presented framework to industry.
- Indicate improvements required and prioritise them.
- Assess the validity of the following assumptions made in this framework.

The responses were analysed by identifying similarities, differences and unique responses across the different participants. The outcomes from this analysis are summarised further along in this Chapter.

Table 5-1 Experts Involved in EEE-FORCE Framework Workshop

Expert Number	Organisation	Role	Years of Relevant Experience	Obsolescence Expert
1	ORG_A	Project Manager	25	YES
2	ORG_B	Systems Engineering and Obsolescence Support	25	YES
3	ORG_B	Engineering Manager Across CADMID	31	YES
4	ORG_A	Director Through Life Support	25	YES
5	ORG_C	Programme Manager	15	NO
6	ORG_A	Pricing and Forecasting	20	NO
7	ORG_E	LCC Analyst	3	NO

5.2.2 Detailed Research Methodology for Preliminary Study

Prior to starting the "Obsolescence Resolution Profiles Study", it was necessary to conduct a preliminary study to establish the basic concepts in the area of obsolescence management (see Figure 5-2).

The first step was to clarify the differences between the terms "mitigation" and "resolution". This took place in collaboration with five experts from different organisations with a range of 5 to 12 years work experience in the field. It was identified that there was a lack of consistency across industry with the usage of these terms, with some individuals using them interchangeably. Therefore, it was necessary to define each one appropriately to provide a common understanding. Also, the possible resolution approaches that can be applied to tackle an obsolescence issue for an EEE component were identified and defined. This was based on literature, the Ministry of Defence Obsolescence Cost Metrics Study 2004 (MoD, 2004) and discussions with the five experts on obsolescence from industry.

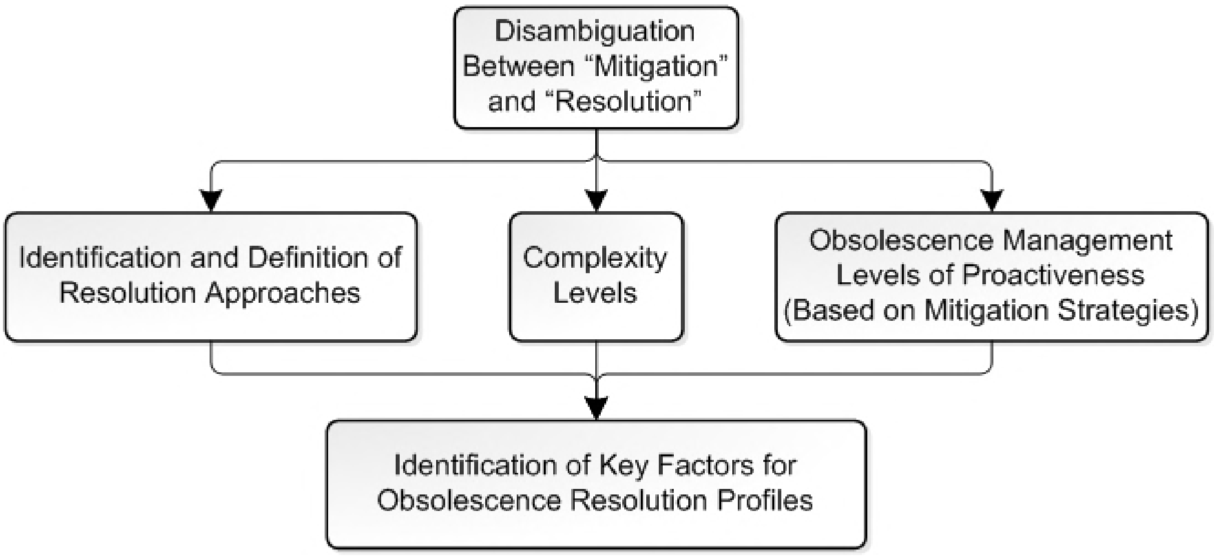


Figure 5-2 Preliminary Study Methodology

The second step was the development of a classification of EEE components according to their level of "complexity". The concept of "complexity" can be regarded as tacit knowledge that obsolescence experts develop as they deal with obsolescence issues. In order to define explicitly this concept, the Critical Incident Technique (Flanagan, 1954) was followed during a 4-hour workshop with one obsolescence expert (7 years industry experience in the field). This methodology allowed capturing the logic and key parameters that define the complexity of an electronic component by comparing features of different components (Hollnagel, 2003). The outcomes of this session were refined and validated in collaboration with another obsolescence expert (10 years industry experience in the field). Subsequently, the concept has been presented at several Component Obsolescence Group (COG) quarterly meetings and conferences, where it was approved by the attendees (more than 70 obsolescence experts).

The next step was the classification of the obsolescence management strategies according to the level of proactiveness deployed. This classification was based on the information gathered through several semi-structured interviews with more than ten obsolescence experts from several defence organisations (a total of 53 hours) and an exhaustive literature review. In the same manner as the complexity concept, this classification was presented at several COG quarterly meetings and conferences, where it was approved by the attendees (more than 70 obsolescence experts).

By means of the interactions with industry described hitherto, it was identified that the probability of using a resolution approach to tackle an obsolescence issue for an EEE component depends mainly on these two parameters: the level of complexity of the obsolete component and the level of proactiveness deployed to manage obsolescence. This novel finding provided the basis for the development of the Obsolescence Resolution Profiles (ORPs).

5.2.3 Detailed Research Methodology for ORP Study

The Obsolescence Resolution Profiles Study is composed of three major phases, which are drafted in Figure 5-3 and explained as follows.

5.2.3.1 Phase 1: Delphi Method

The results of the Preliminary Study and the membership of the Component Obsolescence Group (COG) set the appropriate circumstances for deploying the Delphi method to estimate the probability of using each resolution approach to tackle an obsolescence issue, taking into account the complexity level of the electronic component and the obsolescence management level. The Delphi method is “an iterative process to collect and distil the anonymous judgments of experts using a series of data collection and analysis techniques interspersed with feedback” (Skulmoski et al., 2007). This research tool is particularly well suited to new research areas and exploratory studies such as the development of Obsolescence Resolution Profiles (Okoli and Pawlowski, 2004; Linstone and

Turoff, 1975). The key reason for using the Delphi method is the lack of appropriate historical data about the resolution approaches used to resolve obsolescence issues, and thus expert judgment is required (Rowe and Wright, 1999).

Firstly, a questionnaire was developed to be used in the first round with the COG panel (see Appendix A.6). Prior to this, it was piloted with an obsolescence expert (7 years experience) to make sure it was clear, unambiguous and precise. In the questionnaire, the participant is initially requested to input the years of experience on obsolescence and the obsolescence management level that best represents the current practice of the company or project that they are involved in. Subsequently, the participant can assess the likelihood of having resolved an obsolescence issue following each of the given approaches for each complexity level of the component. Keeney and von Winterfeldt (1988) support the use of probabilities to quantify expert judgements in examining complex technical and engineering problems. In the light of this, the score provided by each participant is based on an 11-point Likert Scale ranging from zero (never used) to 10 (certainly used), which provides the right level of granularity for this study; and during the analysis phase, these results are turned into percentages. A total of 38 experts in obsolescence participated in the first round and the responses were subsequently analysed. During this analysis, the mean and standard deviation of the responses were calculated, and a 95% confidence was considered in order to remove the outliers (the 5% of the responses, which were beyond the limits of this interval, were ignored).

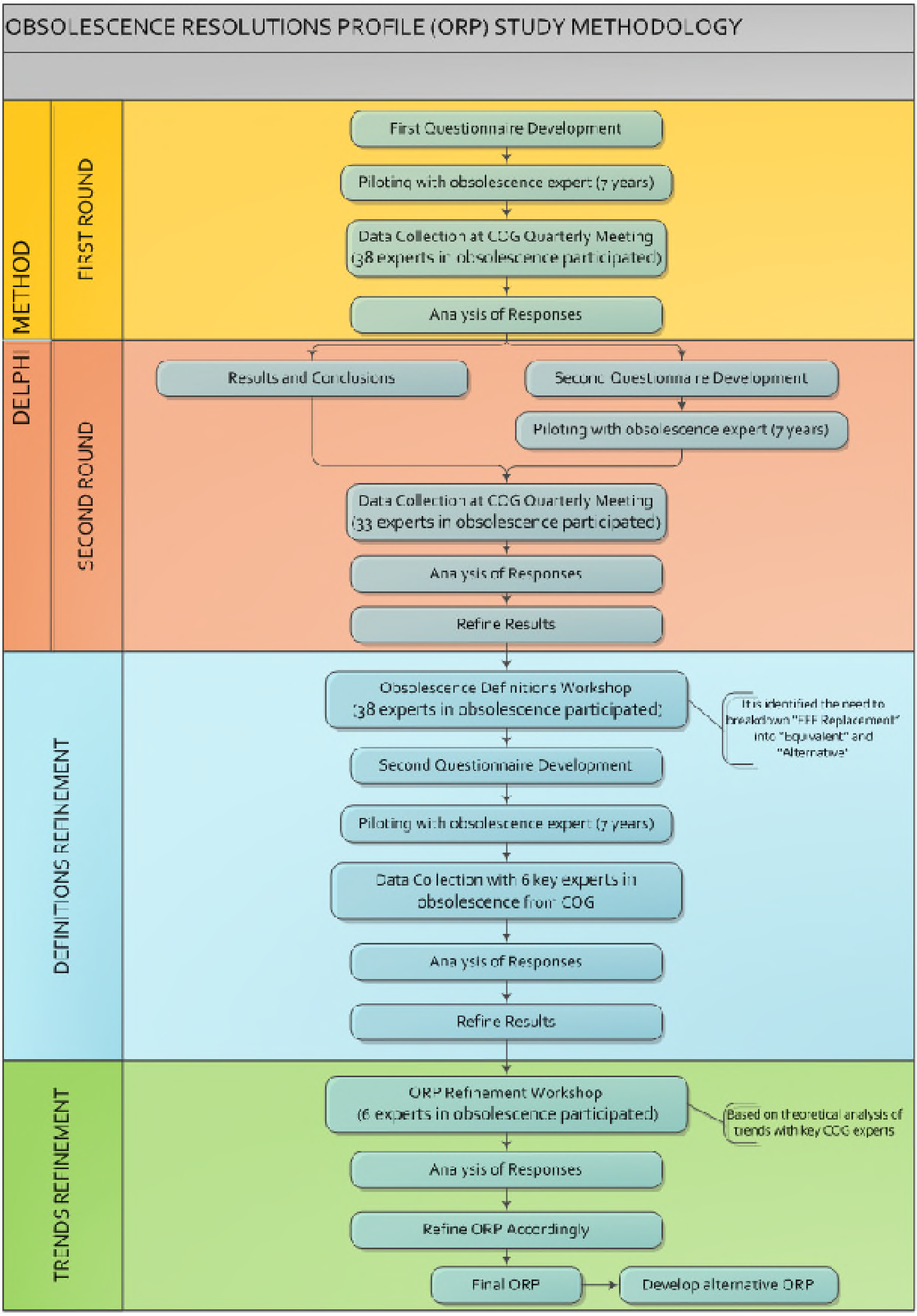


Figure 5-3 Obsolescence Resolution Profiles Study Methodology Phases

The outcomes of this analysis were presented at a second round to 33 obsolescence experts, out of which 13 had also participated in the first round. The years of experience on obsolescence of the participants in the Delphi study are shown in Table 5-2. They took the opportunity to discuss about the results and fill in a new questionnaire (see Appendix A.7) either corroborating the results or correcting them. The participants were given the possibility to amend any percentages from any pie-chart, by writing the new figure next to the old one in the questionnaire, so that the rest of percentages would be adjusted during the analysis phase, keeping the same proportion. If the participant believes that no amendments are required for a pie-chart, they will circle the "OK" below it. A final analysis of these responses allowed refining the outcomes of the first round, providing as a result a set of obsolescence resolution profiles (ORPs). The results of the first and second round converged, so there was no need for further iterations in the Delphi study.

Table 5-2 Years of Experience of Participants in Obsolescence for Delphi study

ROUND 1

Years of Experience	Number of Participants
Less than 5 years	7
5 years up to 9 years	4
10 years up to 19 years	17
20 years up to 29 years	6
30 years or more	4

ROUND 2

Years of Experience	Number of Participants
Less than 5 years	5
5 years up to 9 years	4
10 years up to 19 years	17
20 years up to 29 years	4
30 years or more	3

5.2.3.2 Phase 2: Definitions Refinement

A total of 38 obsolescence experts from different organisations participated in the "Obsolescence Definitions Workshop" in order to properly define the different resolution approaches and generate a common understanding of these terms across the UK defence sector. During Phase 1, one of the resolution approaches considered was the replacement of the obsolete component using another with the same Form, Fit and Function (FFF). However, the outcomes of the "Obsolescence Definitions Workshop" leaded to the decision of breaking down this approach into "Equivalent" and "Alternative". The distinction between them is that an equivalent component is functionally, parametrically and technically interchangeable with the obsolete one, while the performance of the alternative component may be different from that specified. Therefore, a subsequent study was carried out with six key obsolescence experts from five different organisations (their experience ranged from 11 to 40 years) to split the probability of using a FFF replacement into equivalent and alternative. A questionnaire was filled in by each expert, indicating the proportion in which the FFF replacement percentage needed to be broken down for each of the 15 ORPs. The responses collected were analysed, and the mean was applied to refine the ORPs resulting from the Delphi study.

5.2.3.3 Phase 3: Trends Refinement

The potential problem of confidence resulting from the low sample size in the Delphi Study has been tackled by means of the Trends Refinement session. The ORPs were analysed in terms of identifying the trends in probability of usage for each resolution approach across the different levels of complexity or levels of proactiveness to manage obsolescence. Those trends were presented at the “ORP Refinement Workshop”, where six key experts on obsolescence from different organisations participated (their level of experience is detailed in Table 5-3). The objective was to validate the trends by checking their plausibility (Robson, 2002), making sure that the patterns and figures made sense. The experts discussed each trend, concluding whether it matched the anticipated trend based on their experience or not, and justifying it.

Table 5-3 Years of Experience on Obsolescence of Participants on Trends Refinement

Participant	*Years of Relevant Experience*
Participant 1	12
Participant 2	11
Participant 3	5
Participant 4	10
Participant 5	3
Participant 6	30
Average	12

Additionally, alternative obsolescence resolution profiles were derived to adapt them to the termination stage of the in-service phase (typically, the last five years of the project). During this phase, the likelihood of resolving obsolescence issues by means of cannibalisation and Last-time Buy (LTB) increases, while using equivalents and alternatives or doing redesigns or emulation become less likely. The assumption made for this adjustment is that the probability of using equivalents and alternatives, redesigns or emulation will reduce by 50%. The increase in the probability of using cannibalisation and LTB will be proportional to their probabilities in the original obsolescence resolution profiles. In principle, the experts agreed that these adjustments make the alternative ORPs more suitable for the end of the in-service phase than the original ones.

5.2.4 Detailed Research Methodology for OCM Study

A total of 21 obsolescence experts with different backgrounds, from six organisations (BAE Systems, Ministry of Defence (MoD), MBDA, COG, Sellafield Ltd. and Selex Galileo), participated in a workshop to derive obsolescence cost metrics. Their experience on obsolescence ranges from 4 to 15 years and their roles were mainly obsolescence managers and support engineers. The experts were arranged into groups of seven following a careful selection based on their backgrounds, areas of expertise and their organisations. The intention was to create three heterogeneous groups whose members might reasonably be expected to have expertise in different fields (e.g. electronic components obsolescence, materials, software, systems support) from different organisations. This approach reduces the subjectivity and bias that can be expected from expert opinion.

A brainstorming session in groups, followed by discussion among all the participants, allowed the identification of the main parameters that define the complexity of a system and influence the obsolescence resolution cost. Subsequently, further discussion in groups allowed setting obsolescence cost metrics, based on expert judgement, according to the parameters defined previously. A further analysis of the cost metrics developed by each group led to integrating them by identifying commonalities and finally deriving a set of obsolescence cost metrics. One of the cost drivers, the level of integration, depends mainly on two parameters, namely the package density and the coupling level. The weighting of those parameters was done in collaboration with a project manager and a support engineer, which have 12 and 10 years of experience on obsolescence respectively.

The key parameters that define the obsolescence cost, and the interactions between them, were validated with an obsolescence manager (10 years experience) from a different organisation from those participating in the workshop (GE Aviation). Additionally, the obsolescence cost metrics resulting from the workshop were presented to three key experts from different organisations, so they could validate and refine those results. Their feedback was collated and the obsolescence cost metrics were amended accordingly. The process followed has reduced the subjectivity from each individual by taking into account the views of multiple experts from different organisations.

5.2.5 Detailed Research Methodology for EEE-FORCE Framework Development

A systematic approach has been followed in this study, as shown in Figure 5-4. The first phase aimed to gain an understanding on obsolescence and cost estimation through a literature review and semi-structured interviews with experts from industry. This allowed the identification of key factors and cost drivers for obsolescence, together with the type of information available at different stages of the life-cycle of the system. A MS Excel-based prototype for the cost estimation of obsolescence was developed and iteratively enhanced, based on qualitative validation carried out in collaboration with experts from different organisations (Phase 2). As it will be explained in Chapter 8, the resulting framework was then quantitatively validated using case studies from industry (Phase 3).

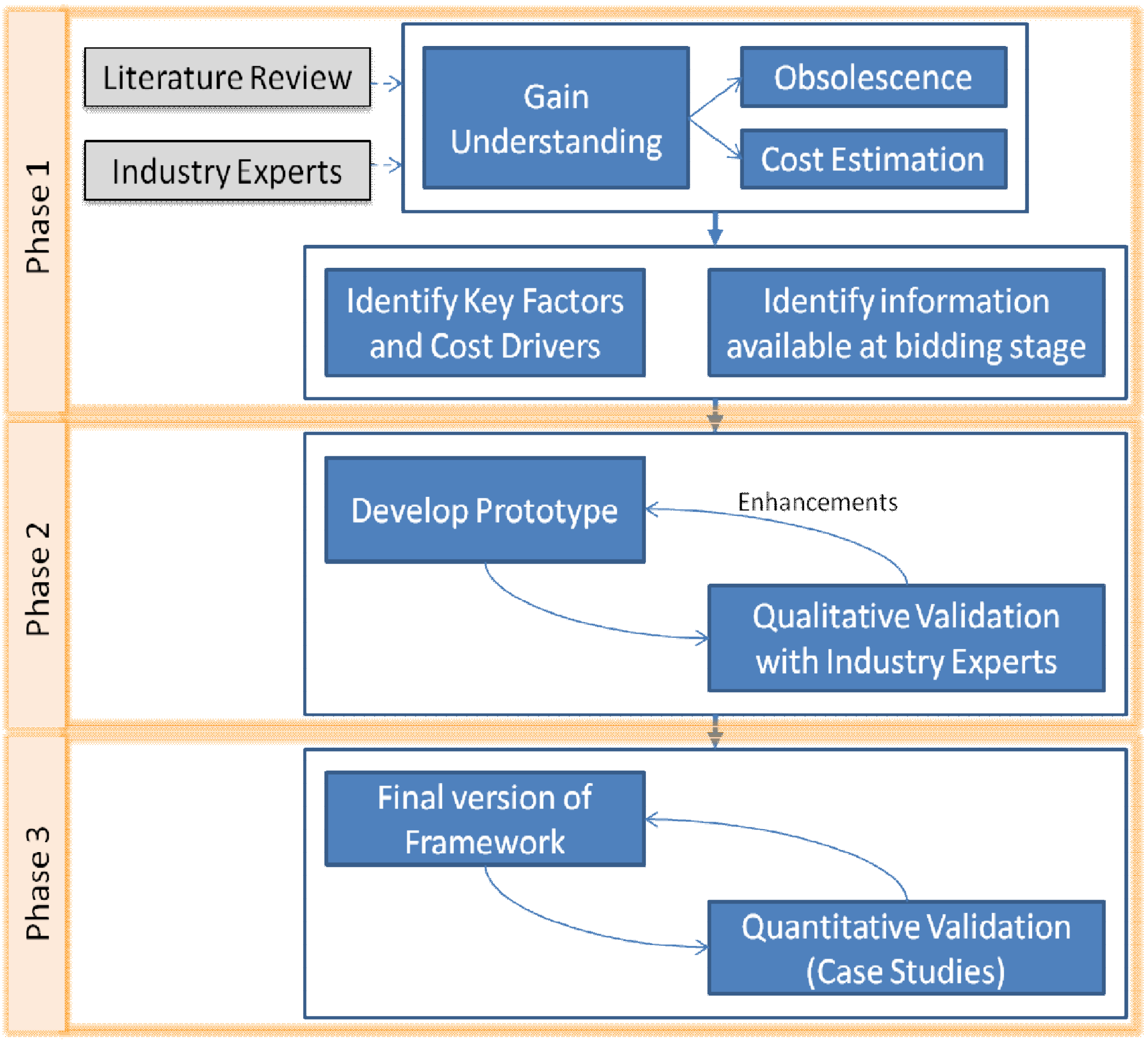


Figure 5-4 Research Methodology for EEE-FORCE Development and Validation

5.3 Requirements for EEE-FORCE Framework

The workshop and interviews with obsolescence experts enabled the identification of the key factors and cost drivers for obsolescence, as well as the level of information available at the bidding stage. The key requirements for the EEE-FORCE framework are described as follows.

- **Flexibility**

  The framework should be capable to adapt to any level of information available, as it may be used at the beginning of the in-service phase, when it is possible that detailed information is unavailable. Likewise, it can be used at different stages of the in-service phase, and as more information becomes available, the framework should be capable of taking it into account to make more reliable cost estimates. It is essential that only one framework is used throughout the in-service phase in order to ensure continuity in the estimates.

- **User-friendly**
  The framework should be easy to use, having a clear interface and structured process to estimate the obsolescence costs.
- **Generic**
  The framework should be easily adaptable to any type of project/system in the defence and aerospace sectors.
- **Robust**
  The framework should be reliable enough to be used as the basis for contract negotiation at the bidding stage for support contracts.
- **Estimate Range**
  It is not enough to have a framework that estimates the cost of obsolescence as a single figure. It is important to estimate as well the range of variability in the cost estimate, taking into account the uncertainties involved. It is suggested that the framework should provide a 3-point estimate for this purpose.

During the workshop, the obsolescence experts highlighted that the framework will provide an effective way to estimate obsolescence costs at the bidding stage (4.5 out of 5). The framework will also enable identifying the obsolescence drivers (4 out of 5) and give confidence to include obsolescence in contracts (3.75 out of 5). The experts also indicated that the framework should have the following features:

- Take into account the possibility of repairing a component and reusing it (4 out of 5).
- Make a distinction between consumable and repairable components (4.25 out of 5).

- Take into account the possibility that some components may become obsolete more than once during the contracted period (4.5 out of 5).
- Use of Monte-Carlo simulation to take uncertainty into account (4.25 out of 5).
- Allow calibration for different projects and domains such as air, land and sea.
- Be able to work at different levels of the product breakdown structure.

5.4 Results from Preliminary Study

The first outcome of this study was a set of definitions agreed across experts in the British defence sector. A distinction has been made between "mitigation strategies" and "resolution approaches". Mitigation strategies are those actions performed in order to reduce the risk or potential impact of obsolescence issues whereas resolution approaches are those actions carried out once an obsolescence issue arises and needs to be addressed.

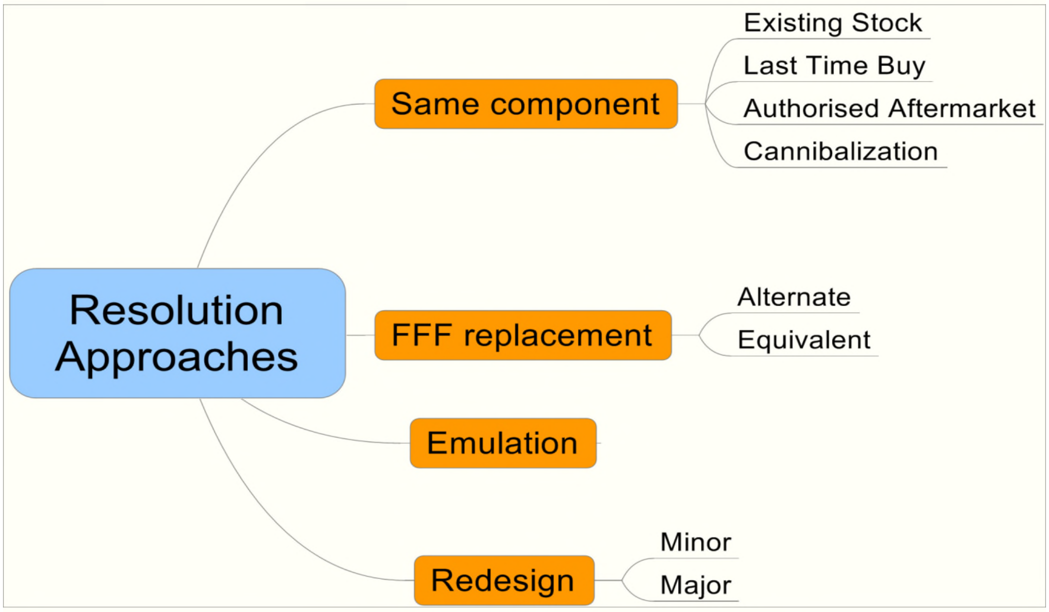


Figure 5-5 Obsolescence Resolution Approaches

Obsolescence Resolution Definitions

The definitions for the different resolution approaches that can be applied to tackle an obsolescence issue for an electronic component are presented in

Table 5-4. The reader should note that the FFF replacement resolution was divided into Alternative and Equivalent as a result of the “definitions workshop” that took place after the first phase of the ORP study. The obsolescence resolutions can be grouped into four categories, as shown in Figure 5-5, which are: use of same obsolete component, use of a FFF replacement, emulation and redesign.

Table 5-4 Obsolescence Resolution Approaches Definitions

Resolution Term	***Definition***
Existing Stock	Available item owned within the supply chain that can be allocated to the project.
Last Time Buy	As a result of a product discontinuance notice, the procurement of items sufficient to support the life cycle of the project or until the next planned technology upgrade.
Reclamation (Cannibalisation)	The use of an item found in surplus equipment or equipment beyond economical repair.
Equivalent	An item which is functionally, parametrically and technically interchangeable (form, fit and function).
Alternative	An item whose performance may be different from that specified for one or more reasons (e.g., quality or reliability level, tolerance, parametric, temperature range).
Authorised Aftermarket	An item is available on the market but not from the original manufacturer or supplier (typically finished goods provided by licensed sources). Note that the components in this category must have the same specifications as the original ones.
Emulation	A manufacturing process that produces a substitute form, fit and function, and interface item for the unobtainable item. Microcircuit emulation can replicate with state-of-the art devices that emulate the original and can be manufactured and supplied on demand.
Redesign	An obsolete item is designed out of the system. Usually used as a last resort because of the cost implications. Redesign typically has the goal of enhancing system performance and improving reliability and maintainability. The cost for redesign can include engineering, programme management, integration, qualification and testing. Redesign can be further broken down into categories, e.g. minor (board re-layout) and major (board replacement).

EEE Component Complexity

The second outcome of this study is the explanation of the "complexity" concept for EEE components, so they can be classified accordingly. The level of complexity will influence the probability of using each resolution approach to resolve an obsolescence issue. EEE components can be classified into three categories based on the complexity level: low, medium and high. Each category and the characteristics that define it are shown as follows (Figure 5-6).

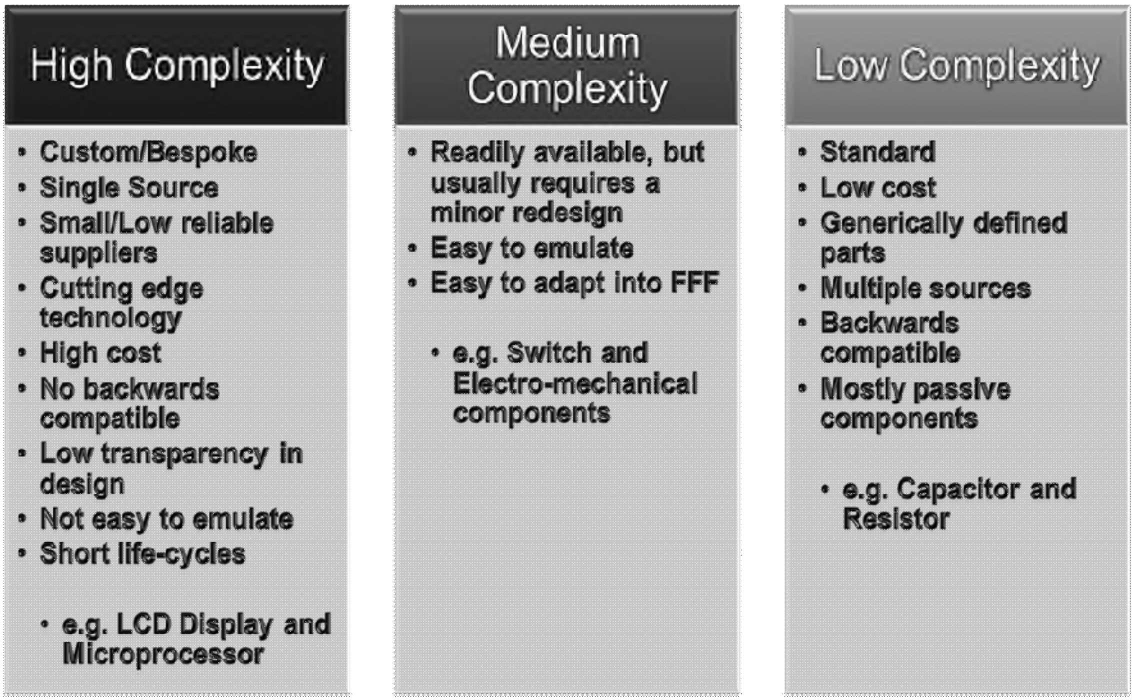


Figure 5-6 Electronic Components Complexity Levels

High-complexity components are characterised as bespoke, expensive, cutting-edge technology and no-backwards compatible. In general, this type of components is single-source supplied and the suppliers are usually small or low reliable. The life-cycle of these components is usually very short (around 1 or 2 years) and they are not easy to emulate. Examples of this type of component are LCD displays and microprocessors.

Medium-complexity components are usually readily available and easily adapted into FFF replacements. Furthermore, they are easy to emulate. Examples of this type of component are switches and electromechanical components.

Low-complexity components are characterised as standard, low-cost, generically-defined and backwards compatible. In general, these components are passives and can be procured from multiple suppliers. Examples of this type of component are standard capacitors and resistors.

Obsolescence Management Levels of Proactiveness

The third outcome of this study is the classification of the obsolescence management (OM) into five levels of proactiveness based on the mitigation strategies employed, which is shown in Figure 5-7.

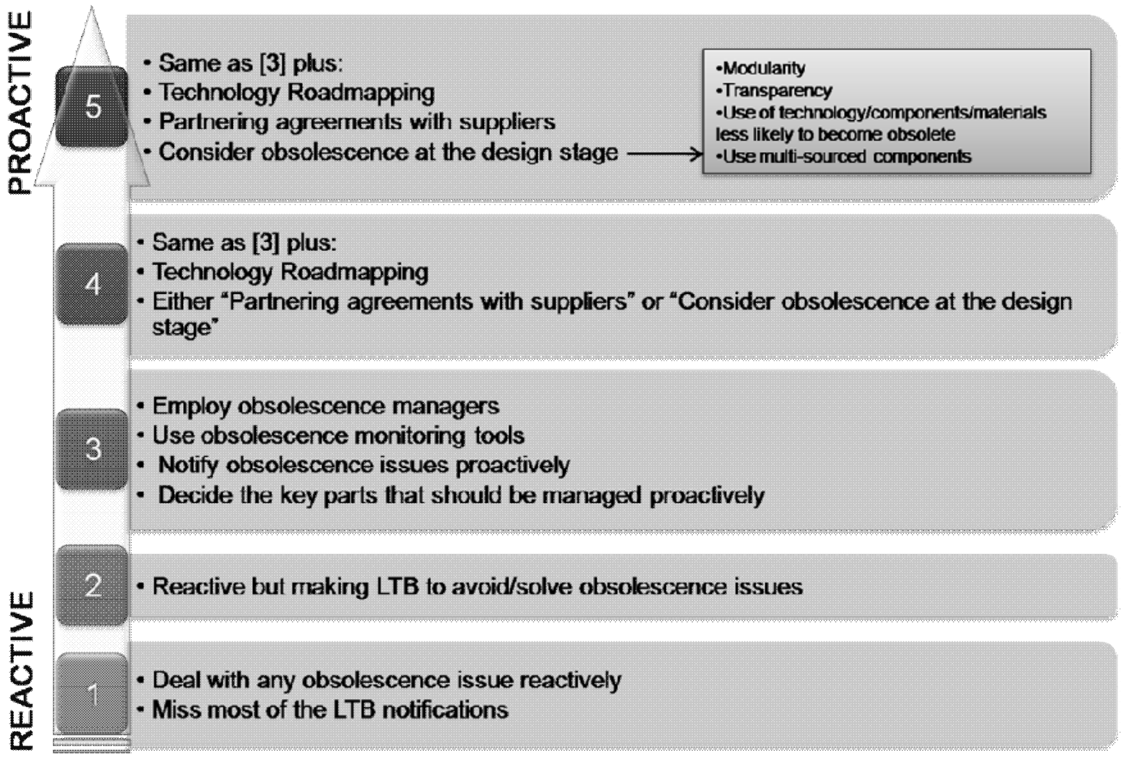


Figure 5-7 Obsolescence Management Levels

In this classification, level 1 represents a purely reactive strategy whereas level 5 represents the most proactive measures, where all the following proactive strategies are taken:

- Employ obsolescence managers
- Use obsolescence monitoring tools
- Notify obsolescence issues proactively
- Decide the key parts that should be managed proactively (after carrying out an obsolescence risk assessment)
- Technology Roadmapping
- Partnering agreements with suppliers
- Consider obsolescence at the design stage:
  - Modularity
  - Transparency
  - Use of technology, components and materials that are less likely to become obsolete
  - Use multi-sourced components

5.5 Obsolescence Resolution Profiles (ORP) Study

5.5.1 Results in Phase 1: Delphi Method

A comparison between the outcomes of the first and second round of the Delphi study shows that most of the figures received little adjustment during the second phase (average of ±1.43%). However, some figures changed by 7% or more, such as the probability of using cannibalisation when the obsolescence management level is 1 (totally reactive) to resolve an obsolescence issue for any level of complexity. As shown in Table 5-5, the cannibalisation probability decreased from 38.3% to 24.8% for low-complexity components, from 35.1% to 26.7% for medium-complexity components and from 32.1% to 24.2% for high-complexity components. For low-complexity components, the probability of using a FFF replacement increased from 7.9% to 18.6% when the obsolescence management level is 1 and from 23% to 29.9% when the obsolescence management level is 4. The reason for this adjustment is that the experts, after considering the figures resulting from the first round of the Delphi study, realised that they were higher than reality for cannibalisation and lower for FFF replacement. It is common practice, when applying the Delphi method, to articulate the thinking of the experts after each iteration, so that the results can be refined.

Table 5-5 Comparison between Results from First and Second Rounds of Delphi Study

OM Level	Complexity Level	Resolution Approach	Round 1	Round 2	Difference
1	Low	Cannibalisation	38.3%	24.8%	-13.6%
1	Medium	Cannibalisation	35.1%	26.7%	-8.4%
1	High	Cannibalisation	32.1%	24.2%	7.9%
1	Low	FFF Replacement	7.9%	18.6%	10.7%
4	Low	FFF Replacement	22.9%	29.9%	7.0%

This comparison of results between the first and second rounds shows that they converge and hence, no further iterations in the Delphi method are required.

5.5.2 Results in Phase 2: Definitions Refinement

As a result of the “Obsolescence Resolution Workshop”, the “FFF replacement” resolution approach was broken down into “Equivalent” and “Alternative”. The results (Table 5-6) reflect that for all level of proactiveness in managing obsolescence, the probability of finding an equivalent instead of an alternative is higher for low-complexity components, but lower for medium and high-complexity components. This is coherent with the characteristics defined for each level of complexity: the higher the complexity of the obsolete component is, the more difficult to find an equivalent to replace it would be.

Table 5-6 Results of Dividing FFF Replacement into Equivalent and Alternative

OBSOLESCENCE MANAGEMENT LEVEL		COMPLEXITY LEVEL	Phase 1	Phase 2	
			FFF	Equivalent	Alternative
	OM1	Low	18.6%	10.1%	8.5%
		Medium	17.6%	7.2%	10.4%
		High	14.2%	2.8%	11.4%
	OM2	Low	24.2%	13.3%	10.9%
		Medium	18.0%	7.8%	10.2%
		High	13.9%	3.5%	10.4%
	OM3	Low	27.3%	16.6%	10.7%
		Medium	19.9%	7.6%	12.3%
		High	15.3%	4.4%	10.9%
	OM4	Low	29.9%	18.5%	11.4%
		Medium	22.6%	9.0%	13.6%
		High	18.2%	5.8%	12.4%
	OM5	Low	27.7%	17.1%	10.6%
		Medium	18.4%	7.4%	11.0%
		High	13.7%	4.9%	8.8%

5.5.3 Results in Phase 3: Trends Refinement

In Figure 5-8 it is shown how the probabilities of using each resolution approach have varied after taking into account the theoretical trends conceived by experts. It can be appreciated that less than 35% of those values have been modified in more that 2%, and none has been modified in more than 9.5%. This indicates that the adjustments made to adapt the ORPs to follow the theoretical trends brought about necessary but not substantial changes to the figures.

Two different trends were analysed for each resolution approach. The first trend represents the evolution of the probability for each level of complexity across the different levels of proactiveness to manage obsolescence. The second trend represents the evolution of the probability for each level of proactiveness across the different levels of complexity in the obsolete component. These trends are analysed as follows.

LOW COMPLEXITY	OBSOLESCENCE MANAGEMENT LEVEL				
	OM1	OM2	OM3	OM4	OM5
Existing Stock	1.4%	-2.3%	-6.8%	-5.5%	-1.7%
LTB	0.9%	-1.6%	-0.2%	-1.0%	-3.9%
Cannibalisation	1.6%	-0.1%	0.0%	-0.2%	-0.6%
Equivalent	0.6%	-1.2%	-0.1%	-1.0%	-2.9%
Alternative	0.5%	-1.0%	-0.1%	-0.6%	-1.9%
Authorised Aftermarket	-6.3%	-1.0%	-0.1%	-0.8%	-0.9%
Emulation	0.0%	1.5%	-0.5%	0.8%	1.6%
Minor Redesign	0.5%	6.1%	7.8%	6.4%	5.3%
Major Redesign	0.8%	-0.3%	0.0%	1.9%	4.9%

MEDIUM COMPLEXITY	OBSOLESCENCE MANAGEMENT LEVEL				
	OM1	OM2	OM3	OM4	OM5
Existing Stock	0.8%	-4.1%	-1.7%	-2.9%	-3.7%
LTB	0.6%	-3.0%	-1.8%	-3.7%	-3.9%
Cannibalisation	1.2%	-0.3%	0.0%	-0.3%	3.6%
Equivalent	0.3%	-1.3%	-0.5%	-2.0%	-4.6%
Alternative	0.5%	-1.7%	-0.9%	-0.4%	-3.9%
Authorised Aftermarket	-3.5%	2.9%	2.6%	0.7%	-0.5%
Emulation	-1.0%	1.7%	-0.1%	2.5%	1.1%
Minor Redesign	0.4%	7.0%	2.8%	4.3%	7.2%
Major Redesign	0.6%	-1.3%	-0.4%	1.8%	4.6%

HIGH COMPLEXITY	OBSOLESCENCE MANAGEMENT LEVEL				
	OM1	OM2	OM3	OM4	OM5
Existing Stock	0.5%	-3.1%	-3.1%	2.8%	-1.8%
LTB	0.7%	-3.1%	-3.7%	-8.7%	-2.9%
Cannibalisation	0.8%	-0.2%	-0.1%	3.9%	3.7%
Equivalent	0.8%	0.5%	0.4%	0.3%	-1.6%
Alternative	0.4%	-1.4%	-1.6%	-2.1%	-7.2%
Authorised Aftermarket	-2.0%	9.5%	7.4%	-1.5%	-1.3%
Emulation	-2.0%	-0.5%	1.7%	0.6%	-0.4%
Minor Redesign	0.4%	0.8%	-2.7%	3.2%	7.0%
Major Redesign	0.4%	-2.4%	1.6%	1.5%	4.5%

The values for which the variation is higher than 2% have been highlighted

Figure 5-8 Comparison between ORP before and after Trends Refinement

Evolution of ORP across Level of Proactiveness for OM

Before Refining | **After Refining**

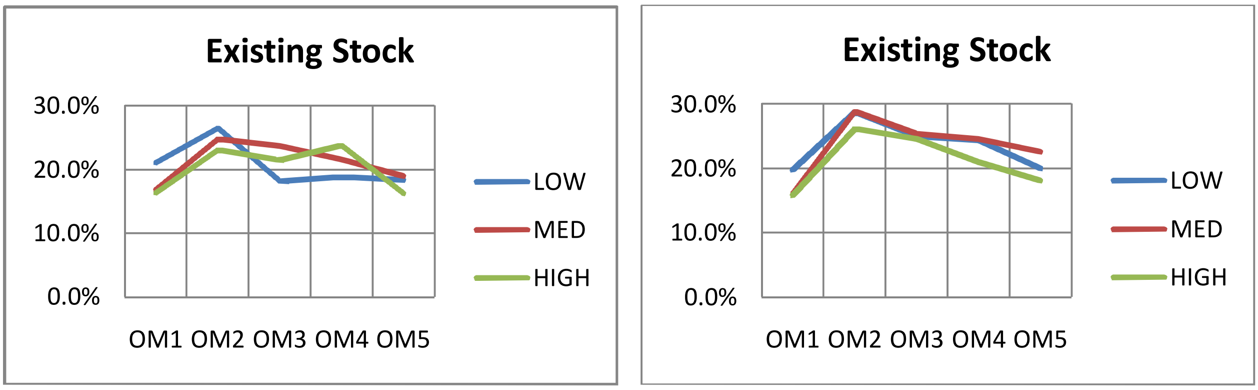


Figure 5-9 Existing Stock Probability Trends across Level of Proactiveness for OM Before and After Trends Refinement

For Existing Stock, the trend is fairly flat for all OM levels and complexity levels (between 15 – 25%). It is expected that the higher the complexity level is, the lower it is the probability of finding Existing Stock for any level of proactiveness for OM (Figure 5-9). The changes resulting from refining the results, based on the theoretical trends, are minor.

Before Refining | **After Refining**

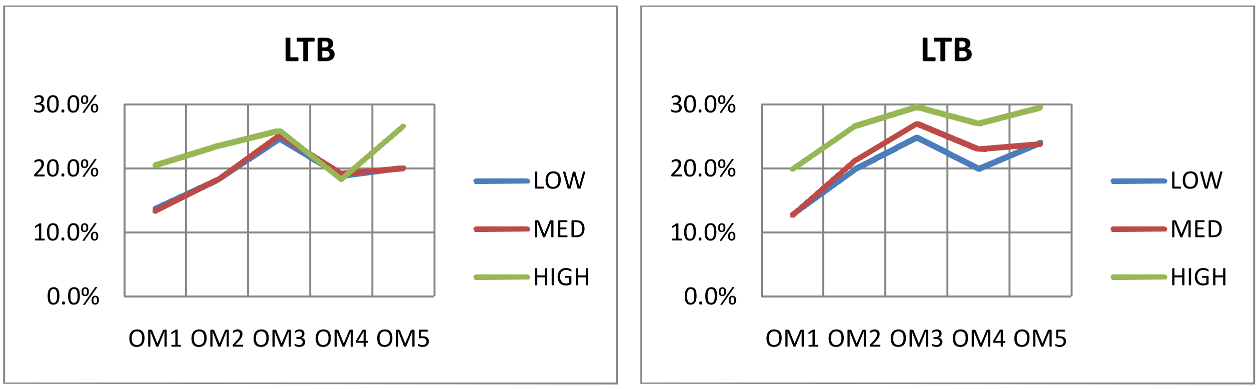


Figure 5-10 Last-Time Buy Probability Trends across Level of Proactiveness for OM Before and After Trends Refinement

It is expected that the higher the complexity level is, the higher it is the probability of making a LTB for any level of proactiveness for OM (Figure 5-10).

The reason is that it is usually difficult to find a FFF replacement for a high complexity component, and hence, it is advisable to prevent an expensive redesign by making a LTB. Therefore, the results have been adjusted to align them with the experts' expectations.

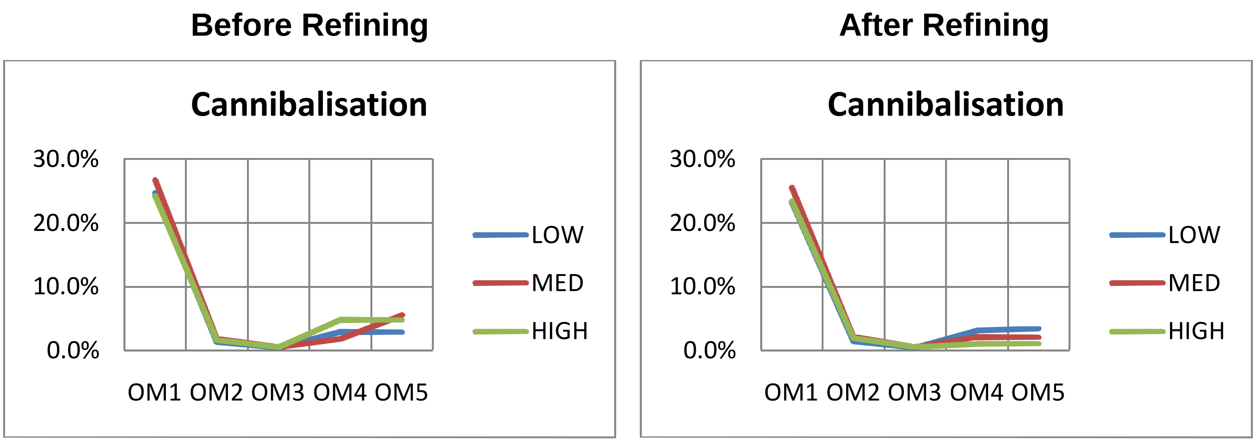


Figure 5-11 Cannibalisation Probability Trends across Level of Proactiveness for OM Before and After Trends Refinement

The trends at OM levels 4 and 5 should be flatter. The probability of using cannibalisation for OM levels 4 and 5 is expected to be lower, the higher the complexity of the component is (Figure 5-11).

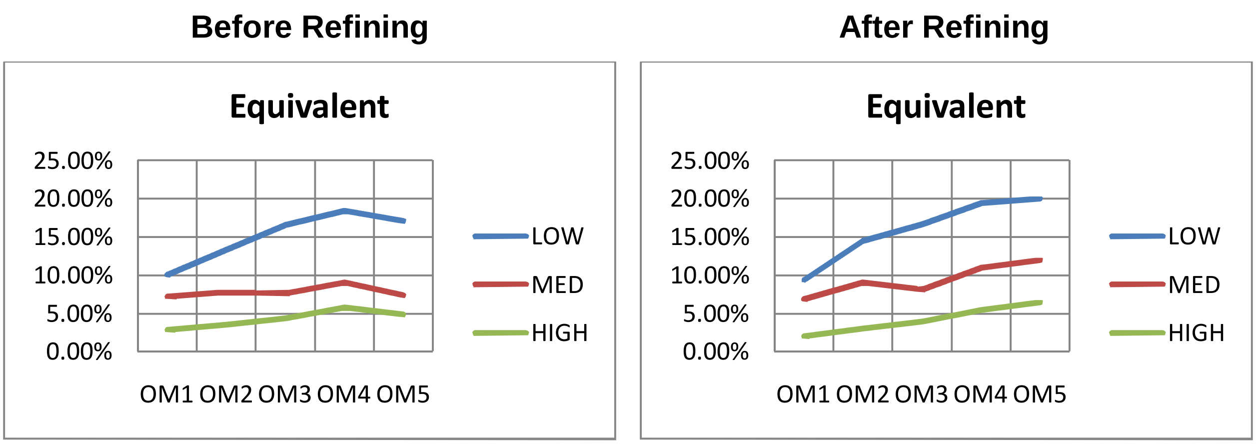


Figure 5-12 Equivalent Probability Trends across Level of Proactiveness for OM Before and After Trends Refinement

The probability of finding an equivalent increases with the proactiveness level to manage obsolescence. Moreover, it is usually more difficult to find an equivalent the higher the complexity of the component is (Figure 5-12).

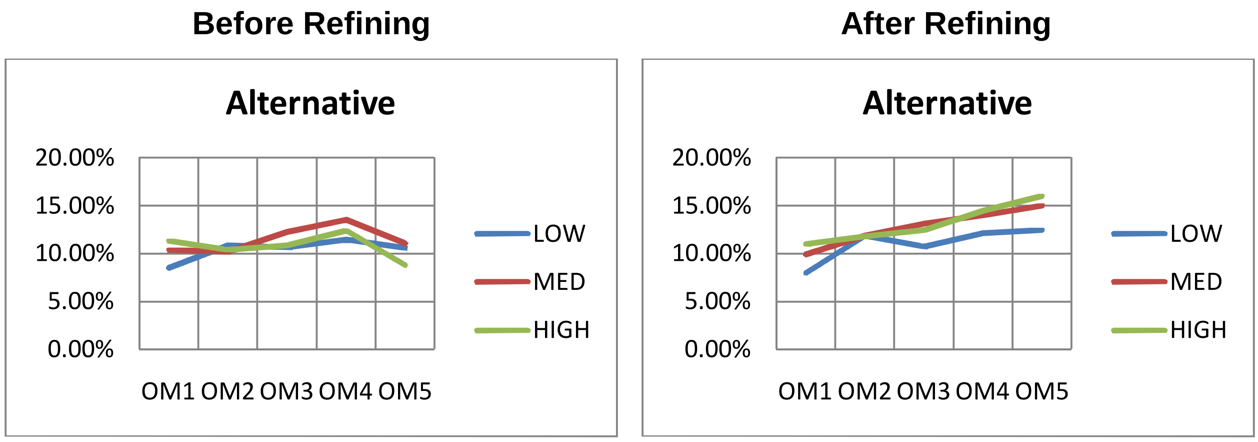


Figure 5-13 Alternative Probability Trends across Level of Proactiveness for OM Before and After Trends Refinement

The probability of finding an alternative is expected to increase with the level of proactiveness to manage obsolescence (Figure 5-13). Probably the reason why the original trends do not reflect this is that some of the experts who participated in the study are second-tier suppliers, so they have a different point of view about the probability of using alternatives.

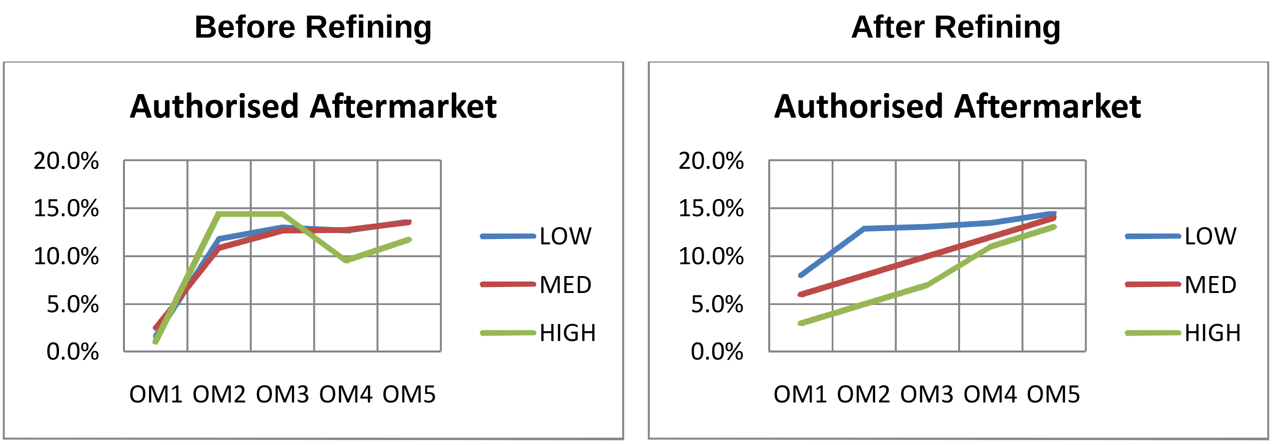


Figure 5-14 Authorised Aftermarket Probability Trends across Level of Proactiveness for OM Before and After Trends Refinement

The probability of using authorised aftermarket is expected to be higher at OM level 1 and increase with the level of proactiveness (Figure 5-14). Additionally, it is usually more difficult to find the obsolete component in the authorised aftermarket as the complexity of the component increases. Therefore, the results have been adjusted to align them with the experts' expectations. The trends for authorised aftermarket are expected to be similar to the equivalent (Figure 5-12).

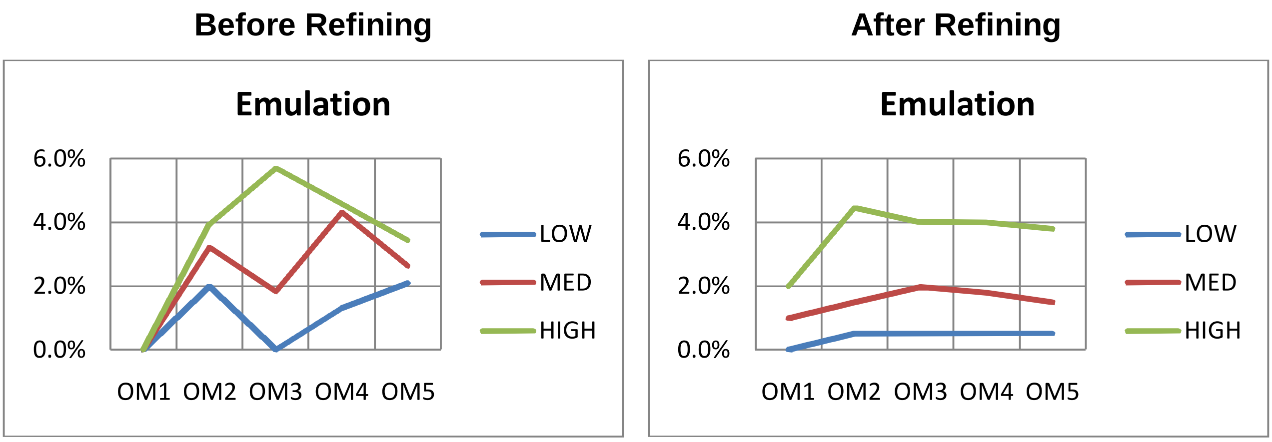


Figure 5-15 Emulation Probability Trends across Level of Proactiveness for OM Before and After Trends Refinement

According to the experts, for low and medium complexity components, the probability of using emulation is expected to be low and flat across the different levels of OM because this resolution approach is very expensive to be applied to that type of components (Figure 5-15). The trend for high complexity components is expected to become flat from OM level 3 to 5. Additionally, the fact that, for every level of proactiveness in obsolescence management, the probability of using emulation is higher for high-complexity components and lower for low-complexity components is coherent with the theoretical expectations. Therefore, the results have been adjusted accordingly.

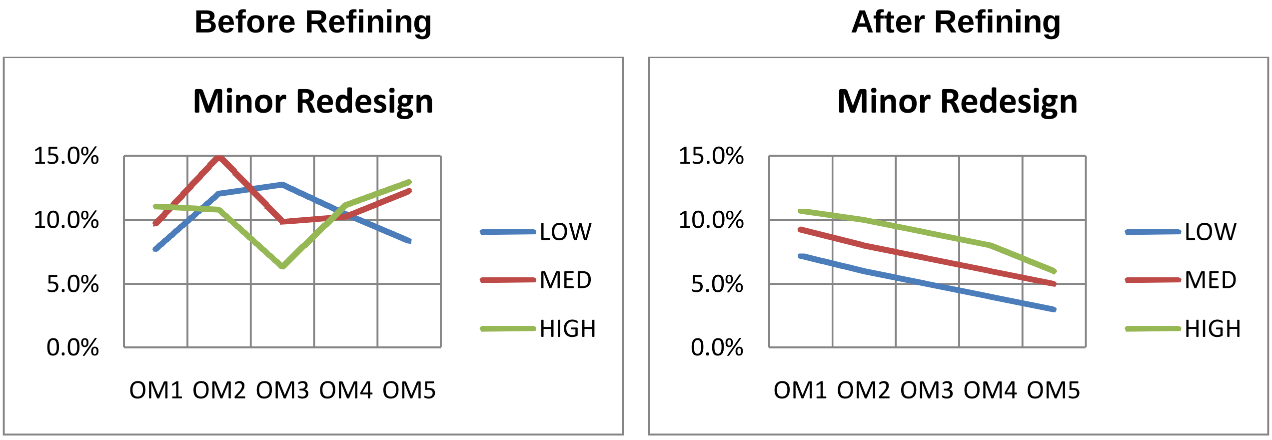


Figure 5-16 Minor Redesign Probability Trends across Level of Proactiveness for OM Before and After Trends Refinement

The trend for minor and major redesign is expected to decrease with the level of proactiveness to manage obsolescence. In addition, the higher the complexity level is, the more likely is having to do a redesign to resolve the obsolescence issue (Figure 5-16 and Figure 5-17). The main aim of being proactive is to avoid redesigns because they are very expensive. Therefore, the results have been adjusted to align them with the experts' expectations.

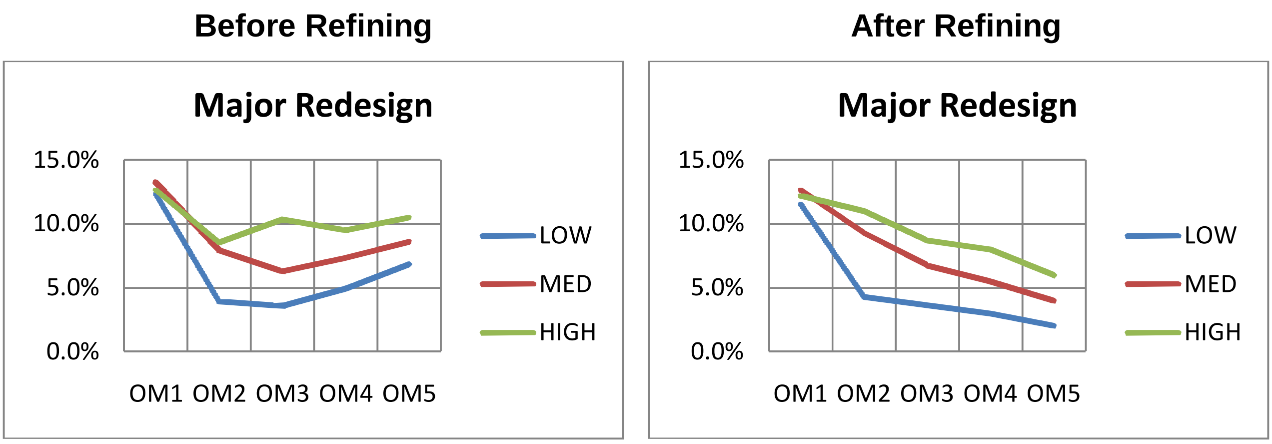


Figure 5-17 Major Redesign Probability Trends across Level of Proactiveness for OM Before and After Trends Refinement

Evolution of ORP across Levels of Complexity

Before Refining **After Refining**

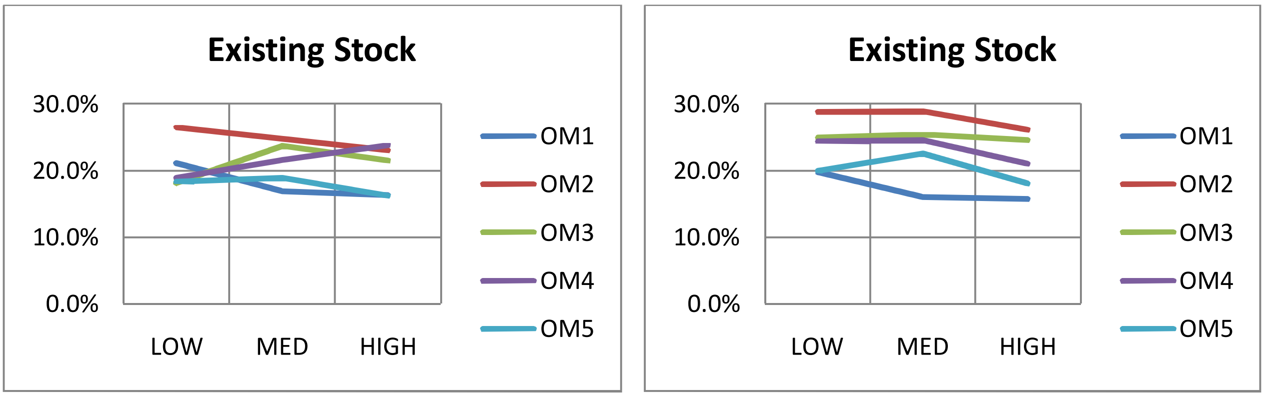


Figure 5-18 Existing Stock Probability Trends across Level of Complexity Before and After Trends Refinement

The trend for all OM levels should be flat or decreasing because it is less likely to find existing stock for high complexity components. Therefore, the trend for OM level 4 has been adapted to fit the theoretical trend (Figure 5-18).

Before Refining **After Refining**

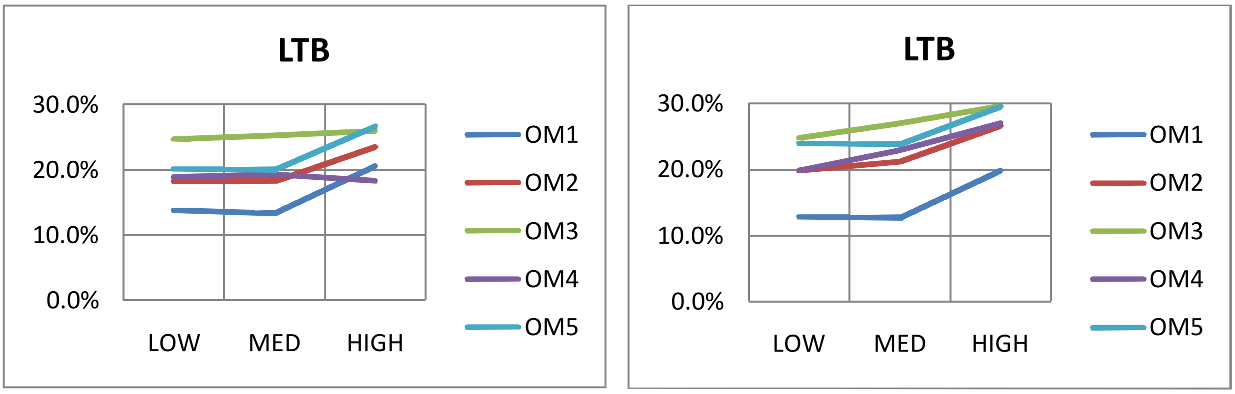


Figure 5-19 Last-Time Buy Probability Trends across Level of Complexity Before and After Trends Refinement

The trend for all OM levels should be increasing because it is more likely to make a Last-Time Buy (LTB) for high complexity components in order to avoid redesigns. Therefore, the trend for OM level 4 has been adapted to fit the theoretical trend (Figure 5-19). Additionally, it is logical that for the most reactive level of obsolescence management (OM1) the probability of making a last time buy (LTB) is lower that for more proactive strategies, because most of the product change notifications (PCN) will be ignored or not addressed on time. Therefore, most of the LTBs will be missed.

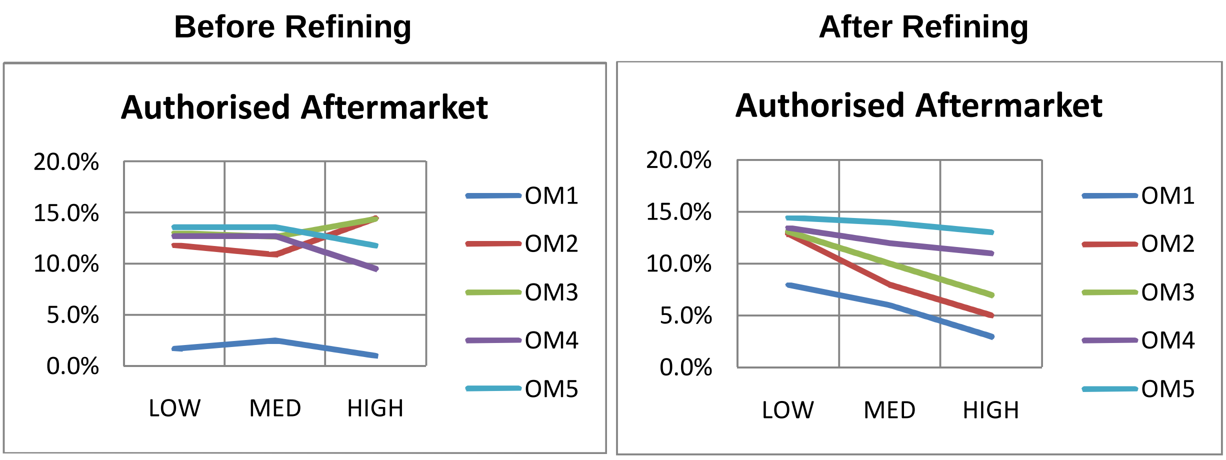


Figure 5-20 Authorised Aftermarket Probability Trends across Level of Complexity Before and After Trends Refinement

The trend for all OM levels should be decreasing because it is less likely to use authorised aftermarket for high complexity components. Therefore, the trend for OM level 2 and 3 has been adapted to fit the theoretical trend (Figure 5-20). The probability of using authorised aftermarket increases with the level of proactiveness for managing obsolescence.

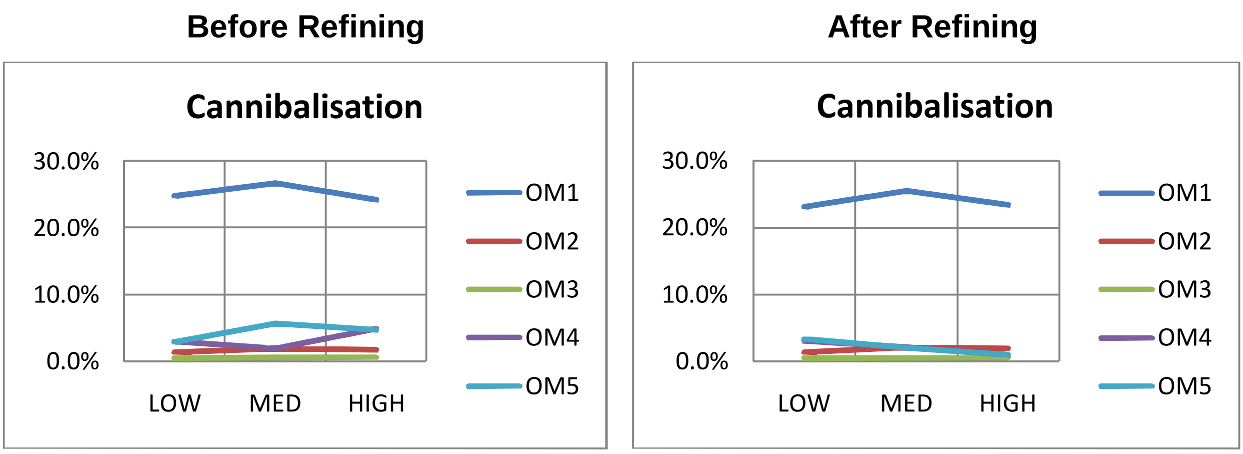


Figure 5-21 Cannibalisation Probability Trends across Level of Complexity Before and After Trends Refinement

The probability of using cannibalisation is higher for OM level 1 than for more proactive management strategies. The trend remains flat across all the levels of complexity (Figure 5-21).

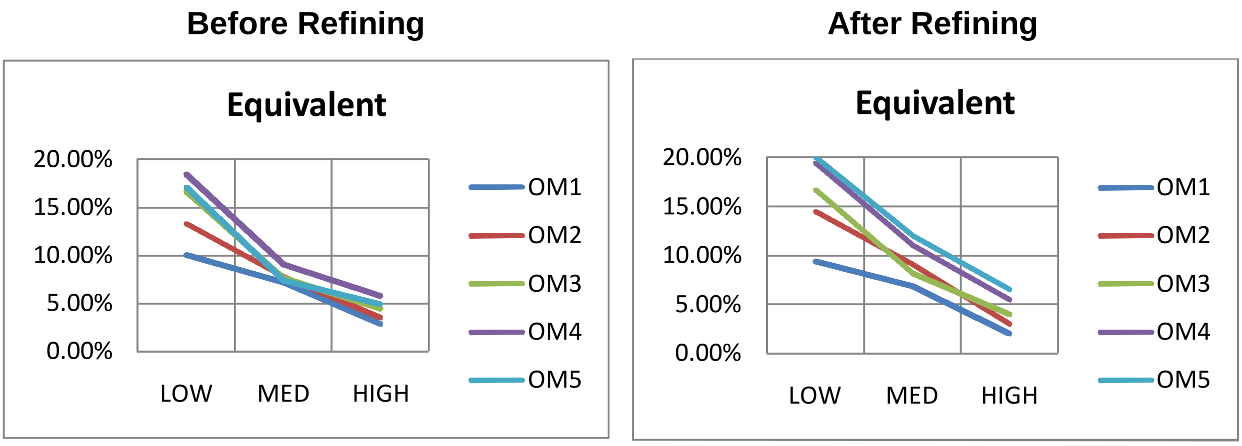


Figure 5-22 Equivalent Probability Trends across Level of Complexity Before and After Trends Refinement

The probability of finding an equivalent decreases with the complexity of the obsolete component. Moreover, the probability would be higher for higher levels of proactiveness (Figure 5-22).

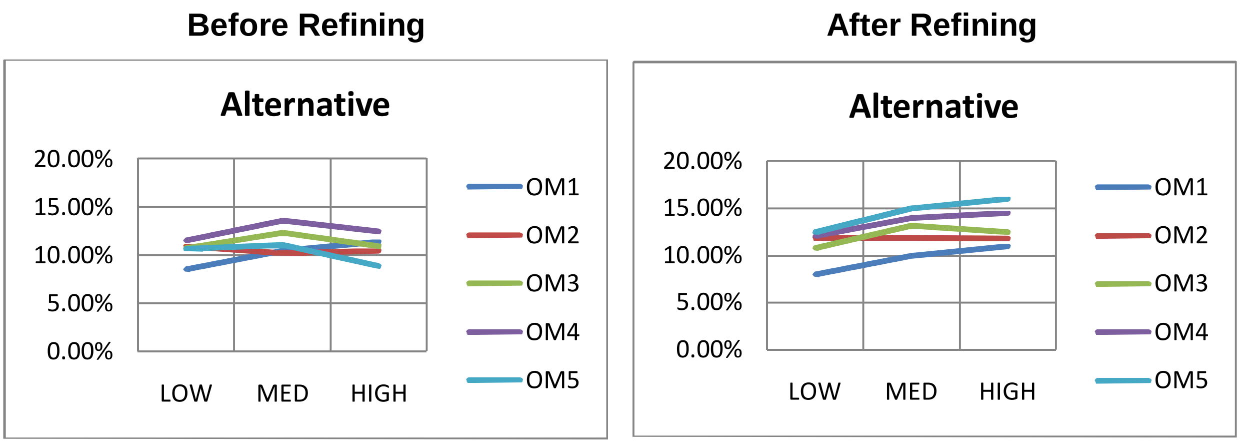


Figure 5-23 Alternative Probability Trends across Level of Complexity Before and After Trends Refinement

The probability of finding an alternative is expected to increase with the level of complexity of the obsolete component (Figure 5-23). The reason is that for high-complexity levels it is unlikely to find FFF replacements, and alternatives will be used instead. Additionally, the higher the level of proactiveness is, the more likely it will be to find an alternative.

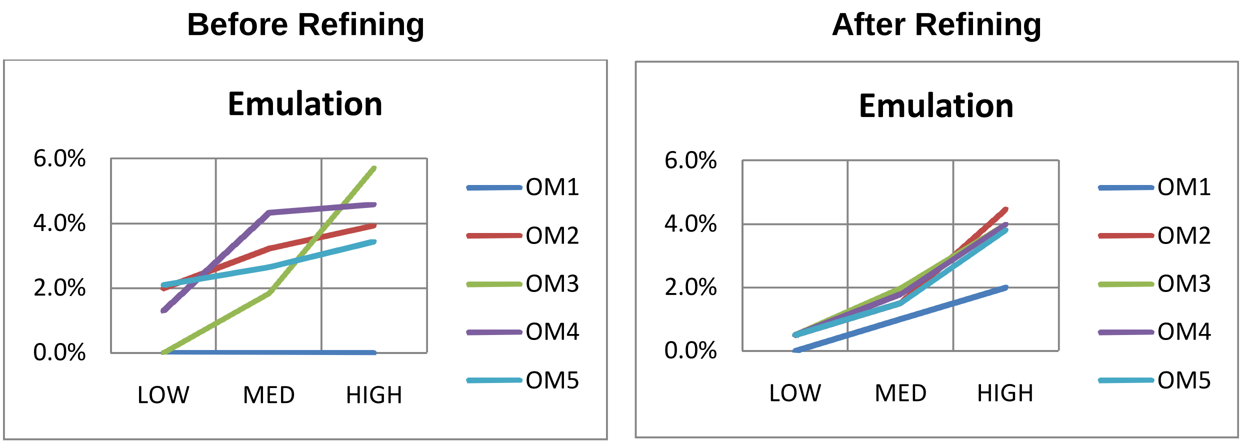


Figure 5-24 Emulation Probability Trends across Level of Complexity Before and After Trends Refinement

For all OM levels, the probability of using emulation is expected to follow a similar trend to OM3, which grows with the level of complexity of the obsolete component (Figure 5-24). However, the probability is lower when obsolescence is managed reactively (OM1). Therefore, the results have been adjusted to align them with the experts' expectations.

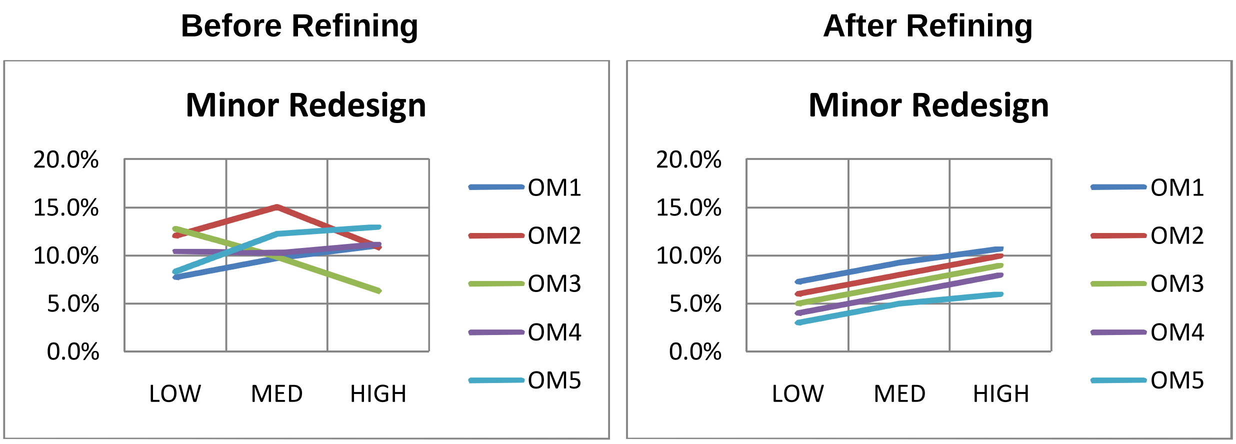


Figure 5-25 Minor Redesign Probability Trends across Level of Complexity Before and After Trends Refinement

The trend for minor and major redesign is expected to increase with the level of complexity of the obsolete component. In addition, the higher the level of proactiveness is, the less likely is having to do a redesign to resolve the obsolescence issue (Figure 5-25 and Figure 5-26). Therefore, the results have been adjusted to align them with the experts' expectations.

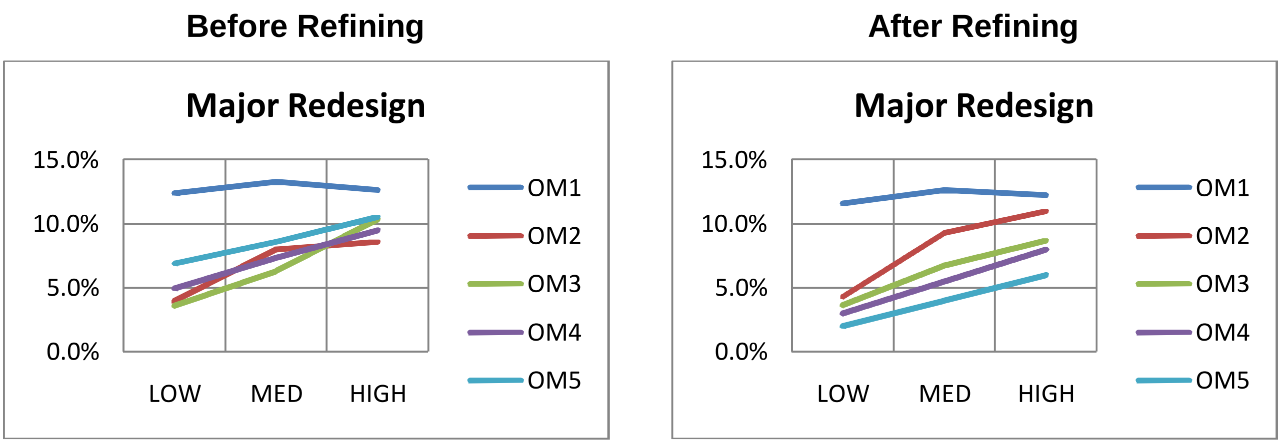


Figure 5-26 Major Redesign Probability Trends across Level of Complexity Before and After Trends Refinement

Obsolescence Resolution Profiles (ORPs)

Finally, the main outcomes of this study are the obsolescence resolution profiles (Figure 5-27). It shows a total of 15 columns (ORPs), where each one represents the probability of using each obsolescence resolution approach to tackle an obsolescence issue. Each obsolescence resolution profile is characterised by one level of component complexity (low, medium or high) and one level of proactiveness for obsolescence management (from 1 to 5, where 1 represents total reactiveness and 5 represents the highest level of proactiveness). For instance, if a low-complexity component becomes obsolete and obsolescence is managed at the lowest level of proactiveness (OM1), then the probability of making a Last Time Buy (LTB) is 12.9% and the probability of solving the obsolescence issue by doing a minor redesign is 7.2%.

	OBSOLESCENCE MANAGEMENT LEVEL				
LOW COMPLEXITY	OM1	OM2	OM3	OM4	OM5
Existing Stock	19.7%	28.8%	25.0%	24.4%	20.0%
LTB	12.9%	19.9%	24.8%	19.9%	24.1%
Cannibalisation	23.2%	1.4%	0.5%	3.1%	3.4%
Equivalent	9.42%	14.5%	16.7%	19.5%	20.0%
Alternative	7.97%	11.8%	10.8%	12.1%	12.5%
Authorised Aftermarket	8.0%	12.8%	13.1%	13.5%	14.5%
Emulation	0.0%	0.5%	0.5%	0.5%	0.5%
Minor Redesign	7.2%	6.0%	5.0%	4.0%	3.0%
Major Redesign	11.6%	4.3%	3.6%	3.0%	2.0%

	OBSOLESCENCE MANAGEMENT LEVEL				
MEDIUM COMPLEXITY	OM1	OM2	OM3	OM4	OM5
Existing Stock	16.1%	28.9%	25.4%	24.6%	22.6%
LTB	12.7%	21.3%	27.0%	23.0%	23.9%
Cannibalisation	25.5%	2.2%	0.5%	2.1%	2.0%
Equivalent	6.9%	9.1%	8.2%	11.0%	12.0%
Alternative	9.9%	11.8%	13.2%	14.0%	15.0%
Authorised Aftermarket	6.0%	8.0%	10.0%	12.0%	14.0%
Emulation	1.0%	1.5%	2.0%	1.8%	1.5%
Minor Redesign	9.3%	8.0%	7.0%	6.0%	5.0%
Major Redesign	12.6%	9.3%	6.8%	5.5%	4.0%

	OBSOLESCENCE MANAGEMENT LEVEL				
HIGH COMPLEXITY	OM1	OM2	OM3	OM4	OM5
Existing Stock	15.8%	26.1%	24.6%	21.0%	18.1%
LTB	19.9%	26.7%	29.7%	27.0%	29.6%
Cannibalisation	23.4%	1.9%	0.6%	1.0%	1.0%
Equivalent	2.0%	3.0%	4.0%	5.5%	6.5%
Alternative	11.0%	11.8%	12.5%	14.5%	16.0%
Authorised Aftermarket	3.0%	5.0%	7.0%	11.0%	13.0%
Emulation	2.0%	4.5%	4.0%	4.0%	3.8%
Minor Redesign	10.7%	10.0%	9.0%	8.0%	6.0%
Major Redesign	12.2%	11.0%	8.7%	8.0%	6.0%

Figure 5-27 Obsolescence Resolution Profiles

The alternative obsolescence resolution profiles, that represent the likelihood of using each resolution approach during the termination stage of the in-service phase, can be calculated from Figure 5-27 by reducing by half the probability of using equivalents, alternatives, redesigns and emulations. The existing stock and authorised aftermarket shall remain unchanged, and cannibalisation and Last-time Buy (LTB) should increase proportionally to their probabilities in the original obsolescence resolution profiles.

5.6 Obsolescence Cost Metrics (OCM) Study

5.6.1 Obsolescence Cost drivers

During the first half of the workshop the experts were encouraged to brainstorm in groups, followed by discussion among all the participants, to identify the main parameters that define the complexity of a system and influence the obsolescence resolution cost. The discussion held during this session of the workshop resulted in the experts concurring that there are four key obsolescence cost drivers:

1. Resolution approach applied to resolve the obsolescence issue. The list of resolution approaches is defined in Table 5-4.
2. Type of platform. They can be divided into five categories, which are shown as follows.
    - Space systems
    - Air systems / Safety Critical
    - Surface sea-based systems / Submersible sea-based systems
    - Mobile land-based systems (military)
    - Land-Fixed systems / Office-Industrial (consumer)
3. Requalification testing required, which depends upon the level of safety/criticality of the obsolete component, the required level of reliability and whether any legislative approvals apply.

Table 5-7 Level of Integration Assessment Based on Package Density and Coupling Level

LEVEL OF INTEGRATION		Package Density			
		Small (standalone)	Medium	Large	Very Large (fully integrated)
Coupling Level	Low	Small	Small	Medium	Medium
	Medium	Small	Medium	Large	Very Large
	High	Medium	Large	Very Large	Very Large

4. Level of Integration of the obsolete item. This is characterised by two parameters, as shown in Table 5-7:
   - o The Package Density, which is defined by two parameters (See Table 5-8):
     1. The space available in the product (e.g. LRU or assembly) that contains the obsolete item, which is a measure of how constrained the space is that the obsolete item is fitted in; either a big space or a constrained space, and
     2. The level of interaction within the obsolete item, which is a measure of the complexity within the obsolete item; either low, medium or high. It can be classified as:
        - High – Items such as: Very-Large-Scale Integration (VLSI) integrated circuits (e.g. ASIC, CPU, DSP devices) or board mounted modules.
        - Medium – Items such as: Medium-Scale Integration (MSI) or Small-Scale Integration (SSI) integrated circuits (e.g. RAM, ROM or Logic devices)
        - Low – Items such as: discrete semiconductors or passive board mounted components.

Table 5-8 Package Density Level Assessment

Package Density		Level of Interaction		
		Low	Medium	High
Space Available	Big	Small	Medium	Large
	Constrained	Medium	Large	Very Large

- The Coupling Level, which is defined by the number of interfaces that the obsolete item has with adjacent items (e.g. mechanical, optical, electrical, software or communications protocols) and the characteristics of each interface. It can be classified as follows (see Table 5-9).
  - High – mechanical or optical interfaces with high tolerances, finishes, or exotic materials requiring specialised design, manufacture, and assembly; electrical or software interfaces with demanding voltage, current, bandwidth, latency, or jitter requirements; complex communication protocols which are difficult to modify and test
  - Medium – Complex protocol and few interactions or Simple protocol and many interactions
  - Low – Simple protocol and few interactions

Table 5-9 Coupling Level Assessment

Coupling Level		**Number of Interactions**	
		Few	Many
Protocol	Simple	Low	Medium
	Complex	Medium	High

A representation of how the level of integration is defined by these parameters is illustrated in Figure 5-28. This representation and the definitions are based on the information captured at the workshop with experts, and they were further refined and validated in collaboration with three obsolescence experts.

The experts highlighted that the level of integration and type of platform will especially have an impact on the cost of redesign and emulation due to the requalification costs implied.

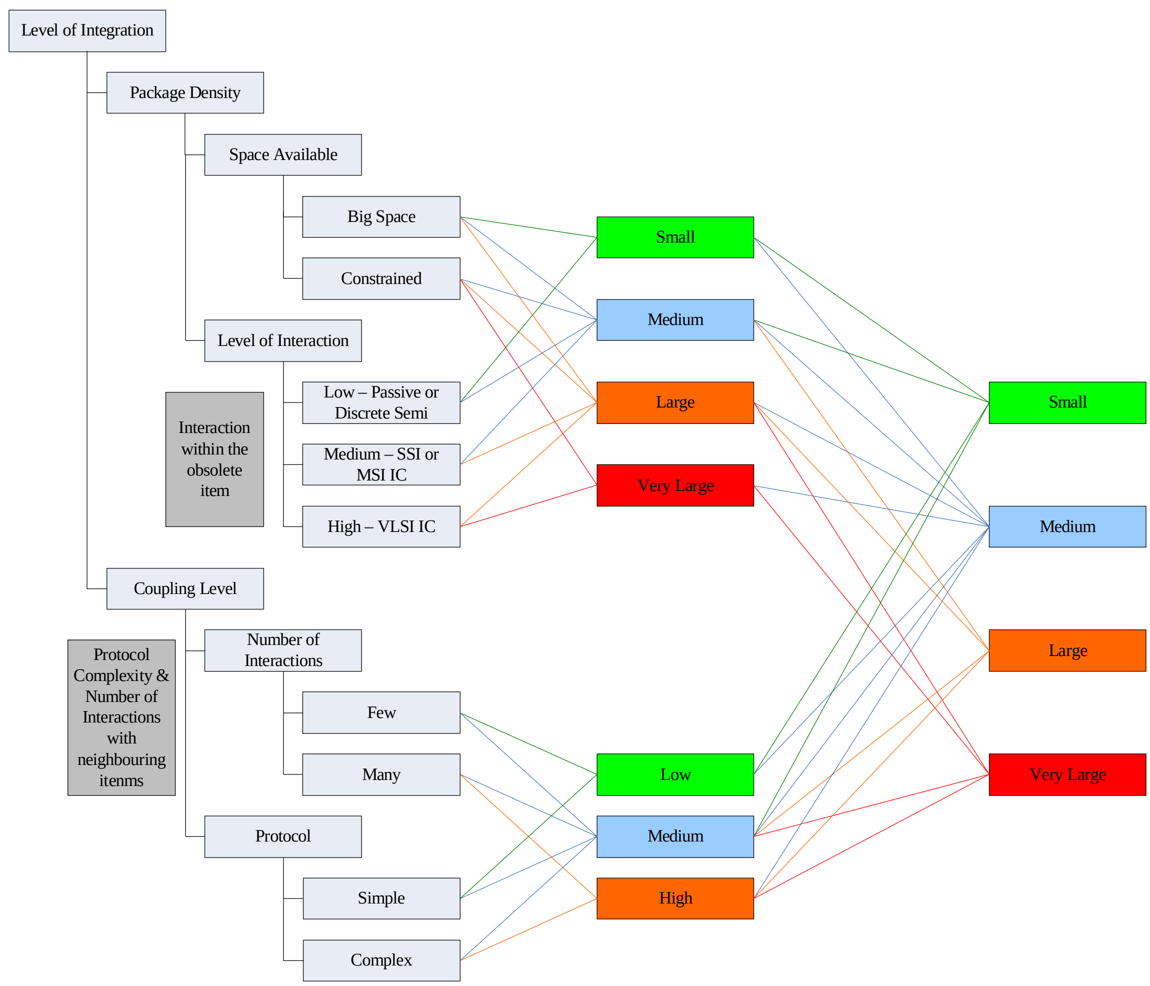


Figure 5-28 Level of Integration Assessment

5.6.2 Obsolescence Cost Metrics

Taking into account the parameters identified as cost drivers for obsolescence, the participants provided cost metrics in groups, based on their experience, the results from the “MoD – 2004 obsolescence cost metrics study” (MoD, 2004) and the discussions about this topic. Consequently, the obsolescence cost metrics concluded in this workshop are based on the expert judgement of the participants rather than on historical data.

The analysis of the cost metrics provided by each group was aggregated to produce a single set of results. These were validated with three key obsolescence experts, and their feedback was applied to give the refined metrics in Figure 5-29. The reader should note that these metrics are a consolidation of all participant organisations' expert opinions and are not attributable to any one individual or organisation.

	COST METRICS - NO REQUALIFICATION			
INTEGRATION LEVEL:	Small	Medium	Large	Very Large
Existing Stock	£ 300	£ 300	£ 300	£ 300
LTB	£ 2,000	£ 2,000	£ 2,000	£ 2,000
Cannibalisation	£ 1,700	£ 2,500	£ 3,400	£ 4,500
Equivalent	£ 3,500	£ 3,500	£ 3,500	£ 3,500
Alternative	£ 3,500	£ 3,500	£ 3,500	£ 3,500
Authorised Aftermarket	£ 4,500	£ 4,500	£ 4,500	£ 4,500
Emulation	£ 26,700	£ 150,000	£ 350,000	£ 1,900,000
Minor Redesign	£ 21,300	£ 59,000	£ 84,300	£ 298,300
Major Redesign	£ 100,000	£ 200,000	£ 400,000	£ 5,000,000

Type of Platform	FACTOR 3 (C)
Space	1.30
Air / Safety Critical	1.00
Sea/Submersible	0.73
Land-Mobile (military)	0.53
Land-Fixed (consumer) Office - Industrial	0.30

	COST METRICS - WITH REQUALIFICATION			
INTEGRATION LEVEL:	Small	Medium	Large	Very Large
Existing Stock	£ 300	£ 300	£ 300	£ 300
LTB	£ 2,000	£ 2,000	£ 2,000	£ 2,000
Cannibalisation	£ 1,700	£ 2,500	£ 3,400	£ 4,500
Equivalent	£ 3,500	£ 3,500	£ 3,500	£ 3,500
Alternative	£ 10,000	£ 10,000	£ 15,200	£ 21,500
Authorised Aftermarket	£ 13,000	£ 13,000	£ 19,800	£ 25,800
Emulation	£ 52,000	£ 193,200	£ 488,600	£ 2,690,800
Minor Redesign	£ 50,000	£ 167,400	£ 243,700	£ 549,200
Major Redesign	£ 250,000	£ 2,000,000	£ 3,400,000	£ 13,745,000

Figure 5-29 Refined Obsolescence Cost Metrics

The adjustments resulting from the validation sessions were minor for FACTOR 3, which represents the impact of the type of platform, and for most of the cost metrics. The main change was in the cost metric for emulation for very large level of integration when requalification is not required, which was reduced by £600k, from £2,500k to £1,900k. This significant modification results from the fact that in this situation (emulation for very large level of integration) it is very unusual that requalification is not required, and hence, some experts suggested cost figures that include requalification.

Based on those results, the cost metrics were parameterised according to the key cost drivers identified, as shown in Figure 5-30. In this parameterisation process, the base cost has been normalized (Q), so that these cost metrics can be used regardless of the currency and unaffected by inflation and fluctuations in the currency exchange. However, it is necessary to generate the cost metrics that will be applied to a particular project by benchmarking one value based on past experience. For instance, if it is known for a particular project that the NRE cost of solving an obsolescence issue – with no requalification required and small level of integration – by finding an equivalent is £3,500, then the base cost for minor redesign is £3,500 × 6.09 = £21,300, and the rest of cost metrics can be analogously calculated.

	NORMALISED BASE COST (Q)
Existing Stock	0.09
LTB	0.57
Cannibalisation	0.49
Equivalent	1.00
Alternative	1.00
Authorised Aftermarket	1.29
Emulation	7.63
Minor Redesign	6.09
Major Redesign	28.57

FACTOR 1 (A)	Level of Integration			
	Small	Medium	Large	Very Large
Existing Stock	1	1	1	1
LTB	1	1	1	1
Cannibalisation	1	1.47	2	2.65
Equivalent	1	1	1	1
Alternative	1	1	1	1
Authorised Aftermarket	1	1	1	1
Emulation	1	5.62	13.11	71.16
Minor Redesign	1	2.77	3.96	14
Major Redesign	1	2	4	50

Type of Platform	FACTOR 3 (C)
Space	1.3
Air / Safety Critical	1
Sea/Submersible	0.73
Land-Mobile (military)	0.53
Land-Fixed (consumer)	0.3

Requalification Required	FACTOR 4 (X)
Yes	1
No	0

FACTOR 2 (B)	Level of Integration			
	Small	Medium	Large	Very Large
Existing Stock	0	0	0	0
LTB	0	0	0	0
Cannibalisation	0	0	0	0
Equivalent	0	0	0	0
Alternative	1.86	1.86	3.34	5.14
Authorised Aftermarket	1.89	1.89	3.4	4.73
Emulation	0.95	1.62	5.19	29.62
Minor Redesign	1.35	5.09	7.48	11.78
Major Redesign	1.5	18	30	87.45

Figure 5-30 Normalised and Parameterised Obsolescence Cost Metrics

$$Cost\_Metric = Q^* \times (A + B \times C \times X) \quad (1)$$

$$Q^* = Q \times k \quad (2)$$

Where:

Q= Normalised Base Cost

Q^*= Base Cost

k= Calibration Point

$A = \text{FACTOR 1}$

$B = \text{FACTOR 2}$

$C = \text{FACTOR 3}$

$X = \text{FACTOR 4}$

The cost metrics illustrated in Figure 5-30 represent the non-recurring costs of resolving an obsolescence issue using each of the resolution approaches listed in the first column. These costs are calculated according to the parameters that characterise the obsolescence issue by applying Equation (1), combining the base cost with the four factors.

- FACTOR 1 (A) is applied to estimate the resolution cost without requalification. It depends upon the resolution approach and the level of integration.
- FACTOR 2 (B) is applied to estimate the requalification cost. It depends upon the resolution approach and the level of integration.
- FACTOR 3 (C) is applied to take into account the type of platform in the estimation of the re-qualification cost.
- FACTOR 4 (X) indicates whether requalification testing is required or not.

The calibration point (k) is the NRE cost of using a form, fit and function (FFF) replacement (either alternate or equivalent) to resolve an obsolescence issue in an air platform, with small level of integration and no requalification required. By applying Equation (2), the base cost (Q^*) can be calculated and then, Equation (1) can be used to calculate the cost metrics. It is suggested for the calibration point (k) to be linked with the approved escalation values that MoD publish periodically for use in contracts.

5.7 EEE-FORCE Cost Estimation Process

Figure 5-31 outlines how the information input to the framework is combined to estimate the NRE cost. The three main elements are:

- Number of obsolescence issues during the contracted period
- Obsolescence Resolution Profiles (ORP)
- Obsolescence Cost Metrics (OCM)

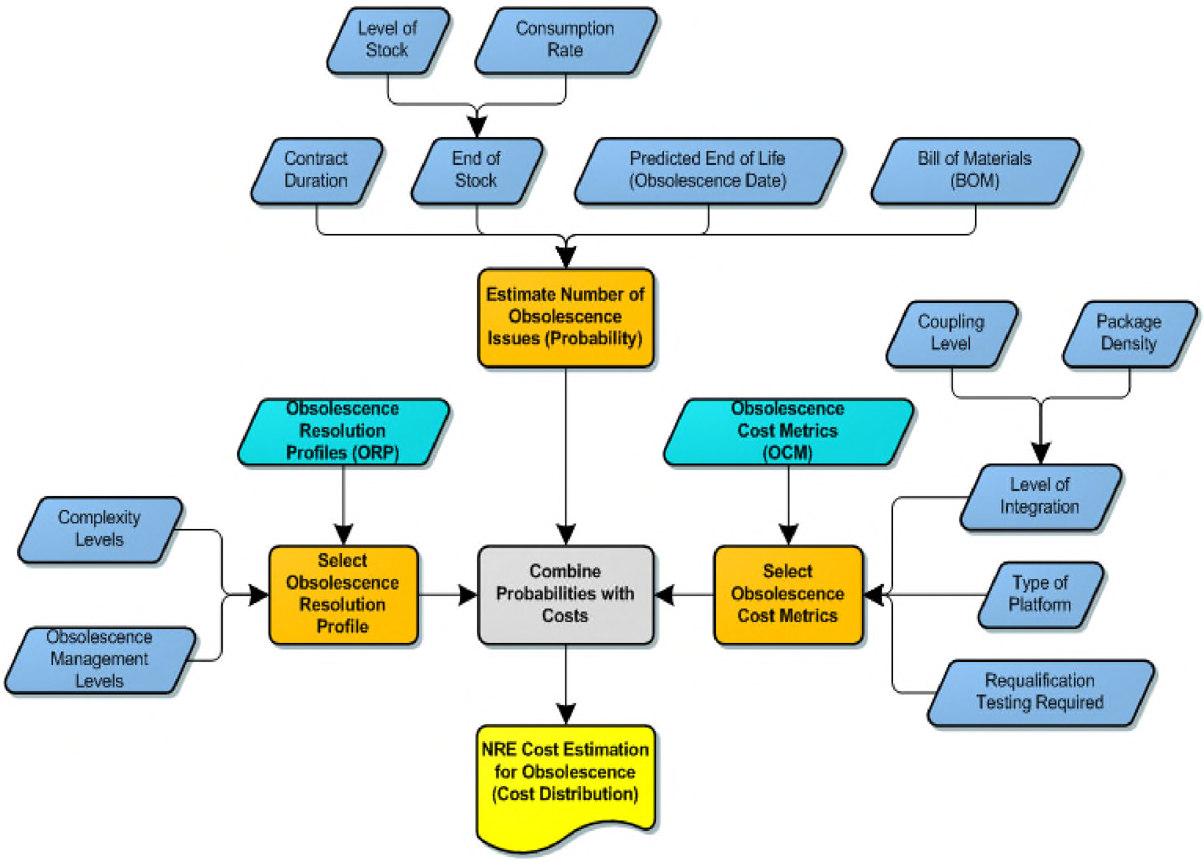


Figure 5-31 EEE Obsolescence Cost Estimating Framework Structure

The number of obsolescence issues and its probability is calculated based on the information available, which may include:

- Bill of Materials
- Contract duration
- Level of stock exclusive to the project of concern

- Consumption rate
- Predicted end of life (obsolescence date)
- Mean Time Between Failures (MTBF)
- Fleet size
- Number of same components per platform
- Percentage of scrap – It represents the percentage of items that are discarded once they fail. The rest are repaired and go back to stock.
- Probability of running out of stock during the contracted period

The consumption rate (items used per year) for each component can be input directly by the user or it can be calculated using the following formula:

$$Consumption\ Rate = \frac{Fleet\ size\ \times \#\ of\ same\ comp.per\ platf.\ \times\ \%\ of\ Scrap}{MTBF}$$

The framework combines this information with the level of stock available (exclusive to the project of concern) to estimate the date by which the stock will run out if no more is bought using the following formula:

$$Date\ Run\ out\ of\ Stock =\ Date\ Review + \frac{365\ \times\ Stock}{Consumption\ Rate}$$

If that data is not available or the stock is not exclusive to the project of concern, the user will indicate the probability of running out of stock during the contracted period based on expert judgement using the following scale:

- 100% - It is certain that will run out of stock during the contracted period
- 75% - High probability of running out of stock during the contracted period
- 50% - Medium probability of running out of stock during the contracted period
- 25% - Low probability of running out of stock during the contracted period
- 0% - It will certainly not run out of stock during the contracted period

The predicted end of life (obsolescence date) may come from an obsolescence monitoring tool or the usage of obsolescence forecasting algorithms. If they are not available, or the information related to a particular component is not included in those databases, the user can assess the probability of becoming obsolete during the contracted period based on expert judgement, using a scale analogous to the one described above.

An obsolescence issue occurs when a component becomes obsolete and runs out of stock during the contracted period. Therefore, when the user relies on expert judgement, the probability of having an obsolescence issue can be calculated using the following formula:

Probability of Obs. Issue = Probability of Becoming Obsolete during the Contracted Period × Probability of Running Out of Stock during the Contracted Period

For instance, if there is high probability of running out of stock during the contracted period (75%) and low probability of becoming obsolete during the contracted period (25%), then the Probability of Obs. Issue is 75% × 25% = 18.75%. If there is data available that allows estimation of the obsolescence date and the out-of-stock date, the probability can be derived from comparing those dates with the end of the contract.

The five steps followed to estimate the NRE cost are outlined in Figure 5-32. In Step 1, it requires the user information in terms of who is providing the information and when, in order to provide traceability for the cost estimate. Step 2 requires information about the system, including the type of platform, support contract duration, breakdown of the system into product and level of information available for each product. The framework is flexible enough to adapt to any level of information available and still provide a cost estimate, where the level of uncertainty is related to the level of information available and its reliability. For those products for which detailed information is available, it will be provided in Step 3A; whereas Step 3B will be used when little information is available for a product, and hence, expert judgement is required (Rush and Roy, 2001). In

Step 4 and Step 5, it is possible to customise and calibrate the Obsolescence Resolution Profiles and the Obsolescence Cost Metrics respectively.

The Obsolescence Resolution Profiles resulting from the ORP study can be customised to reflect better the current practice in the project for which the framework is going to be applied. Similarly, the Obsolescence Cost Metrics can be customised as well if historical data is available.

The estimated number of obsolescence issues during the contracted period is produced by the framework undertaking a risk assessment based on the contract duration, level of stock, consumption rate and predicted end of life for all the components included in the bill of materials (Figure 5-31). This risk assessment analyses the probability for each component of simultaneously running out of stock and reaching the end of life before the contract ends.

The fact that emulation, minor and major redesigns may resolve several obsolescence issues simultaneously and avoid forthcoming ones has generally been ignored in traditional cost accounting done by obsolescence management groups. Therefore it was necessary to introduce the concept of the "clustering factor" to address this issue. The clustering factor represents the number of redesigns that would be applied to resolve 100 obsolescence issues requiring a redesign. For instance, if the clustering factor is 30%, it represents that if there are ten obsolescence issues requiring a minor redesign, only three minor redesigns will be required rather than ten. As a consequence, for the calculation of the emulation, minor and major redesign costs of resolving an obsolescence issue, the cost metric calculated has to be multiplied by the clustering factor.

Figure 5-32 EEE-FORCE Cost Estimating Process

The level of uncertainty involved in the following inputs is taken into account in this framework:

- Consumption rate – a plus/minus percentage is defined around the figure provided, and a normal distribution is assumed.
- Obsolescence date – a plus/minus number of months is defined around the figure provided.
- Number of components, number of obsolete components and number of requalification testing – When detailed information is not available, the estimates will be provided together with a plus/minus percentage, and a normal distribution is assumed. This percentage will be based on the level of confidence on the figure provide.
- Cost metrics – For the base cost (Q) (see Figure 5-30), a normal distribution is considered, where the mean is the figure provided as "base cost" and the standard deviation has been extrapolated from the results of the MoD cost metrics study (MoD, 2004).
- Clustering factor – a plus/minus percentage is defined around the figure provided, and a normal distribution is assumed.

5.8 EEE-FORCE Framework Development

The framework presented in the previous Section is the result of following an iterative process of interacting with industrials experts from different organisations. The successive versions of the framework were demonstrated to them and their feedback was captured and implemented to enhance the framework.

Once the draft version of the framework was presented in a workshop with seven practitioners from four organisations from the defence and aerospace sectors (Table 5-1), their feedback was implemented. Subsequently, it was presented at the COG conference to more than 100 obsolescence experts, and also demonstrated to three experts in two different organisations. Their feedback was implemented, and the refined version of the framework was demonstrated to four obsolescence experts. Six more iterations took place, involving 13 obsolescence experts from four different organisations.

The feedback received hitherto helped to make several enhancements to the framework:

- Consideration of the whole fleet.
- Focus only on NRE costs.
- Take into account the level of integration of the product that contains the obsolete component.
- Take into account the requalification testing.
- Clarify terminology such as level of integration and product/component.
- Include uncertainty in the inputs so that a Monte Carlo simulation can be applied to estimate the uncertainty in the cost estimate.

Five more iterations took place in collaboration with four experts from four different organisations. Their comments and suggestions lead to the final version of the framework, which was further validated and evaluated by means of seven case studies, as explained in Chapter 7. The main enhancements based on this feedback are as follows.

- Correction of bugs in the algorithms.
- Level of integration based on coupling level and package density.
- Focus only on NRE costs.
- Development of the alternative ORP for the end of in-service phase.
- Development of the “clustering factor” concept.
- Take into account that the stock can be used across different project. It may have an impact on the consumption rate and stock level. Therefore, a new parameter is whether the stock of a component is exclusive for the project.
- Adapt the framework to a pre-contract scenario. Prior to starting a new support contract, it is common practice to sign a pre-contract in order to resolve the pre-existing obsolescence issues
- The user can indicate the resolution approach for an obsolescence issue if known. That increases accuracy in the estimate.

5.9 Summary and Key Observations

In this Chapter, the development of the EEE-FORCE framework was presented. This framework can be used at the bidding stage of a support contract to estimate the obsolescence NRE costs incurred during the contracted period. For the development of this framework it was necessary to carry out three studies, namely, the “Preliminary” study, the “Obsolescence Resolution Profiles” study and the “Obsolescence Cost Metrics” study. Each of them has been described in this Chapter.

In Section 5.2, the research methodology followed for the development of the EEE-FORCE framework was presented. It included a detailed description of the methodology followed in each of the studies required for the development of the framework.

In Section 5.3, the author described the requirements set by industrial practitioners for the EEE-FORCE framework.

Section 5.4 presented the results from the preliminary study, that include the distinction between “mitigation strategies” and “resolution approaches”, the definitions for the different obsolescence resolution approaches, the characterisation of the level of complexity of EEE components, and the classification of the obsolescence management (OM) into five levels of proactiveness based on the mitigation strategies employed.

In Section 5.5, an analysis of the results from each of the three phases of the “Obsolescence Resolution Profiles” study was presented. Additionally, the ORPs resulting from this study were shown. The first phase involved the application of a Delphi Study in two rounds with a panel of obsolescence experts from across the UK industry. No more than two rounds were required due to the small variation between the results of the two rounds. In the second phase, the probability of finding a FFF replacement was subdivided into Equivalent and Alternative. In the third phase, two different trends were analysed for each resolution approach. The first trend represents the evolution of the probability for each level of complexity across the different levels of proactiveness to manage obsolescence. The second trend represents the evolution of the probability for each level of proactiveness across the different levels of complexity in the obsolete component. These trends were adjusted to align them with the experts' expectations, compensating for the low sample size in the first phase (Table 5-10).

Table 5-10 Number of Experts Participating on the First Round of the Delphi Study for each Obsolescence Management Level

OBSOLESCENCE MANAGEMENT LEVEL	***NUMBER OF EXPERTS***
OM 1	5
OM 2	3
OM 3	8
OM 4	10
OM 5	12

In Section 5.6, the author explained the key obsolescence cost drivers that were identified in a workshop with 21 obsolescence experts. Additionally, the obsolescence cost metrics, based on the experience of the participants, was presented.

Section 5.7 described the overall structure of the EEE-FORCE framework, indicating the inputs required, the rationale behind the calculations, and the steps followed to estimate the obsolescence NRE costs.

In Section 5.8, the author described the iterative process followed for the development of the EEE-FORCE framework, and indicated the resulting enhancements.

The next Chapter presents the development of the "Materials - Framework for Obsolescence Robust Cost Estimation" (M-FORCE) that can be used at the bidding stage of a support contract to estimate the NRE costs incurred during the contracted period in resolving materials obsolescence issues.

THIS PAGE IS INTENTIONALLY LEFT BLANK

Chapter 6

6 COST PREDICTION OF MATERIALS OBSOLESCENCE RESOLUTION

6.1 Introduction

In the previous Chapter, the development of the EEE-FORCE framework was described. This framework focused on the obsolescence of EEE components. For the last two decades there has been a significant amount of research on the area of EEE components obsolescence, because the increasingly short life-cycle of this type of components is hindering the sustainability of the systems if not managed properly. However, the obsolescence problem is not restricted to EEE components, and although mechanical components have usually longer life cycles, they are still likely to become obsolete during the in-service phase (Howard, 2002). In general, when a mechanical component becomes obsolete, an alternative can be easily manufactured based on the original design/drawings or applying reverse engineering if these were unavailable. However, if the reason is that the material has become obsolete, then it may be more arduous to resolve, as it can only be done by the Design Authority (DA). Therefore, materials obsolescence is the key reason for obsolescence issues in mechanical components. As explained in Chapter 2, there is a lack of research in the area of materials obsolescence to understand the causes, impact, and mitigation and resolution strategies to manage it.

This Chapter provides an understanding about materials obsolescence and describes the development of the "Materials - Framework for Obsolescence Robust Cost Estimation" (M-FORCE), which can be used to estimate, at the bidding stage, the NRE cost of resolving materials obsolescence issues during the contracted period within the in-service phase. This framework is further developed into an MS Excel-based application named "Materials - Framework for Obsolescence Robust Cost Estimation" (M-FORCE). It has been developed in collaboration with several organisations in the defence and aerospace sector in UK, and has been customized for two different types of platform: aerospace and ammunition.

This Chapter has been organized as follows. Section 6.2 provides a description of the research methodology applied to capture the key concepts about materials obsolescence and to the development of the M-FORCE framework. In Section 6.3, the key concepts about materials obsolescence are described and in section 6.4 the materials obsolescence cost estimating framework (M-FORCE) is presented. A description about the logic developed for ammunition and air platforms is also provided.

6.2 Detailed Research Methodology

The research methodology followed for the development of the M-FORCE framework is shown in Figure 4-3. The first step was to gain a better understanding about materials obsolescence, how it is currently managed in industry and the level of information available at the bidding stage. The next step was the development of the key concepts that will be used in the framework, analogously to the EEE-FORCE. Based on them, the M-FORCE framework was developed following an iterative process in which the experts from industry reviewed it and suggested enhancements that were implemented accordingly.

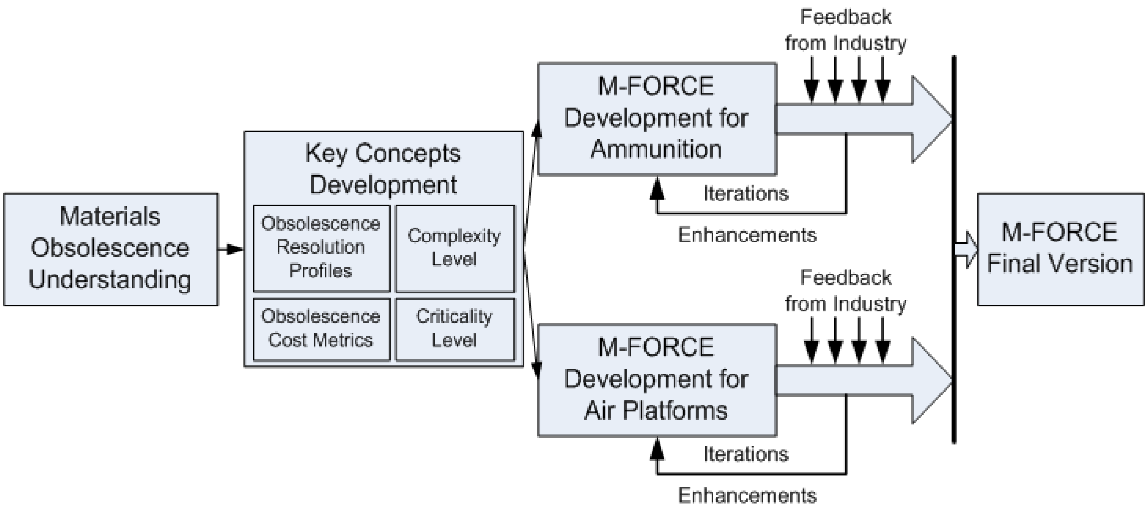


Figure 6-1 Research Methodology for M-FORCE Development

6.2.1 Detailed Research Methodology for Gaining an Understanding about Materials Obsolescence

Apart from the literature review carried out, which is described in Chapter 2, it was necessary to arrange interviews and workshops with experts from industry to gain a good understanding about the differences between obsolescence in EEE components and materials, identifying the peculiarities of the latter. Four interviews/workshops, lasting for three to four hours, were carried out and a total of seven materials obsolescence experts from three different organisations participated (see Table 6-1). Typically, from one to four experts were simultaneously taking part in each interview/workshop to stimulate discussion and reach consensus in their responses. During the interviews, a semi-structured questionnaire (Appendix A.4) was used. Its development was based on the information collected in previous meetings with obsolescence experts and the information found in literature. Due to the exploratory purpose of these interviews, it is justified the usage of a semi-structured questionnaire because it combines open questions, to gain an overall understanding about the concept of materials obsolescence, with others more specific about the current practice in materials obsolescence management. That questionnaire was piloted with an engineering manager from industry (31 years experience) to ensure the quality for the interviews. Examples of those questions are shown as follows.

- What are the main reasons why a material becomes obsolete?

- Do you forecast obsolescence issues? How?
- What are the possible resolution strategies that can be applied to resolve a material obsolescence issue?
- Is there any mitigation strategy that can be applied to minimise the impact or probability of having a material obsolescence issue?
- What do you regard as the key cost drivers for materials obsolescence?

The responses were taken down during the interviews and subsequently they were analysed by identifying similarities, differences and unique responses across the different participants. The outcomes from this analysis are described further along in this Chapter.

Table 6-1 Experts Participating in Materials Obsolescence Interviews

Expert Number	Organisation	Job Role	Years of Experience in Materials	Years of Experience in Obsolescence
A	ORG_J	Obsolescence Manager	26	4
B	ORG_J	Materials Engineer	26	10
C	ORG_J	Materials Engineer	45	10
D	ORG_J	Product Qualification Manager	35	3
E	ORG_K	Obsolescence Manager	23	4
F	ORG_K	Obsolescence Technician	5	2
G	ORG_L (ACADEMIC)	Head of Materials Department	33	2

6.2.2 Detailed Research Methodology for Development of M-FORCE

The information captured during the previous phase led to the decision of customising the development of the M-FORCE framework for ammunition and air-based platforms. The differences between these two environments justify the usage of slightly different concepts and processes for the cost estimation of materials obsolescence. Therefore, the development of each version of the M-FORCE was carried out in collaboration with two set of experts, specialised in either environment.

Three of the experts (A, B and C) included in Table 6-1 participated in two five-hour workshops focused on the development of the M-FORCE for the air domain (M-FORCE AIR). Based on the information collected during the previous phase, a set of concepts were defined, including the level of integration, the complexity levels, the criticality levels, the obsolescence resolution profiles and the cost metrics. The M-FORCE was developed following a similar logic to the EEE-FORCE but based on these concepts. During the workshops, these concepts were refined and the M-FORCE was enhanced accordingly, in an iterative manner.

Analogously, experts E and F included in Table 6-1 participated in two five-hour workshops focused on the development of the M-FORCE for ammunition (M-FORCE AMMO). In this environment it was more suitable to merge the obsolescence resolution profiles and the cost metrics into one single table, due to the nature of the materials used in ammunition. The complexity levels, the level of integration and the criticality levels are also customised for this environment. These concepts were refined and the M-FORCE was enhanced iteratively during the workshops.

A key difference between the M-FORCE AIR and the M-FORCE AMMO is the fact that for the first one, a “weight matrix” was required to generate the cost metrics. The “weight matrix” combines the relative importance of the key cost drivers identified, namely, the level of integration, the complexity level, the criticality level and the resolution approach. The “weight matrix” was developed in collaboration with an expert in materials obsolescence (expert B in Table 6-1), by taking him through a pairwise comparison of the relative importance between each of the cost drivers and the levels for each of them. An AHP software package called "Expert Choice 11" was used in this process to facilitate the pairwise comparison and calculations. The results were validated with other two experts in materials obsolescence (expert A and C in Table 6-1).

6.3 Obsolescence in Materials

This section presents the results from the "Understanding Materials Obsolescence" stage. This is a summary of the information gathered in the workshops and interviews. The analysis revealed that the views of the different experts were congruent and complementary, as some were specialised on aerospace and others on ammunition.

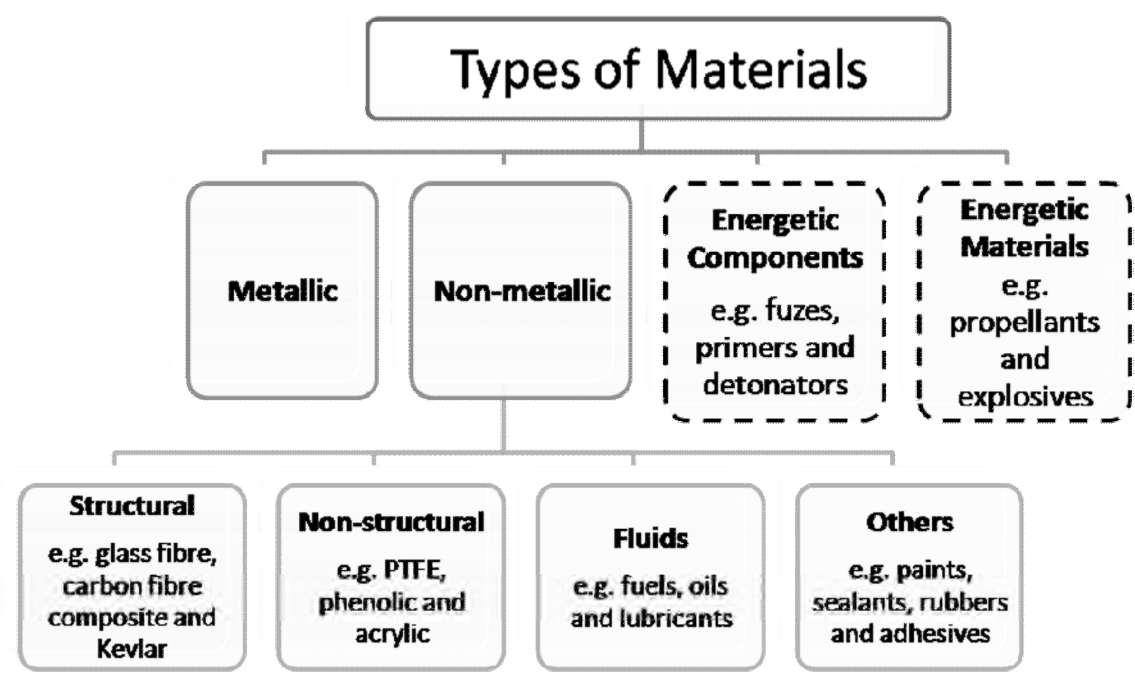


Figure 6-2 Materials Classification

As shown in Figure 6-2, the different types of materials can be broadly classified into two categories: metallic and non-metallic. Metallic materials are grouped by chemical composition, and their characteristics (e.g. fatigue, strength, corrosion resistance…) are usually tabulated. Non-metallic materials can be classified into four categories: structural (e.g. glass fibre, carbon fibre composite and Kevlar), non-structural (e.g. PTFE, phenolic and acrylic), fluids (e.g. fuels, oils and lubricants) and others (e.g. paints, sealants, rubbers and adhesives). In the ammunition context, two additional categories can be considered: energetic components (e.g. fuzes, primers and detonators) and energetic materials (e.g. propellants and explosives).

A material becomes obsolete when it is no longer available from the suppliers to the original specification, or its procurement is not affordable. The key reasons why materials become obsolete during the in-service phase are as follows.

- The main reason is that just small amounts are required. This lack of demand for a particular material's specification makes it no longer profitable for the supplier to produce it. Manufacturers are unwilling to pull resources from high volume, high demand, high margin businesses to serve a historically low volume, low demand, low margin business.
- The minimum order quantity (MOQ) can be far larger than the amount of material required. New government regulations, related to Safety Health and Environmental legislation, can trigger obsolescence issues because the material usage is directly banned or because the use of other materials or substances, such as oils and lubricants, required in the manufacturing process of that material is banned (Howard, 2002). This is quite common for non-metallic materials.
- Changes in suppliers that imply a loss of skills or modifications in the manufacturing process can derive on changes in the original specifications (especially for non-metallic materials). There are different standard specifications (e.g. British, American and European) which are continuously evolving, so that a superseded specification turns into a new obsolescence issue for the materials that conform to it (Figure 6-3).

The main differences between the aerospace and the ammunition context regarding materials obsolescence are that ammunition does not require maintenance or upgrade and also the production of ammunition is simpler, so it has less integration issues.

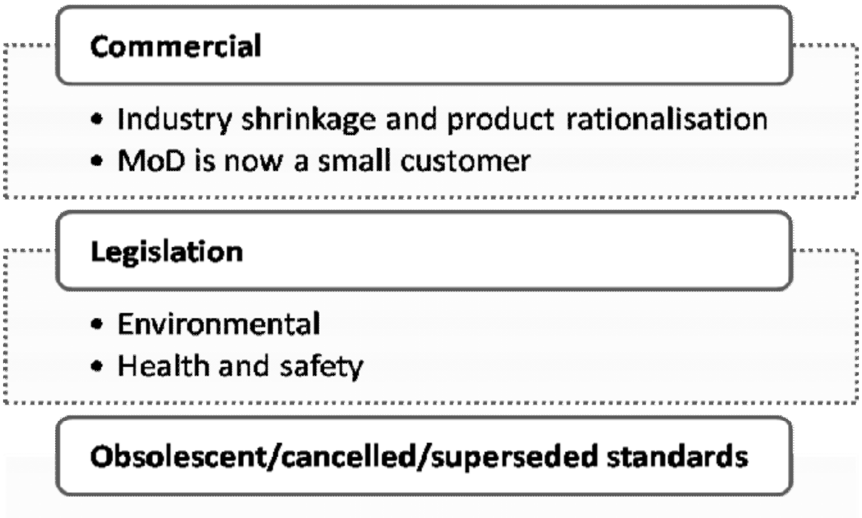


Figure 6-3 Common causes of materials obsolescence

6.3.1 Obsolescence Management

Currently in the defence sector, few organisations have standard procedures in place to manage materials obsolescence proactively. All the experts interviewed agreed that materials obsolescence is commonly managed reactively and as a result, readiness and supportability effects are not apparent until component managers try to buy the part (Howard, 2002). As a result of this research, it has been identified a set of mitigation strategies:

- Plan ahead – Use of technology roadmaps
- Participate in committees – Find out about new regulations earlier
- Keep good relationships with suppliers
- Design the system endeavouring to use well established materials – Minimising the risk associated with using bespoke materials

These strategies may reduce the risk of having an obsolescence issue and allow extra time to tackle the problem.

In order to resolve an obsolescence issue, there are mainly two possibilities: to find a form, fit and function (FFF) replacement or to redesign it, as contrasted with the EEE components, where eight different obsolescence resolution approaches can be applied. The resolution selected will depend on the remaining life of the system and the characteristics of the obsolete material. A priori it is preferred to find a FFF replacement, for which it is necessary to take some considerations:

- Make sure it keeps the same performance requirements.
  - Fabrication/application constraints
  - Mechanical
  - Operating environments
- Make sure it complies with health, safety and environmental legislation.
- Ensure continuation of future supply
  - Open specification
  - Specify performance requirements
- Consider that it may not be a single solution for all uses

6.4 Concepts for the M-FORCE Development

The literature review presented in Chapter 2 and discussions with materials obsolescence experts (see Table 6-1) from different organisations in the defence and aerospace sector and members of the Component Obsolescence Group (COG) have revealed a need for a framework that can be systematically used to estimate the cost of materials obsolescence during the in-service phase at the bidding stage. The diagram that represents the framework developed is shown in Figure 6-4.

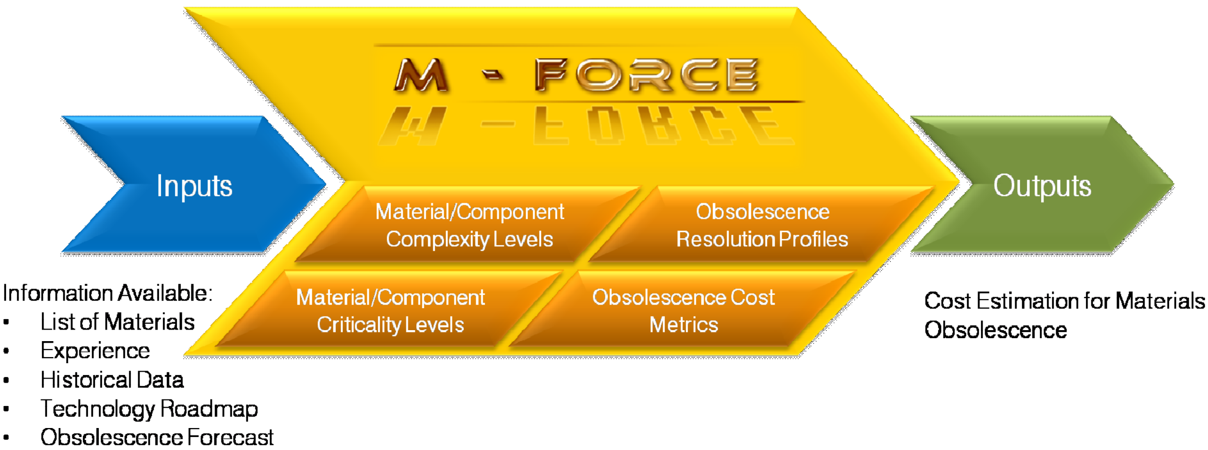


Figure 6-4 Materials Obsolescence Cost Estimating Framework (M-FORCE) Diagram

For the development of this framework it was necessary to properly define the following concepts:

6.4.1 Obsolescence Issue

All the experts agreed that an obsolescence issue arises when the material becomes obsolete, that is to say, it is no longer available from the suppliers to the original specification, or its procurement is not affordable, and there is no stock available of that material. In general, it is challenging to store enough stock of material during the in-service phase in order to overcome possible obsolescence issues due to the following reasons:

- Most of the non-metallic materials are affected by the “shelf-life”, which is defined by the United States Department of Defense (DoD) Shelf-Life Program as “the total period of time beginning with the date of manufacture, date of cure (for elastomeric and rubber products only), date of assembly, or date of pack (subsistence only), and terminated by the date by which an item must be used (expiration date) or subjected to inspection, test, restoration, or disposal action; or after inspection/laboratory test/restorative action that an item may remain in the combined wholesale (including manufacture's) and retail storage systems and still be suitable for issue or use by the end user” (DoD, 2003). This prevents the purchase and storage of enough material to cover the whole in-service phase, as this is usually a lengthy period (30 years or more).
- The stock of metallic materials is usually classified into different sizes, thicknesses and shapes. Therefore, the amount of stock required for each material becomes much higher due to the huge variety of shape characteristics.

6.4.2 Criticality Level

The DoD defines that an item is considered critical when one or more of the following criteria are met (DoD, 2003):

- **Critical chemically**. Items which are of such nature that any degree of deterioration (in the form of corrosion, stain, scale, mold, fungi, or bacteria) caused by oxygen, moisture, sunlight, living organisms, and other contaminants which are time or temperature dependent, will result in premature failure or malfunction of the item or equipment in which the item is installed or with which the item interfaces.
- **Critical physically**. Items that would become unfit for use as a result of physical action on the item or any integral surfaces thereof. This includes, but is not limited to items having a surface finish of 64 microinches root mean square or less, items which have surfaces that mate with surfaces of other parts, optical and reflective devices having highly polished surfaces, items requiring a high degree of cleanliness, and items requiring special protection against shock, vibration, or abrasion.
- **Critical application**. Items that, either in assembly or operation, provide an essential attribute to attaining critical military objectives.

According to this, and based on the discussion that the experts had during the workshops/interviews, it was agreed that, for an air platform, the criticality level should be based on the application of the item:

- **High Criticality**. Items that provide an essential attribute to attaining critical military objectives
- **Medium Criticality**. Items required but not essential for the operation of the system.
- **Low Criticality**. Accessory items, which are not required but not essential for the operation of the system.

In the ammunition environment, the experts agreed that all of the components/materials can be considered critical, based on the application, in that there is nothing that can be removed that would allow the product to continue to be sold or used. Therefore, in the ammunition context, the level of criticality is defined as in terms of the function of the product or its safety and storage:

- **High Criticality**. Items critical to function.
  e.g. Energetic materials, Energetic Components, Metallic components
- **Medium Criticality**. Items critical to safety/storage.
  e.g. Paints, Lacquers, Adhesives, Chemicals
- **Low Criticality**. Manufacturing aids.
  e.g. Non metal parts (paper discs, O rings)

6.4.3 Complexity Level

The experts agreed that the complexity is defined according to the type of material. The complexity level classification for materials in the aerospace industry is as follows.

- **Low Complexity**
  - Common Metallics
  - Non-Metallic Non-Structural
- **Medium Complexity**
  - Exotic Metallics (e.g. Aluminium-Lithium alloy, Beryllium alloy, Titanium)
  - Non-Metallic Structural
  - Fluids (Fuels, Oils, Lubricants)
  - Others (Paints, sealants, rubbers, adhesives) with standard specifications
- **High Complexity**
  - Others (Paints, sealants, rubbers, adhesives) without standard specifications

The types of materials used in the aerospace industry differ from those used in the ammunition environment. Therefore, it is convenient to make another complexity level classification specific for ammunition. The experts concurred that complexity is assessed in terms of ease of procurement, potential suppliers, specification and tolerance within the specification (e.g. for energetics, even variations within a specification can cause a production process to fail or require qualification).

- **High Complexity** (high specification, tight tolerances, limited suppliers)
  - Energetic materials
  - Energetic components
- **Medium Complexity**
  - Exotic Metallics
  - Non-Metallic
  - Others (Paints, Lacquers, Adhesives)
  - Chemicals (chemical mixtures, explosive compatible materials)
- **Low Complexity**
  - Chemicals (e.g. solvents)
  - Common Metallics

6.4.4 Level of Integration

According to the experts, the level of integration of the obsolete component/material in the aerospace industry can be classified as follows.

- **Low Level of Integration**

  It represents an individual component/material that has low interaction with the rest of the system. This feature ensures total interchangeability.
- **Medium Level of Integration**

  It represents a component/material assembled to others with which it interacts. In this case, interchangeability depends on the compatibility of the alternative with the assembly.
- **High Level of Integration**

  It represents a component/material that heavily interacts with the rest of the system. This fact constrains the possibility of replacing it without having an impact on other parts of the system. It may happen when the interaction is not only mechanical but also electrical.

In the ammunition environment, the main concerns within the design are as follows.

- Strength - Projectiles have to survive the high G-forces of gun launch.
- Weight - Weight of projectile and charges is generally governed by pressure budgets of the weapon system.
- Space Envelope - Interfaces with the weapon system, and aerodynamics are important.

Product design generally has to optimise the performance of the product and weapon system within those limiting constraints. Any change which affects other components within the product, the overall performance of the product, or the overall performance of the weapon system in which it is used has to be assessed. The level of integration in the ammunition environment is related to those issues and can be classified as follows.

- **Low Level of Integration.** Components or materials which if changed would be expected to have no or very little affect on performance or reliability of the product or on the weapon system. E.g. Paper / Textile components; low strength metal components; components not subject to high G forces or high pressures.
- **Medium Level of Integration.** Components or materials which if changed would be expected to reduce performance or reliability of the product, but not affect the weapon system. E.g. Energetic materials & components.
- **High Level of Integration.** Components or materials which if changed would be expected to affect the performance of the weapon system and performance or reliability of the product. E.g. Structural components subject to high G forces or high pressures.

According to the experts in materials obsolescence that participated in this study (see Table 6-1), in contrast with EEE components obsolescence, the level of proactiveness deployed in managing materials obsolescence does not have a significant impact on cost at the project level. However, if materials obsolescence is managed proactively across several projects, this can result in a cost reduction because resolutions can be shared. Therefore, the level of proactiveness for managing obsolescence is not taken into account in the M-FORCE framework.

6.5 Materials - Framework for Obsolescence Robust Cost Estimation (M-FORCE)

A total of five experts have participated on the development of this framework. Their details are indicated in Table 6-1 (experts A, B, C, E and F), including years of experience and job role. There are several differences between ammunition and air platforms, which make the cost estimation process different for each one. The key difference is that the nature of the materials is different between them, and hence, the parameters that define the characteristics of an obsolescence issue for ammunition are correlated, whereas in an air platform they are independent. Therefore, the range of different obsolescence issues for air platforms is much wider than for ammunition. Consequently, the M-FORCE framework has been customised for the aerospace industry and for ammunition. The details related to each one are provided as follows.

6.5.1 M-FORCE for Air Platform

The usage process for this framework is divided into five steps, as shown in Figure 6-5. The user can feed the cost estimating framework with the data available from the system to be supported, by means of the first 3 steps. In step 4, the user can customise the obsolescence resolution profile, and finally in step 5, the user can customise the obsolescence cost metrics. These two concepts are explained further down in this section. The output will be a cost estimate of the materials obsolescence in the system during the contracted period.

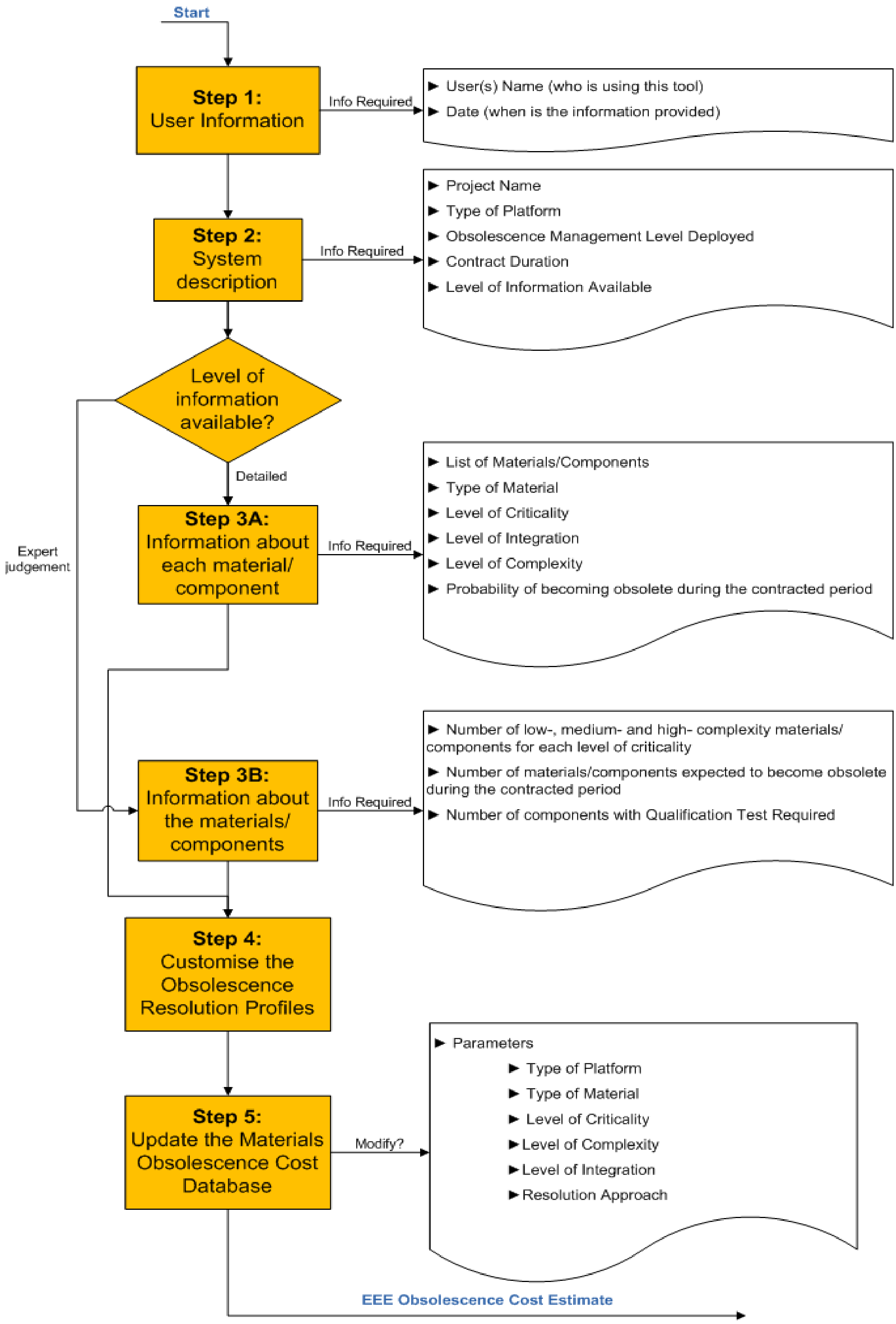


Figure 6-5 M-FORCE Process

The process depicted in Figure 6-5 is described in more detail as follows.

6.5.1.1 STEP 1

The first step requires information about who is going to use the framework and when. This allows more traceability of the origin of the information input to the framework.

6.5.1.2 STEP 2

The information required at this step is related to the project, obsolescence management level deployed, type of platform that will be supported and the duration of the supporting contract. The user is requested to indicate the level of information available. If the list of materials/components is available, the user will provide it at step 3A. Otherwise, step 3B shall be used instead.

6.5.1.3 STEP 3A

The list of materials/components shall be input at this step. The information required for each component is related to the level of complexity, the level of criticality, the level of integration and the probability of becoming obsolete during the contracted period. This assessment would be based on the information available from technology roadmaps, committees and experience.

6.5.1.4 STEP 3B

If the list of materials/components is not available, it is necessary to base on experience and/or supplier information. The information required is related to the number of components estimated for each level of criticality, complexity and integration. It is also necessary to indicate the percentage of them that is expected to become obsolete during the contracted period.

6.5.1.5 STEP 4

The obsolescence resolution profile represents the probability of using each resolution approach to tackle an obsolescence issue for a material/component.

This probability depends mainly on the level of complexity, that is to say, the type of material. The default figures represented in these profiles have been derived from a workshop with three experts (A, B and C from Table 6-1) on the materials obsolescence area from industry, and subsequently refined and validated on another workshop with experts B and C (see Figure 6-6). However, the user has the possibility to customize the probabilities if necessary.

AIR PLATFORM	COMPLEXITY LEVEL		
	Low	Medium	High
FFF replacement - Low effort	90.0%	50.0%	30.0%
FFF replacement - High effort	9.0%	40.0%	50.0%
Minor Redesign	0.9%	9.9%	19.8%
Medium Redesign	0.1%	0.1%	0.2%

Figure 6-6 Obsolescence Resolution Profile

6.5.1.6 STEP 5

Based on the interviews/workshops with experts, the four key cost drivers identified are:

- Complexity Level (Low / Medium / High)
- Criticality Level (Low / Medium / High)
- Integration Level (Low / Medium / High)
- Type of Resolution Approach
    - FFF replacement – Low Effort
    - FFF replacement – High Effort
    - Minor Redesign
    - Major Redesign

The 108 different combinations of these parameters represent the range of possible obsolescence issues. It has been carried out an exercise with an expert on materials obsolescence (B from Table 6-1) in order to assess the relative weight of each parameter using an AHP software package called “Expert Choice 11”. Two steps were followed in this process. Firstly, a pairwise comparison was undertaken between the four cost drivers.

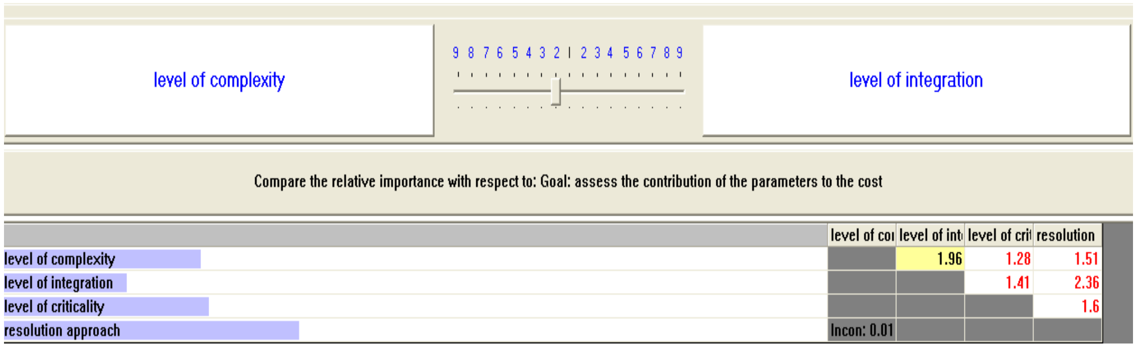


Figure 6-7 Pairwise Comparison of Cost Drivers

Figure 6-7 shows at the top an example of how the pairwise comparison between the level of complexity and the level of integration can be carried out by means of a Likert scale. The inconsistency factor, shown in the figure, indicates that there is incongruence between the results of the pairwise comparisons if it is higher than 0.1. In this case the factor value is 0.01<0.1, so the assessment is consistent. Figure 6-8 provides the results of comparing the relative importance (weight) of each cost driver.

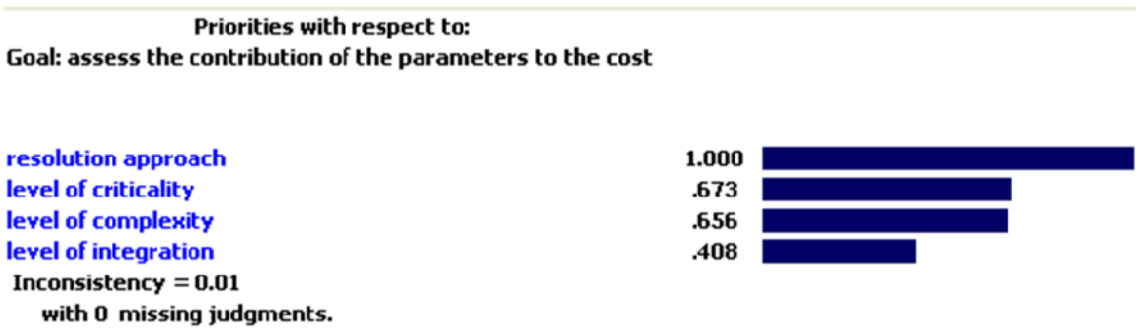


Figure 6-8 Results of Pairwise Comparison of Cost Drivers

Subsequently, a pairwise comparison was performed between the different levels for each of the four cost drivers. Figure 6-9 shows at the top an example of how the pairwise comparison between the low and medium levels of complexity can be carried out by means of a Likert scale.

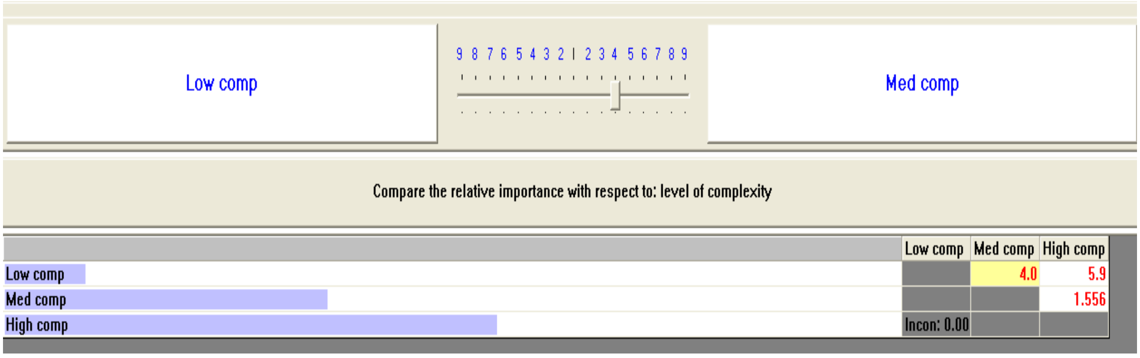


Figure 6-9 Results of Pairwise Comparison of Different Levels for Each Cost Driver

The final results of the pairwise comparison are shown in Figure 6-10 as a tree diagram, and the synthesis of the results from both stages is shown in Figure 6-11, aggregating the weights for each branch of the tree.

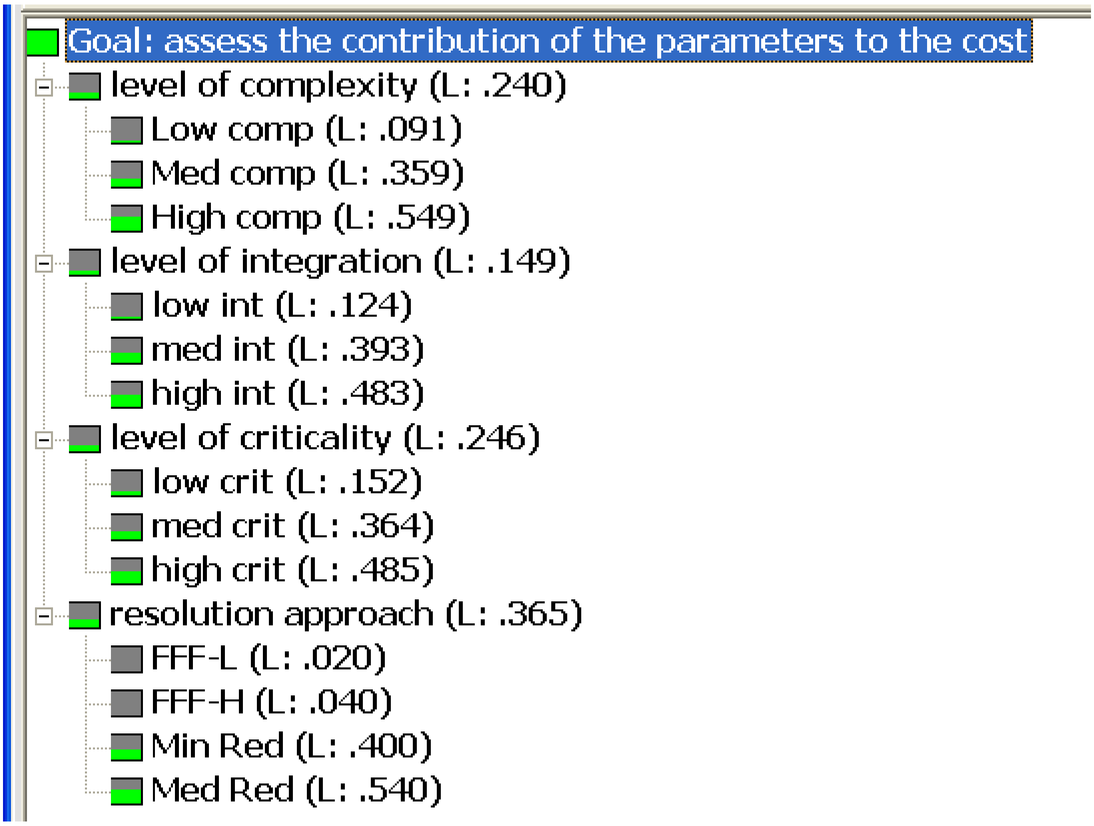


Figure 6-10 Final Results of the Pairwise Comparison

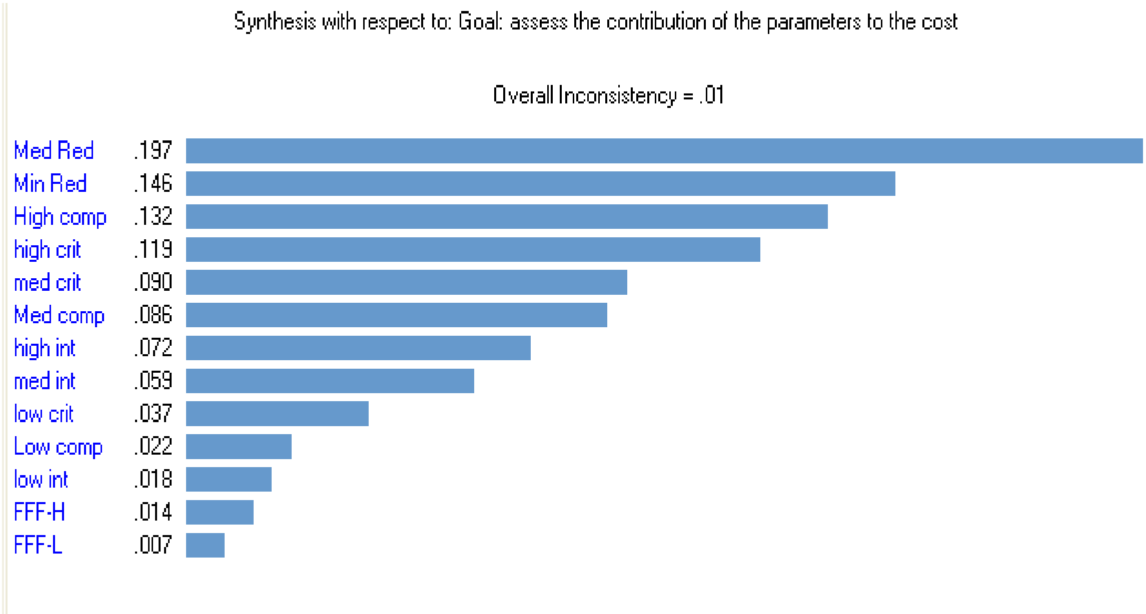


Figure 6-11 Synthesis of Results of the Pairwise Comparison

The combination of weights resulted in a weight matrix (see Figure 6-12), which varies proportionately to the obsolescence cost. The obsolescence cost metrics can be derived from the weight matrix by applying a calibration point. This would be a known cost of solving a particular obsolescence issue characterized by the four cost drivers. For instance, the calibration point could be the cost of solving an obsolescence issue finding a FFF replacement (with low effort) for a low complexity, low integration and low criticality material.

	COMPLEXITY	LOW	LOW	LOW	LOW	HIGH	HIGH	HIGH	HIGH	HIGH
	CRITICALITY	LOW	LOW	LOW	MEDIUM	MEDIUM	MEDIUM	HIGH	HIGH	HIGH
	INTEGRATION	LOW	MEDIUM	HIGH	LOW	MEDIUM	HIGH	LOW	MEDIUM	HIGH
RESOLUTION	FFF REPLACEMENT - LOW EFFORT	72	192	240	156	2080	2600	1020	2720	3400
	FFF REPLACEMENT - HIGH EFFORT	144	384	480	312	4160	5200	2040	5440	6800
	MINOR REDESIGN	1440	3840	4800	3120	41600	52000	20400	54400	68000
	MEDIUM REDESIGN	2160	5760	7200	4680	62400	78000	30600	81600	102000

Figure 6-12 Weight Matrix for Air Platform

The results of the development of the M-FORCE framework for air platform including: the concepts developed, the figures of the Obsolescence Resolution Profile and the figures of the Weight Matrix, were further validated with experts from different organisations, as explained in succeeding Chapters.

6.5.2 M-FORCE for Ammunition

The usage process for this framework is divided into four steps. The user can feed the cost estimating framework with the data available from the system to be supported, by means of the first three steps. These three steps are analogous to those described for the air platform. The only difference in Step 2 is that the user can indicate the life cycle for each type of material. The default life cycle duration for each type has been derived from a workshop with two experts on materials obsolescence (D and E from Table 6-1) and is shown as follows.

- Long Life-Cycle materials (25 years life-cycle)
    - Metallic (Shell bodies; Containers)
    - Non Metallic parts (Cotton bags; Plastics)
    - Energetic Components (Fuzes; Primers; Detonators)
- Medium Life-Cycle materials (12.5 years life-cycle)
    - Energetic Materials (Propellants; Explosives)
- Short Life-Cycle materials (5 years life-cycle)
    - Other Materials (Adhesives; Paints; Lacquers; Chemicals)

6.5.2.1 STEP 4/5

As it was indicated above, there is correlation between the parameters that define an obsolescence issue in ammunition. The type of platform and the type of material are the independent variables, and the rest of parameters are defined accordingly. There are three types of ammunition platform:

- Large Calibre Ammunition (Artillery, Tank, Mortar)
- Medium Calibre Ammunition (20-40 mm)
- Small Calibre Ammunition (5.5-7.62 mm)

There are five types of material:

- Metallic (Shell bodies; Containers)
- Non Metallic parts (Cotton bags; Plastics)
- Energetic Components (Fuzes; Primers; Detonators)
- Energetic Materials (Propellants; Explosives)
- Other Materials (Adhesives; Paints; Lacquers; Chemicals)

Therefore, in theory, the 15 combinations of these parameters define the range of possible obsolescence issues. However, in reality, some of those combinations can derive in different set of parameters (Complexity Level; Criticality Level; Integration Level), and hence, a different resolution approach and different obsolescence cost.

By means of a workshop with two experts on materials obsolescence for ammunition (D and E from Table 6-1), it has been defined the spectrum of feasible combinations of parameters, resulting into 23 different combinations (Table 6-2).

There are seven combinations of type of platform and type of material that will define univocally the rest of parameters, resolution approach and cost. Each of the other eight combinations split into two different sets of parameters, resolution approach and cost. The probability associated to each set of parameters has been defined by the experts based on their experience.

Table 6-2 Materials Obsolescence Cost Metrics for Ammunition

#	Type of Platform	Type of Material	Level of Criticality	Level of Complexity	Level of Integration	Resolution Approach	NRE Cost	Probability
1	Large Calibre	Energetic Components	High	Medium	High	FFF - High effort	£200,000	100%
2	Large Calibre	Energetic Materials	High	Medium	High	FFF - High effort	£500,000	100%
3	Large Calibre	Metallic	High	Medium	High	FFF - High effort	£400,000	90%
4	Large Calibre	Metallic	High	Medium	Medium	FFF - High effort	£300,000	10%
5	Large Calibre	Non Metallic parts	Low	Low	Low	FFF - Low effort	£25,000	85%
6	Large Calibre	Non Metallic parts	Low	Low	Medium	FFF - Medium effort	£50,000	15%
7	Large Calibre	Other	Medium	Medium	Low	FFF - Low effort	£10,000	85%
8	Large Calibre	Other	Medium	Medium	Medium	FFF - Medium effort	£30,000	15%
9	Medium Calibre	Energetic Components	High	Medium	High	FFF - High effort	£150,000	100%
10	Medium Calibre	Energetic Materials	High	Medium	High	FFF - High effort	£200,000	100%
11	Medium Calibre	Metallic	High	Low	High	FFF - High effort	£150,000	60%
12	Medium Calibre	Metallic	High	Low	High	FFF - Medium effort	£50,000	40%
13	Medium Calibre	Non Metallic parts	High	Medium	High	FFF - High effort	£150,000	60%
14	Medium Calibre	Non Metallic parts	Low	Low	Low	FFF - Low effort	£25,000	40%
15	Medium Calibre	Other	Medium	Medium	Low	FFF - Low effort	£10,000	75%
16	Medium Calibre	Other	High	Low	Medium	FFF - Medium effort	£30,000	25%
17	Small Calibre	Energetic Components	High	Medium	High	FFF - High effort	£40,000	100%
18	Small Calibre	Energetic Materials	High	High	High	FFF - High effort	£60,000	100%
19	Small Calibre	Metallic	Medium	Low	High	FFF - High effort	£20,000	100%
20	Small Calibre	Non Metallic parts	Low	Medium	Low	FFF - Low effort	£5,000	90%
21	Small Calibre	Non Metallic parts	Low	Medium	Medium	FFF - Medium effort	£15,000	10%
22	Small Calibre	Other	Medium	Medium	Low	FFF - Low effort	£10,000	80%
23	Small Calibre	Other	Low	Low	Low	FFF - Medium effort	£30,000	20%

6.6 Summary and Key Observations

In this Chapter, the development of the M-FORCE framework was presented. This framework can be used at the bidding stage of a support contract to estimate the NRE costs incurred during the contracted period to resolve materials obsolescence. The M-FORCE framework has been customised for the aerospace and ammunition context, due to their different characteristics. For the development of this framework, it was necessary to carry out a study across industry to understand the features of materials obsolescence in advance.

In Section 6.2, the research methodology followed for the development of the M-FORCE framework was presented. It included a detailed description of the methodology followed to gain a better understanding about materials obsolescence.

In Section 6.3, the author presented the results from the preliminary study, including a classification of the different types of materials, the most common causes of materials obsolescence and the current practice in materials obsolescence management in the defence sector.

Section 6.4 presented the key concepts defined for the development of the M-FORCE framework, namely, the criticality level, the complexity level and the level of integration.

Section 6.5 described the steps proposed in the M-FORCE for the cost estimation of obsolescence, highlighting the differences in the process required in the aerospace and ammunition context. The reasons for these differences were explained and the results from the Materials Obsolescence Resolution Profile study, Weight Matrix for air platform and Materials Obsolescence Cost Metrics for ammunition were presented.

In the following Chapter, the author describes the implementation of the EEE-FORCE framework in an Excel-based tool and its subsequent validation by means of seven case studies with current projects across the defence and aerospace industry, as well as qualitative validation with experts from different sectors.

THIS PAGE IS INTENTIONALLY LEFT BLANK

.

Chapter 7

7 VERIFICATION AND VALIDATION OF EEE-FORCE

7.1 Introduction

In Chapter 5, the iterative development of the “Electronic, Electrical and Electromechanical - Framework for Obsolescence Robust Cost Estimation” (EEE-FORCE), that can be used at the bidding stage of a support contract to estimate the obsolescence NRE costs incurred during the contracted period, was presented. The purpose of this Chapter is to describe the implementation of this framework in an Excel-based tool and its subsequent validation by means of seven case studies with current projects across the defence and aerospace industry, as well as qualitative validation with experts from different sectors.

In Section 7.2, the research methodology followed for the validation of the EEE-FORCE framework is presented. It includes a detailed description of the experts that participated.

In Section 7.3, the author describes the implementation of the EEE-FORCE framework into a tool using MS Excel and Visual Basic for Applications (VBA), detailing the structure of the tool and the data required at each step.

Section 7.4 presents the each of the seven case studies in detail, and subsequently provides a cross-case study analysis synthesis based on the responses that the experts gave to the questionnaire used during the case study sessions.

7.2 Detailed Research Methodology for Case Studies

For the development of each case study, a copy of the tool was sent to the experts who were going to participate (their details are shown in Table 7-1). By means of a WebEx teleconference, the characteristics of the tool were explained to each of the participants, together with a demonstration of the usage of the tool using dummy data. Any questions that the participants had about the tool or the framework were clarified during this session. After this, the experts were in a position to start inputting the required data to the tool from a current project. In the case that the experts had any questions or doubts while doing this, they were able to contact the researcher by telephone to clarify them. Once the tool was populated with the relevant data, a 5- to 6-hour meeting was arranged with the researcher and the experts to run the tool, to discuss the outcomes and to fill in a validation questionnaire (see Appendix A.8) assessing the results of the case study. Examples of the questions are shown as follows.

- How logical is the cost estimating process for obsolescence?
- Is the framework suitable for the bid stage?
- Please comment on how generalisable the framework is within the defence sector and for other sectors (e.g. Nuclear)
- What are the potential limitations and challenges in using and implementing the tool?
- Evaluation of the output of the tool after populating it with information from the case study

Table 7-1 Experts that Participated in EEE-FORCE Validation

Expert Number	Organisation	Role	Years of Experience on Obsolescence
1	ORG_A	Obsolescence Management Policy A&G Lead	5
2	ORG_B	Engineering Manager	10
3	ORG_B	Support Manager	12
4	ORG_B	Supportability Engineer	10
5	ORG_D	Obsolescence & Reliability Manager	4
6	ORG_F	Obsolescence Manager	14
7	ORG_H	Obsolescence Manager	10
8	ORG_H	Obsolescence Manager	5
9	ORG_M	Senior Technical Services Manager	6
10	ORG_N	Obsolescence Manager	13

The responses were analysed by identifying similarities, differences and unique responses across the different participants. The outcomes from this analysis are summarised further along in this Chapter.

7.3 EEE-FORCE Implementation and Verification

The EEE-FORCE framework was implemented into a tool using MS Excel and Visual Basic for Applications (VBA). The tool is structured according to the process described for the EEE-FORCE framework in Chapter 5. The sequence of tabs is as follows, including the data required at each step.

1. **Cover**

   This is the front page of the tool, showing the logo and the developer's name.

2. **Instructions**

   This tab provides a link to the user manual, as well as a summary of the key instructions required to use this tool, including the scope, the definition of key concepts and the data input process.

3. **STEP 1: User Information**

   The user's name and the date of use of the tool are recorded in this tab. This allows having traceability about when the tool has been applied to each particular project and who has input the data or made amendments.

4. **STEP 2: System/Products Information**

   In this tab it is requested to input data related to the system/platform to support, as well as the contract duration and a breakdown of the system into products. The list of inputs is as follows.

   - Project name
   - Type of Platform
   - Obsolescence Management Level deployed

     The user can select the OM level that best describes the OMP defined for the project. If none of them is suitable, the user can select the "bespoke" option.
   - Contract Start/End

     The Contract Duration is automatically calculated based on the two previous inputs.
   - Hierarchy

     It indicates the level in the hierarchy of the Product in the system's PBS.
   - Product Part Number
   - Product Brief Description
   - Coupling Level
   - Package Density
   - Level of Information Available

     Indicated if there is information available about the list of components + monitoring tool + ERP system OR if there is historical data from a similar Product. If none of the above is available, the user will have to base on expert judgement.

- Qualification Environment

  Specify the qualification environment for a particular Product only if it is different from the type of platform selected
- Level of Integration

  By clicking on the button "Calculate Level of Integration", the Level of Integration is automatically calculated, based on the Package Density and the Coupling Level.

Once STEP 2 is populated, the information related to the components contained in each product will be input in either STEP 3A or STEP 3B, depending on the level of information available.

5. STEP 3A: Detailed Component Information (BoM)

In this tab, the information required is related to the components of the products for which detailed information is available. It is important to highlight that repeated components have to be included in the list only once, and then indicate how many products contain them (See Figure 7-1).

- Part Number or Part Description
- Number of Products that contain this Component
- Is the stock for this component shared across different projects?
  - YES - Then indicate the probability of running out of stock in the following column and ignore the following 7 columns (go to point 4 and skip points 5-12)
  - NO - Then skip the following column, indicating the level of stock and consumption rate (skip point 4 and go to points 5-12)
- Probability of Running Out of Stock During the Contracted Period
- Date when the stock level was reviewed
- Stock Level Exclusive for this Project
- Consumption Rate (items used per year)

  Enter the consumption rate directly if known (and then skip points 9-12), or fill in the next four columns to calculate it (skip point 7 and go to points 8-12)

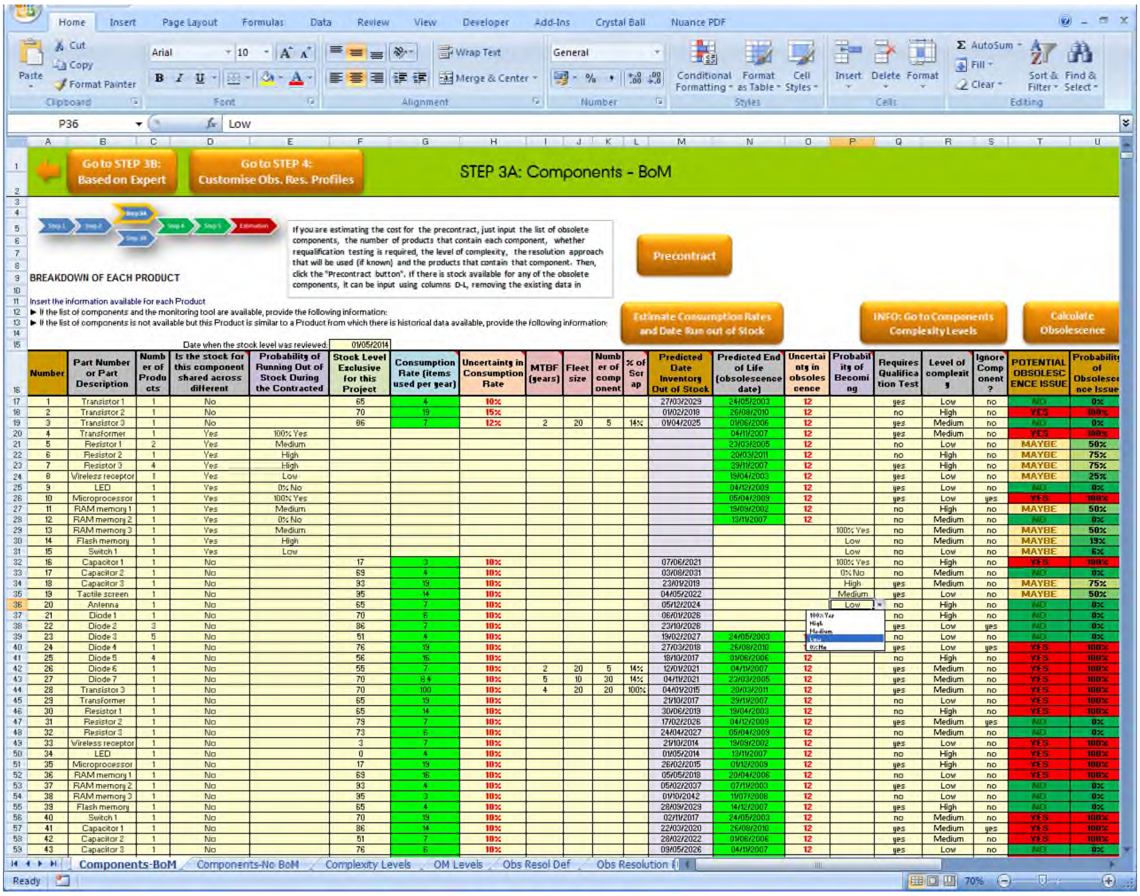


Figure 7-1 EEE-FORCE Input Form STEP 3A

- Uncertainty in Consumption Rate (It follows a normal distribution)

  Default: 10% uncertainty (It represents that the 90 percentile will be regarded as the mean of the consumption rate plus 10% of it). It shall increase with the age of the system and when there is no historical data available.
- Mean time between failures (MTBF) (expressed in years)

  Assumption: components are working continuously
- Fleet size
- Number of components per platform
- % of Scrap

  It represents the percentage of items that are discarded once they fail. The rest are repaired and go back to stock. Default values:
  - Consumables - 100%

  - Rest - 14%

- Predicted Date Inventory Out of Stock

  After clicking the “Estimate Consumption Rates and Date Run out of Stock” button, the Consumption Rate is calculated based on data from points 9-12 and the Predicted Date Inventory out of Stock is calculated based on points 5-7.
- Predicted End of Life (obsolescence date)

  Input comes from obsolescence monitoring tools (e.g. IHS o Q-STAR) If this information is not available skip points 14-15 and provide the "probability of obsolescence".
- Uncertainty in obsolescence date (months)

  It represents that the 90 percentile will be regarded as the obsolescence date plus the number of months indicated as uncertainty.
- Probability of Becoming Obsolete During the Contracted Period

  Indicate this only when the Predicted End of Life (obsolescence date) is not available.
- Requires Qualification Test?
- Level of complexity

  Based on the Components Complexity Levels Classification shown in Chapter 5.
- Ignore Component?

  A component can be deliberately not considered in the cost estimation. (e.g. when there is a clause in the contract that covers it exclusively)
- Potential Obsolescence Issue / Probability of Obsolescence Issue

  After clicking the “Calculate Obsolescence Issues” button, an assessment of the data input so far is made and the probability of having an obsolescence issue is indicated as a percentage.
- Resolution Approach Used
- Select the resolution approach that will be applied to resolve an obsolescence issue (Provide this information only for those

components for which it is certain that no other resolution approach may be applied).

- Products that contain that Component
  Indicate to which Product(s) number this component belongs to. In case it is used in more than one product, enter each product number in a different column.

Once data has been input for all the components, the user has to click the "Calculate Obsolescence Issues" button, so that the Probability of Obsolescence Issue is calculated.

6. **STEP 3B: Component Information Based on Expert Judgement**
   In this tab, the user should input the information related to the components of the products for which detailed information is not available. Expert judgement shall be applied to estimate the number of components contained in each product for each level of complexity, and how many of them are expected to become obsolete during the contracted period. It is also necessary to indicate how many of them will require requalification testing. The user can also specify the level of uncertainty for each input. The default value is 30% (It represents that the 90 percentile will be regarded as the number of components plus 30% of it).

7. **STEP 4: Obsolescence Resolution Profiles (ORP)**
   The Obsolescence Resolution Profiles (ORP) resulting from the study explained in Chapter 5 are provided in STEP 4, so they will be applied for the cost estimation of obsolescence. The ORP that will be applied is chosen according to the OM level selected and the complexity level of the obsolete component. If the user considers that none of the five OM levels represent the current practice for that project, the bespoke OM level can be selected and then, the probabilities of using each resolution approach can be entered manually. If the contract is covering the last 5-7 years of the in-service phase, the user may select "Yes" and that will take him to another set of ORP which have been adapted to this situation. These ORP have been modified taking into account that the probability of using minor redesign,

major redesign, emulation, FFF replacement will decrease, whereas the probability of using LTB or cannibalisation will increase.

8. **STEP 5: Obsolescence Cost Metrics (OCM)**

In this tab it is presented the set of NRE cost metrics derived from the study explained in Chapter 5. The user has the possibility to customise these figures. The formula used to link the parameters is as follows.

$$Cost = Base\_Cost \times Factor\_1 + Base\_Cost \times Factor\_2 \times Factor\_3 \times Factor\_4$$

- FACTOR_1 is applied to estimate the resolution cost without requalification
- FACTOR_2 is applied to estimate the requalification cost
- FACTOR_3 is applied to take into account the type of platform in the estimation of the requalification cost
- FACTOR_4 indicates whether requalification testing is required or not.

The Base_Cost figures are affected by uncertainty. A normal distribution has been applied, and the standard deviation used has been adopted from the analysis of the Obsolescence Cost Metrics study commissioned by the MoD (2004).

9. **Results**

Once the previous steps have been followed, the NRE cost of obsolescence can be automatically estimated. Prior to this, the user should assess the “clustering factor” because emulation, minor and major redesigns may resolve several obsolescence issues simultaneously, and this needs to be taken into account for the cost estimation. The "clustering factor” represents the number of redesigns that would be applied to resolve 100 obsolescence issues requiring a redesign. The default value for the "clustering factor” is 30%. A 100% would represent that all the obsolescence issues that require a redesign are resolved independently, that is to say, the number of redesigns would be equal to the number of obsolescence issues that require a redesign. The "clustering factor" is also affected by uncertainty (by default: 10%).

After clicking the "Calculate Cost Estimation" button, the number of obsolescence issues expected for each level of complexity is shown, together with the number of emulation, minor and major redesigns expected. Additionally, the obsolescence cost estimated for the contracted period will be shown (See Figure 7-2).

In order to apply the Monte Carlo simulation to take uncertainty into account and get as a result a cost distribution, an add-on to MS Excel called Crystal Ball is applied. The user only has to click the "Start" button from the Crystal Ball ribbon, and the simulation will start. Once the simulation has finished, the final distribution of cost will be shown and the user can do a statistical analysis of it and/or print a report of it.

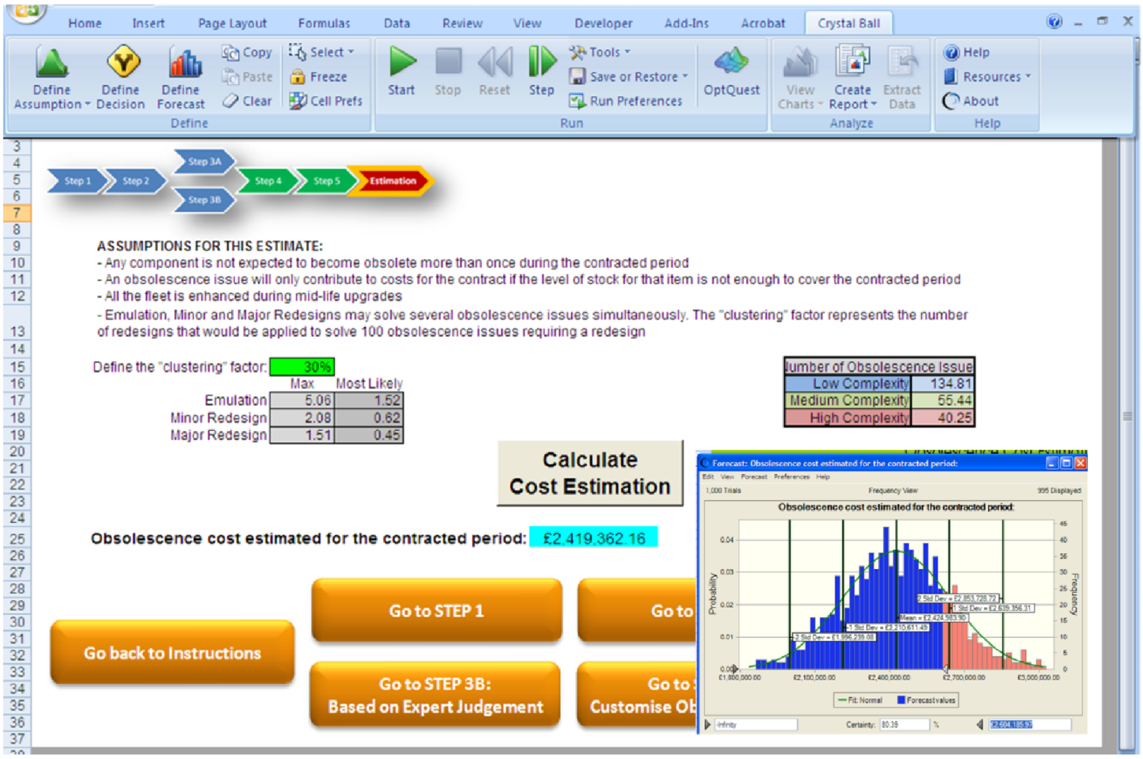


Figure 7-2 EEE-FORCE Output

Macros have been implemented in the development of this tool to facilitate the navigation across the tabs (steps), making it more user-friendly.

The algorithms for the calculations have been implemented using VBA, which extracts the inputs from the MS Excel tabs and reports the results back to the final tab. The rationale for these calculations was explained in Chapter 5. They are listed as follows (Further details are provided in the Maintenance Manual in Appendix C).

- Determining the Level of Integration, based on the Coupling Level and the Package Density.
- Calculation of consumption rate for each component based on the mean time between failures (MTBF), the fleet size, the number of components per platform and the percentage of scrapped components.
- Calculation of date to run out of stock
- Estimation of the Probability of having obsolescence issues for each component.
- Calculation of alternative obsolescence resolution profiles.

  If the contract is covering the last five years of the in-service phase, the original ORP will need to be modified as follows.

Remains constant	Existing Stock	Authorised Aftermarket		
Is reduced by half	Minor Redesign	Major Redesign	Emulation	FFF replacement
Increases proportionally	LTB	Cannibalisation		

Figure 7-3 Modification to Calculate Alternative ORP

The new percentages for each resolution approach are calculated using the following formulae.

$$A_1 = Alt.Existing\ Stock\ (\%) = Existing\ Stock\ (\%)$$

$$A_2 = Alt.Authorised\ Aftermarket\ (\%) = Authorised\ Aftermarket\ (\%)$$

$$A_3 = Alt.Equivalent\ (\%) = \frac{Equivalent\ (\%)}{2}$$

$$A_4 = Alt.Alternative\ (\%) = \frac{Alternative\ (\%)}{2}$$

$$A_5 = Alt.Emulation\ (\%) = \frac{Emulation\ (\%)}{2}$$

$$A_6 = Alt.Minor\ Redesign\ (\%) = \frac{Minor\ Redesign\ (\%)}{2}$$

$$A_7 = Alt.Major\ Redesign\ (\%) = \frac{Major\ Redesign\ (\%)}{2}$$

$$Alt.Cannibalisation\ (\%) = \frac{100\% - (A_1 + A_2 + A_3 + A_4 + A_5 + A_6 + A_7)}{Cannibalisation\ (\%) + LTB\ (\%)} \times Cannibalisation\ (\%)$$

$$Alt.LTB\ (\%) = \frac{100\% - (A_1 + A_2 + A_3 + A_4 + A_5 + A_6 + A_7)}{Cannibalisation\ (\%) + LTB\ (\%)} \times LTB\ (\%)$$

The same formulae apply for Low, Medium and High Complexity Obsolescence Resolution Profiles.

The algorithms have been verified in collaboration with a professor of Cranfield University, who has more than ten years experience in cost engineering and modelling, and amended accordingly. This process took place prior to starting the case studies for validation. The architecture of these algorithms and the procedure followed to combine them in order to do a cost estimation applying the EEE-FORCE framework is represented as a set of flowcharts, as shown in Figure 7-4, Figure 7-5, Figure 7-6 and Figure 7-7. These flowcharts were included in the questionnaire used in the validation process, so the experts were able to further assess the validity of this architecture and formulae.

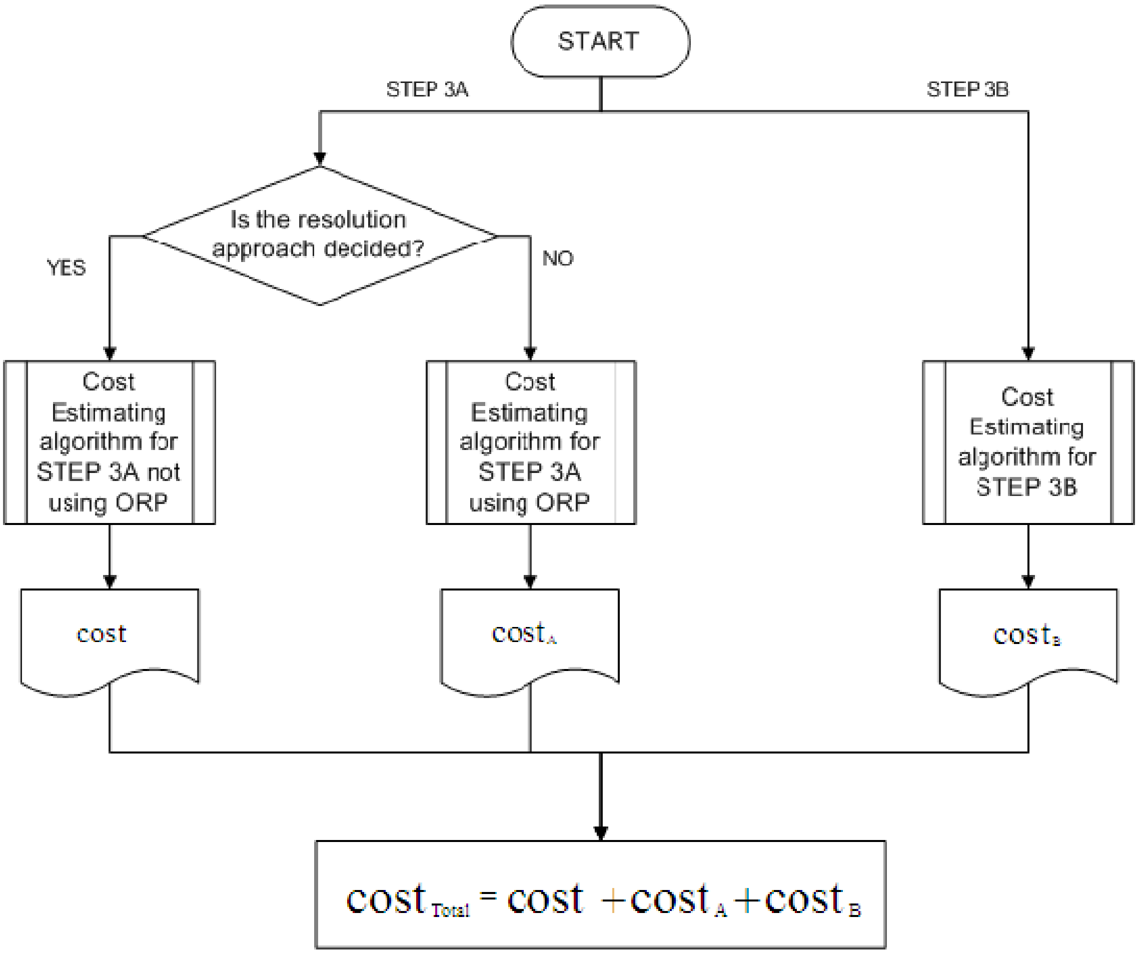


Figure 7-4 Cost Estimation Algorithm

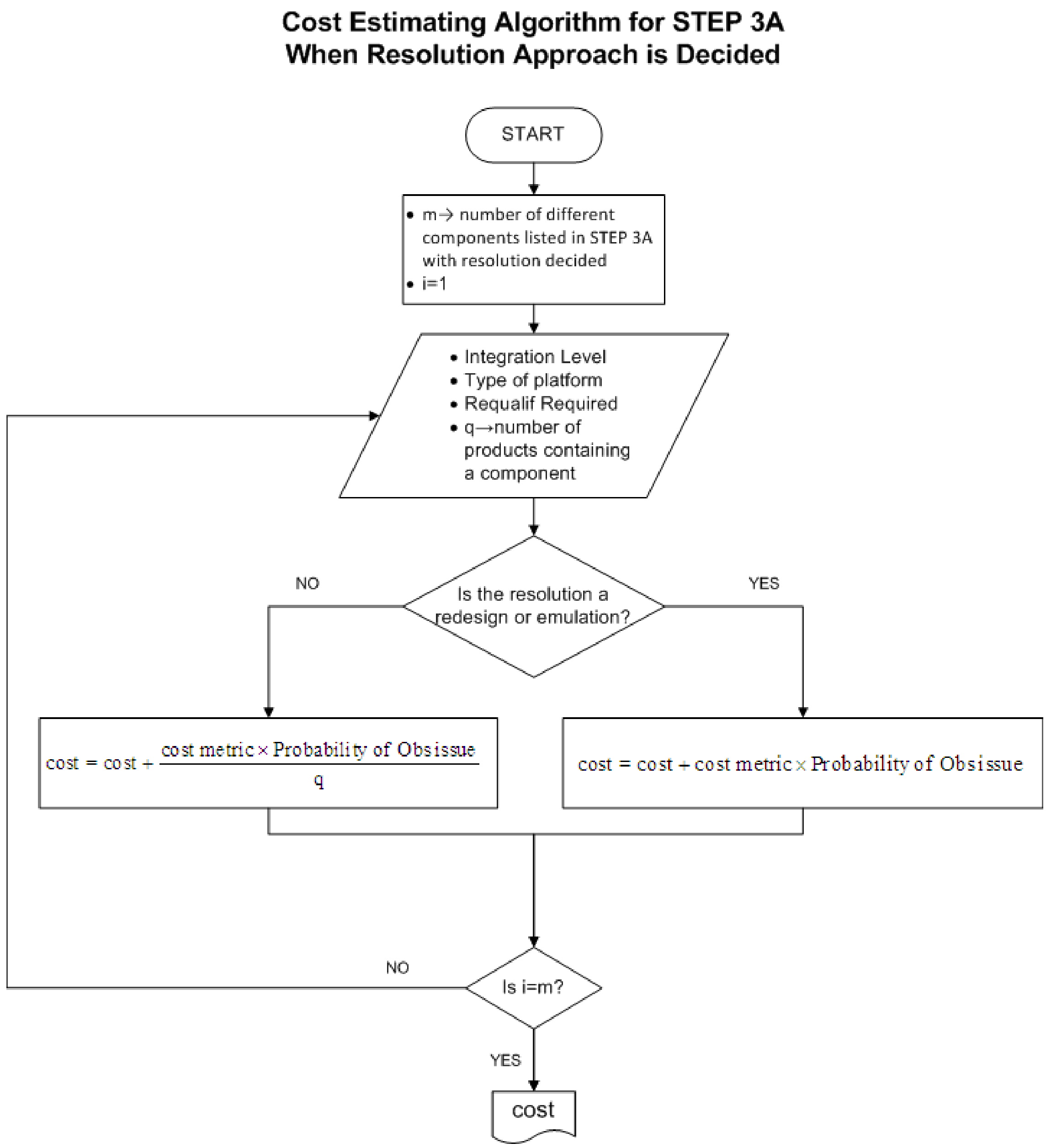


Figure 7-5 Cost Estimation Algorithm for STEP 3A when Resolution Approach is Decided

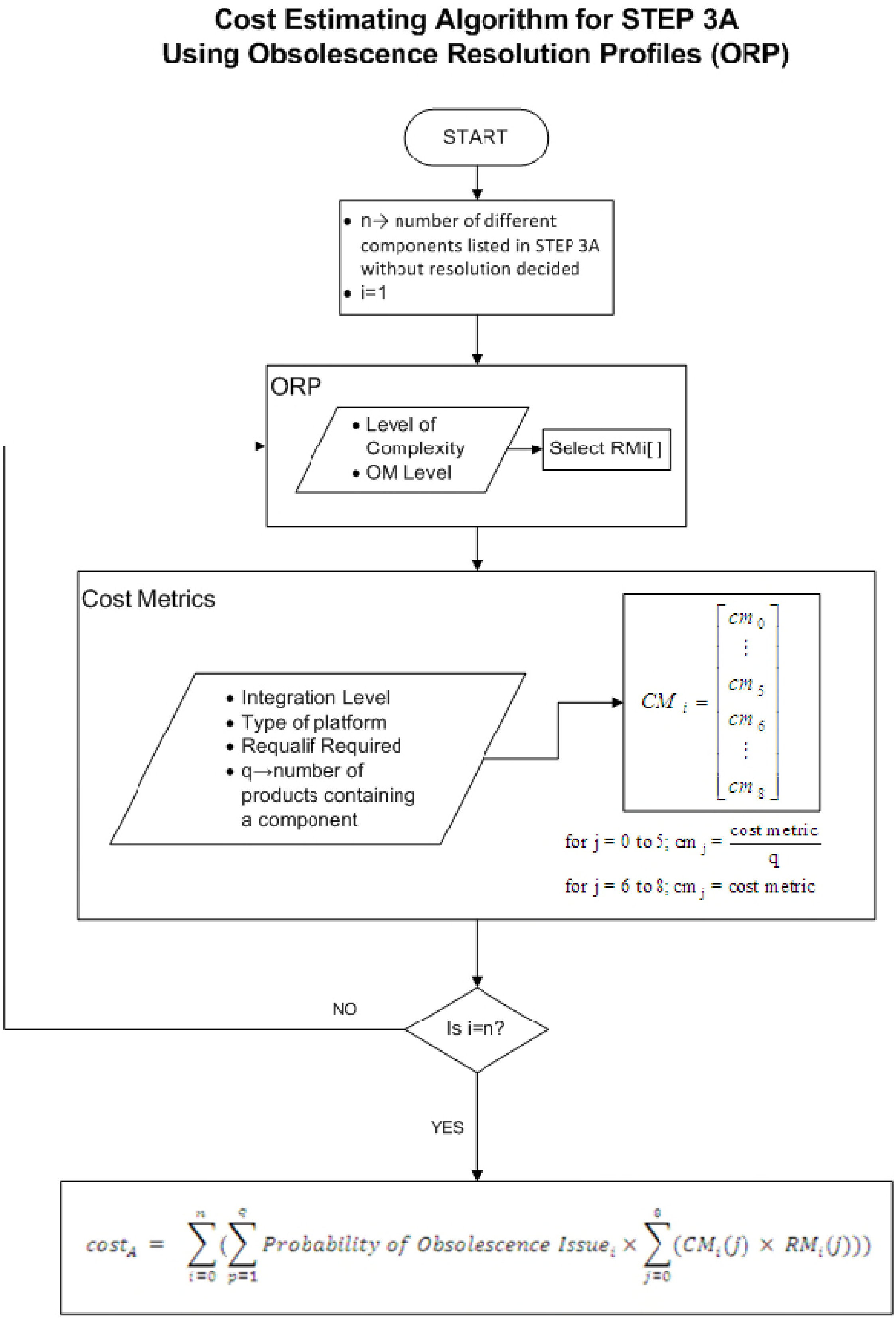


Figure 7-6 Cost Estimation Algorithm for STEP 3A Using Obsolescence Resolution Profiles

Cost Estimating algorithm for STEP 3B

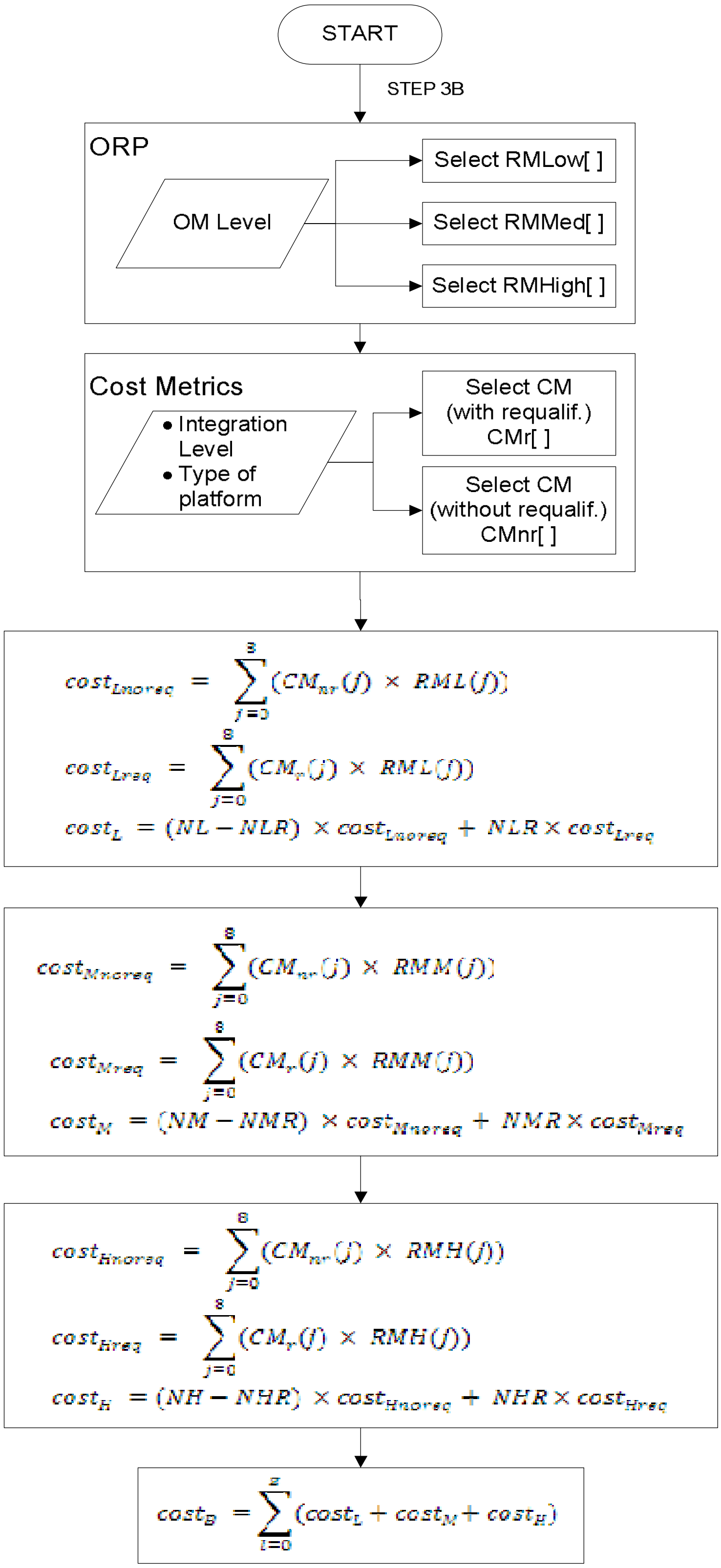


Figure 7-7 Cost Estimation Algorithm for STEP 3B

The assumptions made for the implementation of this framework are indicated as follows.

- Assumption 1: Any component is not expected to become obsolete more than once during the contracted period.
- Assumption 2: An obsolescence issue will only contribute to costs for the contract if the level of stock for that item is not enough to cover the contracted period.
- Assumption 3: All the fleet is enhanced during mid-life upgrades.
- Assumption 4: Emulation, Minor and Major Redesigns may resolve several obsolescence issues simultaneously. The "clustering" factor represents the number of redesigns that would be applied to resolve 100 obsolescence issues requiring a redesign.
- Assumption 5: The obsolescence resolution profiles mainly depend on the level of complexity and the level of proactiveness in managing obsolescence.

These assumptions were included in the questionnaire used in the validation process, so the experts were able to further assess their validity.

7.4 EEE-FORCE Validation Case Studies

The EEE-FORCE framework has been validated by applying it to seven case studies across four different companies in the UK defence sector. For the analysis of five of the case studies, the output provided by the EEE-FORCE framework was compared with the cost estimated at the engineering level, which provides the basis for the price agreed with the customer when signing the contract, after including the profit margins and inflation considerations. For the two remaining case studies, as they are still at early stages in the CADMID cycle, the assessment of the outcomes of the EEE-FORCE was based on expert judgement. A description of each case study is provided as follows.

7.4.1 Case Study 1: Avionic System

This case study covers the obsolescence management for the support of part of the avionics in a military aircraft within the in-service phase of the CADMID cycle, contracted for ten years. The terms of the contract include covering proactive notification of obsolescence issues, last time buy (LTB) and FFF replacements. This case study has been chosen due to the availability of this information and because it represents a good example of the application of the proposed framework.

This case study was carried out in collaboration with the Obsolescence & Reliability Manager of the prime contractor, who has 4 years of experience on managing obsolescence (expert 5 in Table 7-1). The inputs are summarised in Table 7-2.

Table 7-2 Summary of Inputs for Case Study 1

Number of Products	1
Contract Duration	10 years
Obsolescence Management Level	Bespoke
Type of Platform	Air systems / Safety Critical
Coupling Level	Medium
Package Density	Medium
Level of Integration	Medium
Number of Components	270
Level of Information Available	- List of Components - Obsolescence Monitoring Tools - Probability of Running out of Stock - Obsolescence date (51 components) - Probability of having an obsolescence issue (219 components) - Levels of Complexity
Stock shared for all components?	Yes
Requalification Testing Required	None
Components Ignored	0

Obsolescence Resolution Profiles	Bespoke (based on experience and historical data)
Cost Metrics	Bespoke/Default
Clustering Factor	30%

The Obsolescence Resolution Profiles were customised to represent the current practice in this project. As shown in Figure 7-8, for low-complexity components, there is similar probability of applying equivalent (52%) or LTB (48%) to resolve an obsolescence issue. For a medium-complexity component, it is more likely to find an equivalent (60%) than existing stock (20%) or making a LTB (20%). An obsolescence issue in a high-complexity component will always be resolved by making a LTB (100%). For this purpose it is important to apply proactive obsolescence management strategies, so the prime contractor can monitor the status of high-complexity components and avoid missing LTB notifications.

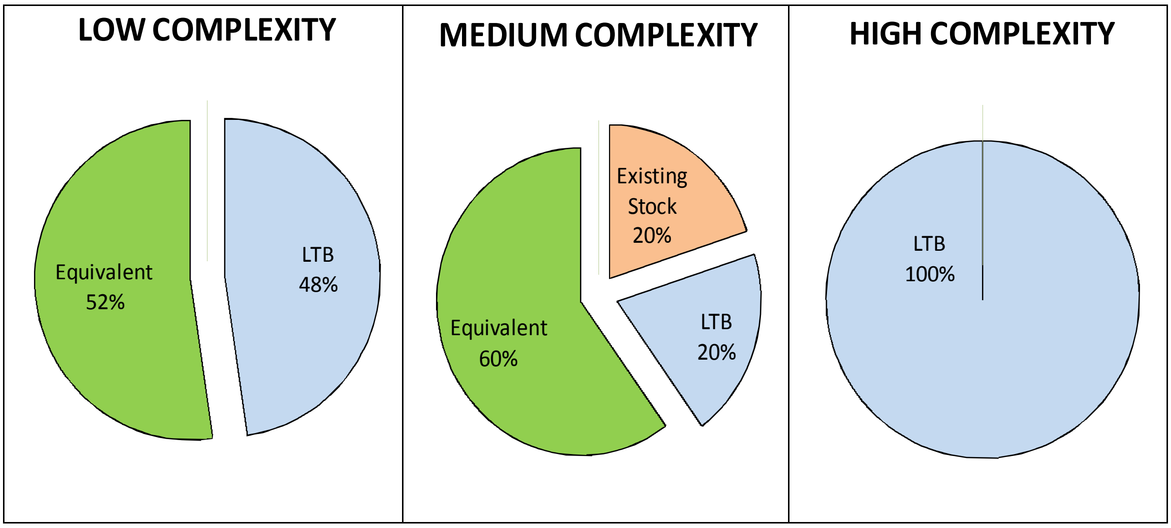


Figure 7-8 Bespoke Obsolescence Resolution Profiles (Case Study 1)

As a result, the EEE-FORCE framework predicted a total of 62.5 obsolescence issues during the contract period, and estimated that the NRE cost of resolving those obsolescence issues will be £262,985. The result of running the Monte Carlo Simulation is displayed in Figure 7-9. It shows that after running 1000 trials, a beta distribution represents the probability of the costs estimated. The mean (μ) of this distribution is £263,456 and the standard deviation (σ) is £13,897.

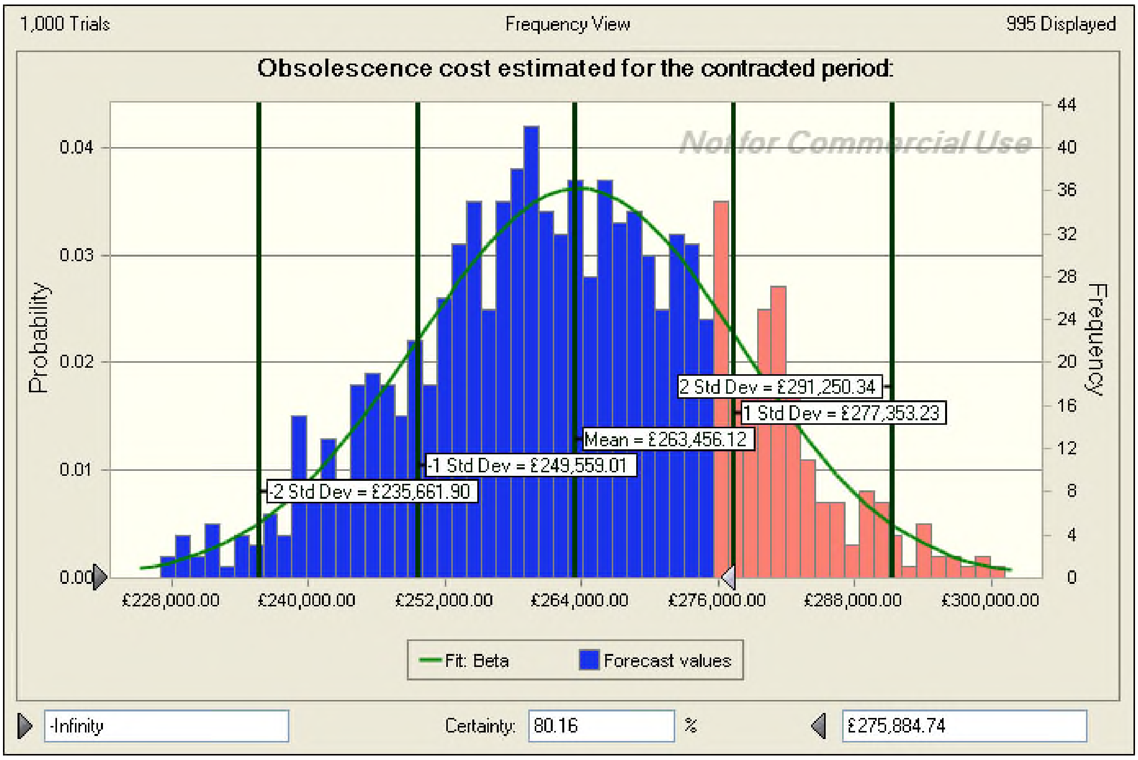


Figure 7-9 Output of EEE-FORCE after Running Monte Carlo Simulation (Case Study 1)

The results were compared with the figures agreed for obsolescence in this contract at the engineering level (not taking into account the inflation), which were calculated using an in-house bespoke model validated with the customer. The obsolescence cost agreed is £259k, which differs in 1.54% with the EEE-FORCE estimate.

Pre-contract

Additionally, for this case study, the EEE-FORCE framework has been applied to estimate the cost of obsolescence at the pre-contract stage. Prior to starting a new support contract, it is common practice to sign a pre-contract in order to resolve the pre-existing obsolescence issues. The EEE-FORCE framework can also be applied to estimate the NRE costs in this scenario. For this purpose, the existing obsolete components were input in STEP 3A (a total of 16). None of them required requalification testing, and the obsolescence resolution approach was indicated for all of them. In a pre-contract scenario, the calculations are made assuming a totally reactive obsolescence management strategy, as the obsolescence issues already appeared. Finally, the EEE-FORCE framework estimated that the NRE cost of resolving those obsolescence issues will be £43,185. The result of running the Monte Carlo Simulation is displayed in Figure 7-10. It shows that after running 1000 trials, a lognormal distribution represents the probability of the costs estimated. The mean (μ) of this distribution is £42,536 and the standard deviation (σ) is £4,689. The actual cost estimation used for contracting it was £45,000, so the difference between it and the estimate is just 4.44%.

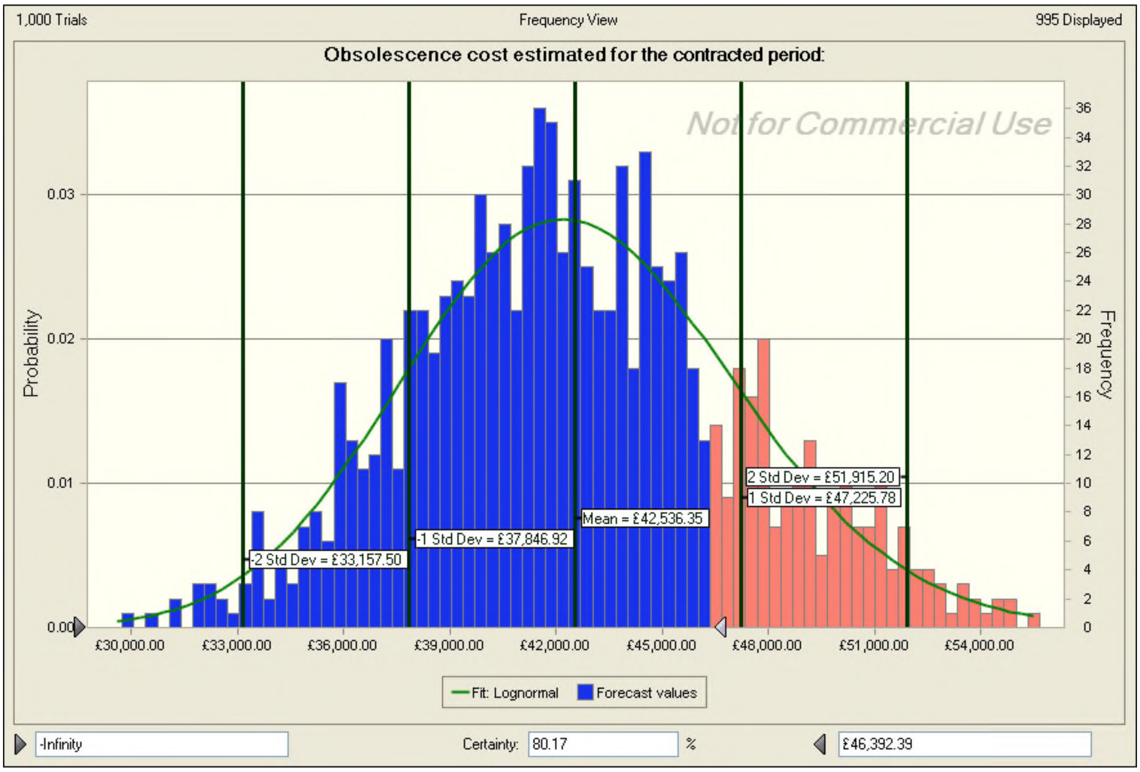


Figure 7-10 Output of EEE-FORCE after Running Monte Carlo Simulation (Case Study 1 – Pre-contract)

7.4.2 Case Study 2

This case study covers the obsolescence management for the support of military avionics system and subsystems within the in-service phase of the CADMID cycle, contracted for seven years. The case study was carried out in collaboration with the Obsolescence Manager of the subcontractor, who has 14 years of experience on managing obsolescence (expert 6 in Table 7-1). The inputs are summarised in Table 7-3.

Table 7-3 Summary of Inputs for Case Study 2

Number of Products	12
Contract Duration	7 years
Obsolescence Management Level	Bespoke
Type of Platform	Air systems / Safety Critical
Coupling Level	3 Low, 4 Medium, 5 High
Package Density	0 Very large, 6 Large, 4 Medium, 2 Small
Level of Integration	5 Very large, 1 Large, 3 Medium, 3 Small
Number of Components	70
Level of Information Available	- List of Components - Consumption Rate - MTBF - Probability of having an obsolescence issue - Levels of Complexity
Probability of Becoming Obsolete	3 (100% Yes) 67 (High)
Level of Complexity	3 Low, 19 Medium, 48 High
Stock shared for all components?	No (none)
Requalification Testing Required	Yes (all)
Components Ignored	0

Obsolescence Resolution Profiles	Bespoke (based on experience and historical data)
Cost Metrics	Default
Clustering Factor	30%

The Obsolescence Resolution Profiles were customised to represent the current practice in this project, as shown in Figure 7-11. The same probabilities have been allocated to all levels of component complexity due to the lack of historical information required to make distinctions between them.

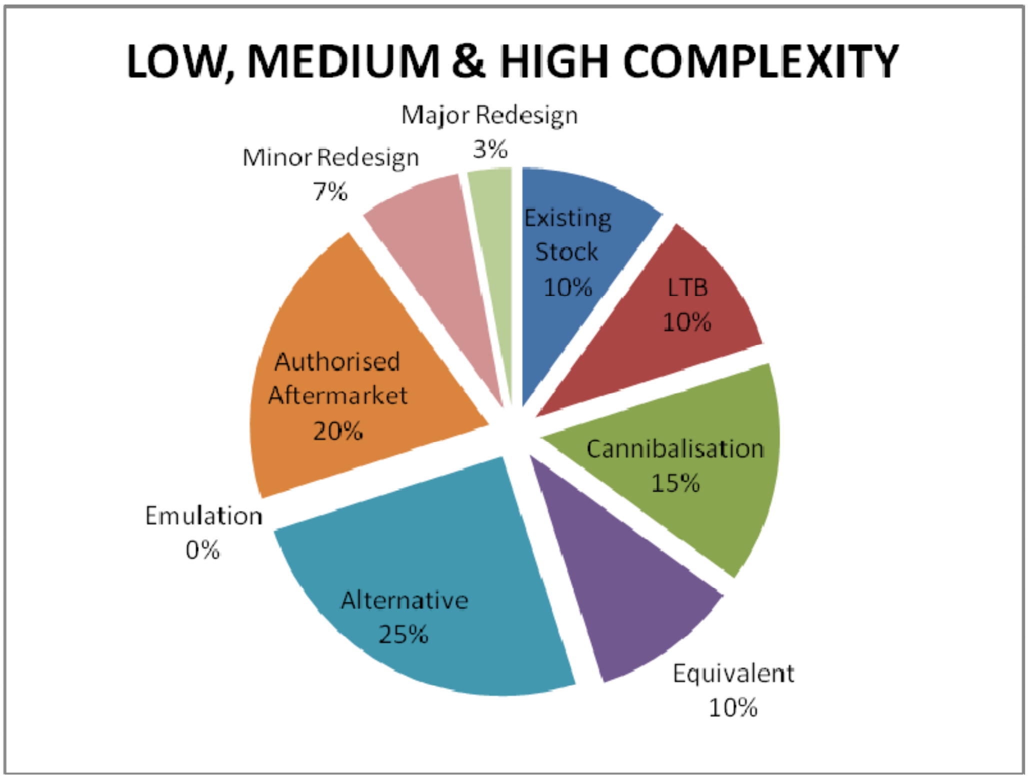


Figure 7-11 Bespoke Obsolescence Resolution Profiles (Case Study 2)

As a result, the EEE-FORCE framework predicted a total of 2.25 obsolescence issues in low complexity components, 12.75 obsolescence issues in medium complexity components and 27.75 obsolescence issues in high complexity components during the contract period. It also estimated that the NRE cost of resolving those obsolescence issues will be £3.19m. The result of running the Monte Carlo Simulation is displayed in Figure 7-12. It shows that after running 1000 trials, a beta distribution represents the probability of the costs estimated. The mean (μ) of this distribution is £3.128m and the standard deviation (σ) is £313.57k.

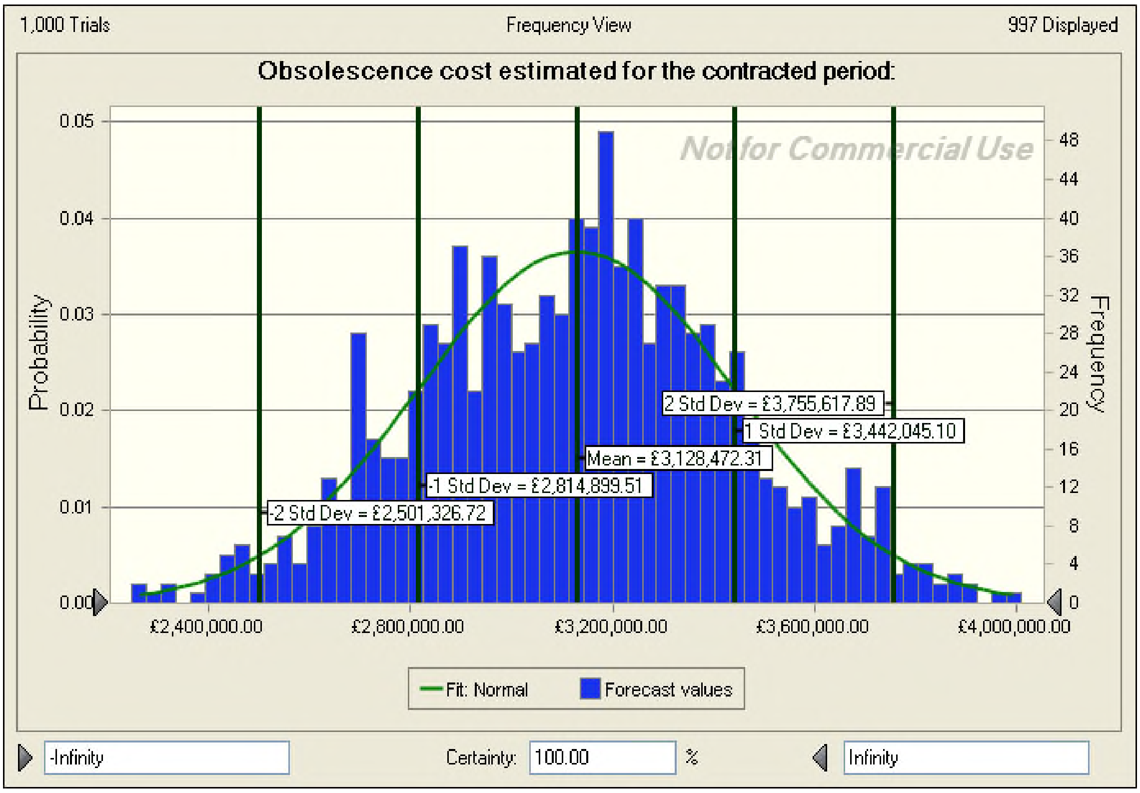


Figure 7-12 Output of EEE-FORCE after Running Monte Carlo Simulation (Case Study 2 – STEP 3A)

The organisation that provided this case study has developed a bespoke in-house model, which is kept confidentially. According to the obsolescence expert, it has been validated in its original form by costing techniques by MoD cost estimating experts, and in principle of operation by University of Maryland CALCE experts. The 3 point estimate provided by the in-house model is (£2.4m, £3.05m, £3.7m) which is congruent with the EEE-FORCE estimate (£2.5m, £3.13m, £3.76m), where the notation is (minimum, most likely, maximum).

In this case study, all the information was provided in STEP 3A (detailed information). In order to test the EEE-FORCE framework, the same case study was repeated but providing all the information in STEP 3B instead. The result of the Monte Carlo Simulation is displayed in Figure 7-13. It shows that after running 1000 trials, a gamma distribution represents the probability of the costs estimated. The mean (μ) of this distribution is £3.16m and the standard deviation (σ) is £306.85k. The results obtained in both cases are similar to each other and congruent with the in-house bespoke model. This shows that the EEE-FORCE framework can be applied to different projects and the predictions are at least the same level of accuracy as the in-house bespoke models.

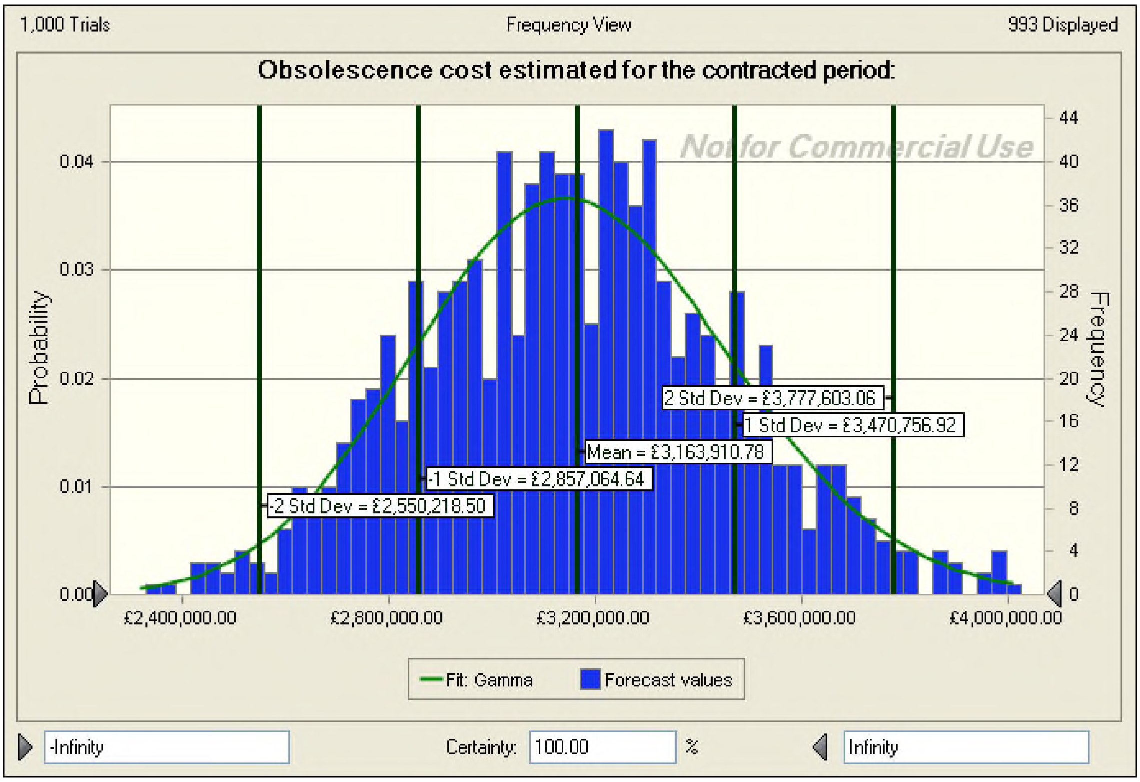


Figure 7-13 Output of EEE-FORCE after Running Monte Carlo Simulation (Case Study 2 – STEP 3B)

7.4.3 Case Study 3

This case study covers the obsolescence management for the support of airborne systems ranging from 60's technology (at the start of the in-service phase) to 90's technology (as a consequence of midlife upgrades). The support contract duration is 11 years and represents the end of the in-service phase for this system. The case study was carried out in collaboration with two Obsolescence Managers, who have five and ten years of experience on managing obsolescence respectively (experts 7 and 8 in Table 7-1). The inputs are summarised in Table 7-4.

Table 7-4 Summary of Inputs for Case Study 3

Number of Products	668
Contract Duration	11 years
Obsolescence Management Level	Bespoke
Type of Platform	Air systems / Safety Critical
Coupling Level	412 Low, 129 Medium, 127 High
Package Density	36 Very large, 89 Large, 133 Medium, 410 Small
Level of Integration	115 Very large, 23 Large, 114 Medium, 416 Small
Number of Components	2880
Level of Information Available	- List of Components - Obsolescence Monitoring Tool - Historical Data (5 years) - Consumption Rate - MTBF - Probability of having an obsolescence issue - Levels of Complexity
Probability of Run Out of Stock	189 (100% Yes) 2691 (High)
Level of Complexity	1080 Low, 972 Medium, 828 High

Stock shared for all components?	Yes
Requalification Testing Required	Yes
Components Ignored	1115
Obsolescence Resolution Profiles	Bespoke (based on experience and historical data)
Cost Metrics	Customised - Equivalent: base cost reduced from £3,500 to £1,500 - Authorised Aftermarket: base cost reduced from £4,500 to £3,500
Clustering Factor	30%

The Obsolescence Resolution Profiles were customised to represent the current practice in this project, as shown in Figure 7-11. It can be highlighted that for a low-complexity component, 50% of the times the obsolescence issue will be resolved by finding an equivalent and 25% of the times by finding an alternative. For medium-complexity component, 50% of the times the obsolescence issue will be resolved by making a last-time buy (LTB); and for a high-complexity component, this resolution approach will be used 65% of the times.

As a result, the EEE-FORCE framework predicted a total of 20.75 obsolescence issues in low complexity components, 33.5 obsolescence issues in medium complexity components and 31.75 obsolescence issues in high complexity components during the contract period. It also estimated that the NRE cost of resolving those obsolescence issues will be £6.42m. The result of running the Monte Carlo Simulation is displayed in Figure 7-15. It shows that after running 1000 trials, a beta distribution represents the probability of the costs estimated. The mean (μ) of this distribution is £6.426m and the standard deviation (σ) is £683.33k. The actual cost estimation used for contracting it was £6.8m, so the difference between it and the estimate is just 5.59%.

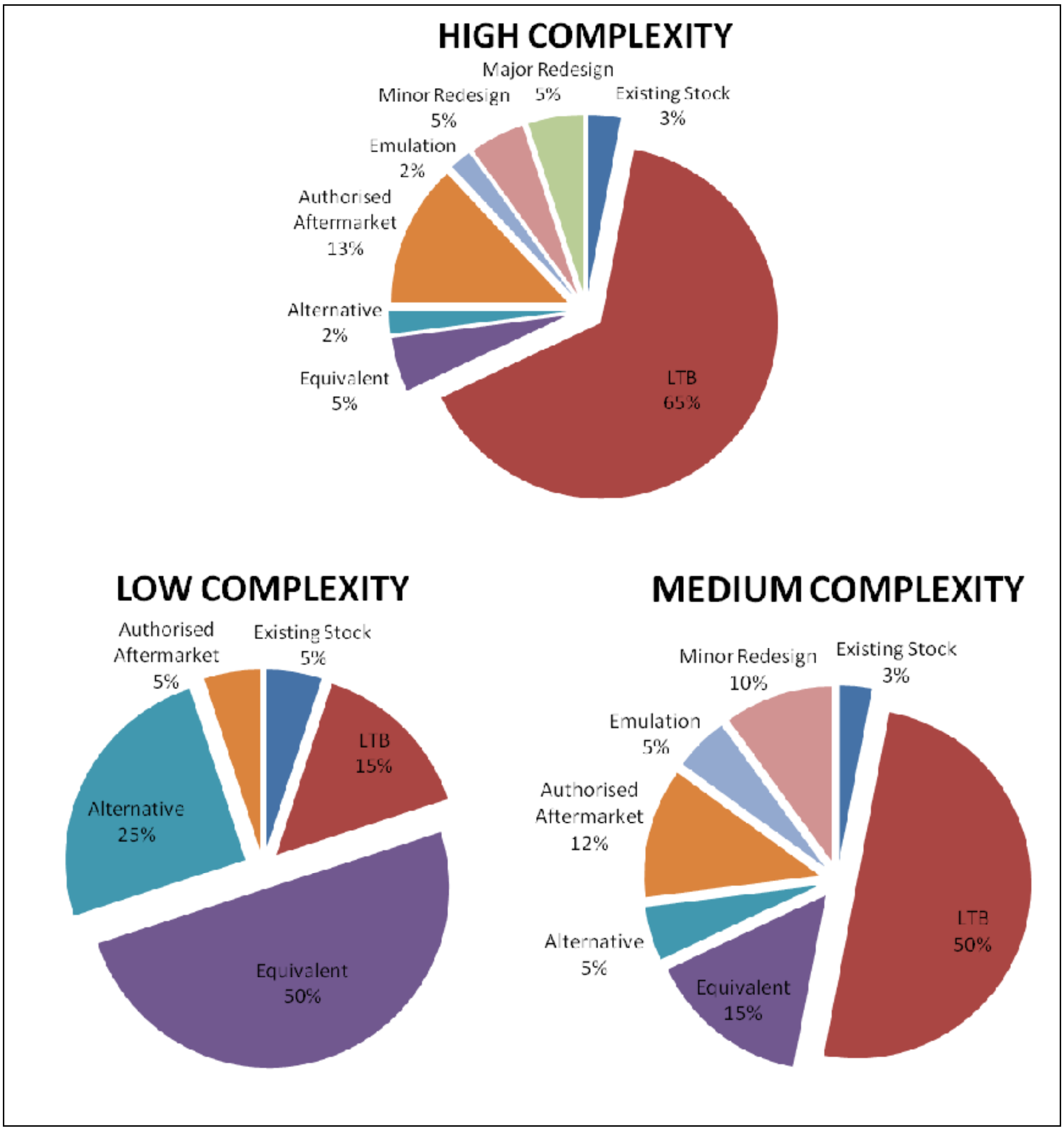


Figure 7-14 Bespoke Obsolescence Resolution Profiles (Case Study 3)

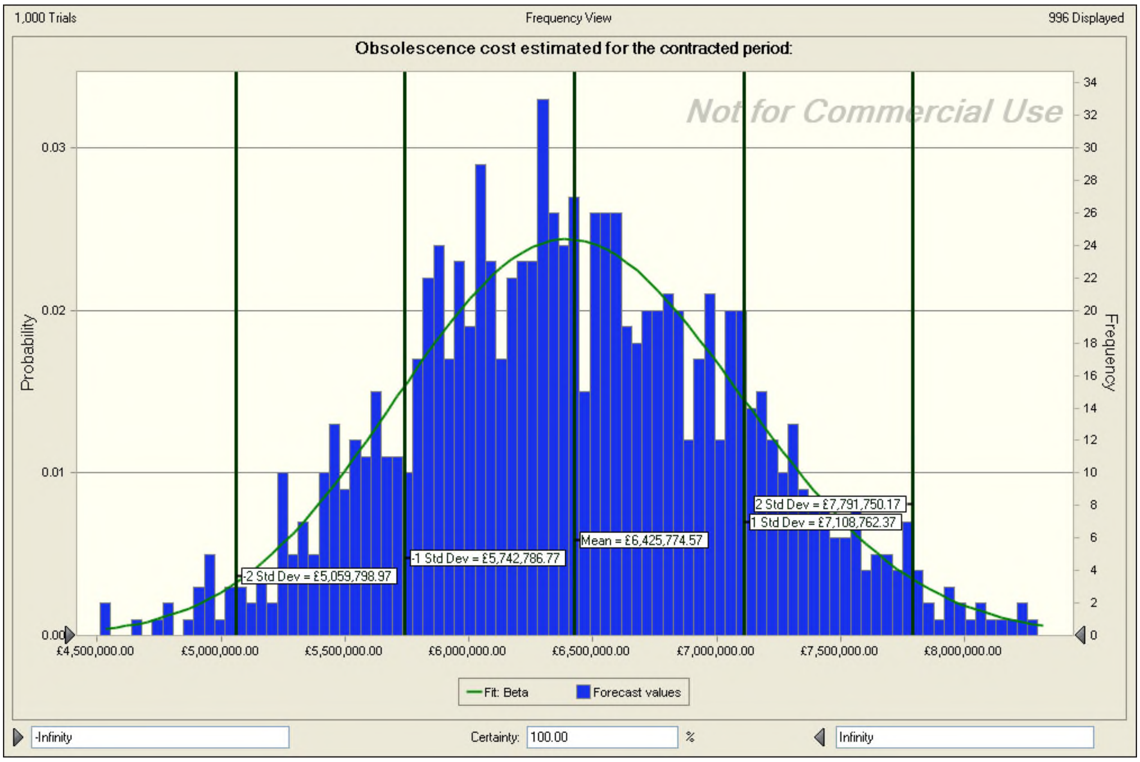


Figure 7-15 Output of EEE-FORCE after Running Monte Carlo Simulation (Case Study 3)

7.4.4 Case Study 4

This case study covers the obsolescence management for the support of eight subsystems in a rotary wing aircraft. The contract period is for the second 5-year phase of a rolling support contract intended to support the subsystems for 30 years. This case study was carried out in collaboration with the same experts as the previous one (experts 7 and 8 in Table 7-1). The inputs are summarised in Table 7-5.

Table 7-5 Summary of Inputs for Case Study 4

Number of Products	81
Contract Duration	5 years
Obsolescence Management Level	3
Type of Platform	Air systems / Safety Critical

Coupling Level	12 Low, 69 Medium, 0 High
Package Density	0 Very large, 48 Large, 19 Medium, 14 Small
Level of Integration	0 Very large, 48 Large, 19 Medium, 14 Small
Number of Components	3547
Level of Information Available	- System level Data only - No BoM available
Number of Obsolete Components	414
Level of Complexity	2802 Low, 661 Medium, 84 High
Requalification Testing Required	26
Obsolescence Resolution Profiles	Default
Cost Metrics	Customised - LTB: base cost reduced from £2,000 to £1,500 - Equivalent: base cost reduced from £3,500 to £1,700 - Alternative: base cost reduced from £3,500 to £2,000 - Authorised Aftermarket: base cost reduced from £4,500 to £3,000 - Minor Redesign: base cost increased from £21,300 to £25,000
Clustering Factor	10%

As a result, the EEE-FORCE framework predicted a total of 298 obsolescence issues in low complexity components, 93 obsolescence issues in medium complexity components and 23 obsolescence issues in high complexity components during the contract period. It also estimated that the NRE cost of resolving those obsolescence issues will be £1.56m. The result of running the Monte Carlo Simulation is displayed in Figure 7-16. It shows that after running

1000 trials, a lognormal distribution represents the probability of the costs estimated. The mean (μ) of this distribution is £1.86m and the standard deviation (σ) is £119.37k. The actual cost estimation used for contracting it was £1.7m, so the difference between it and the estimate is 9.41%.

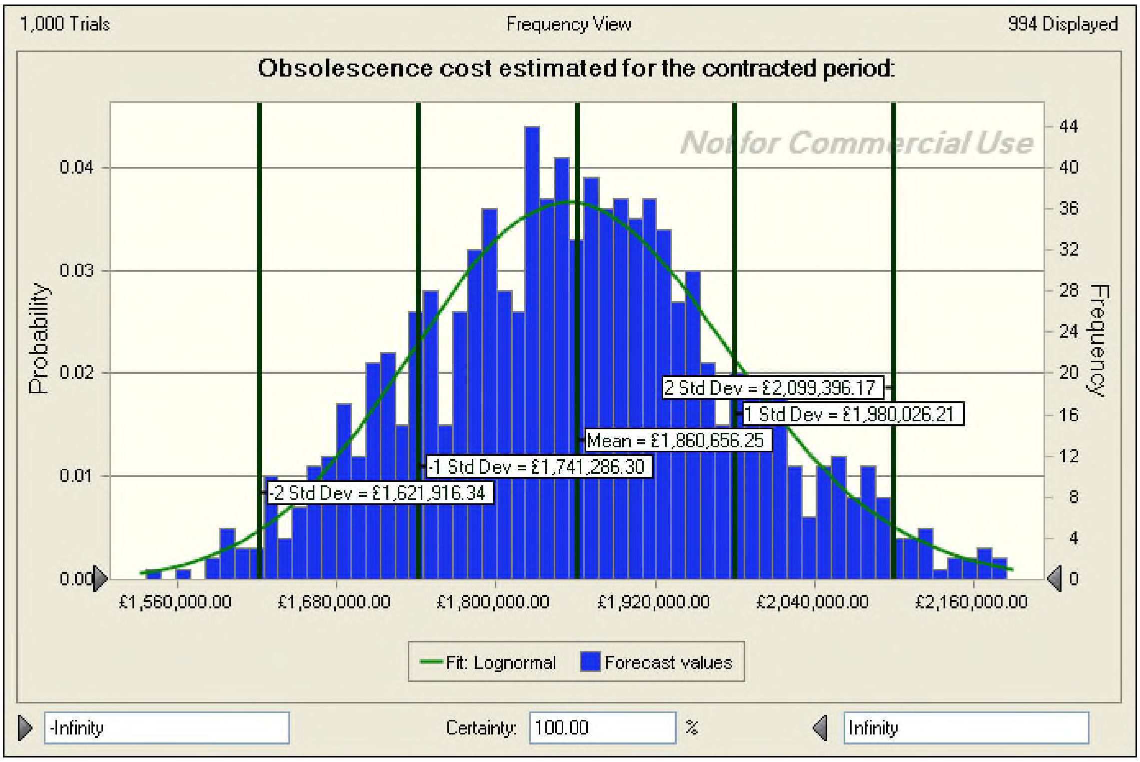


Figure 7-16 Output of EEE-FORCE after Running Monte Carlo Simulation (Case Study 4)

7.4.5 Case Study 5

This case study covers the obsolescence management for the support of a radar in a rotary wing aircraft. The contract period is 5 years at the beginning of the in-service phase. This case study was carried out in collaboration with the same experts as the previous one (experts 7 and 8 in Table 7-1). The inputs are summarised in Table 7-6.

Table 7-6 Summary of Inputs for Case Study 5

Number of Products	5
Contract Duration	5 years
Obsolescence Management Level	3
Type of Platform	Air systems / Safety Critical
Coupling Level	1 Low, 4 Medium, 0 High
Package Density	2 Very large, 1 Large, 1 Medium, 1 Small
Level of Integration	2 Very large, 1 Large, 1 Medium, 1 Small
Number of Components	489
Level of Information Available	- System level data only - No BoM available - Historical data from similar system
Number of Obsolete Components	76
Level of Complexity	415 Low, 61 Medium, 13 High
Requalification Testing Required	2
Obsolescence Resolution Profiles	Default
Cost Metrics	Customised - Equivalent: base cost reduced from £3,500 to £1,500 - Alternative: base cost reduced from £3,500 to £2,000 - Authorised Aftermarket: base cost reduced from £4,500 to £3,000 - Minor Redesign: base cost increased from £21,300 to £25,000
Clustering Factor	20%

As a result, the EEE-FORCE framework predicted a total of 57 obsolescence issues in low complexity components, 12 obsolescence issues in medium complexity components and 7 obsolescence issues in high complexity components during the contract period. It also estimated that the NRE cost of resolving those obsolescence issues will be £3.58m. The result of running the Monte Carlo Simulation is displayed in Figure 7-17. It shows that after running 1000 trials, a beta distribution represents the probability of the costs estimated. The mean (μ) of this distribution is £3.6m and the standard deviation (σ) is £533.88k. The actual cost estimation used for contracting it was £3.7m, so the difference between it and the estimate is 2.7%.

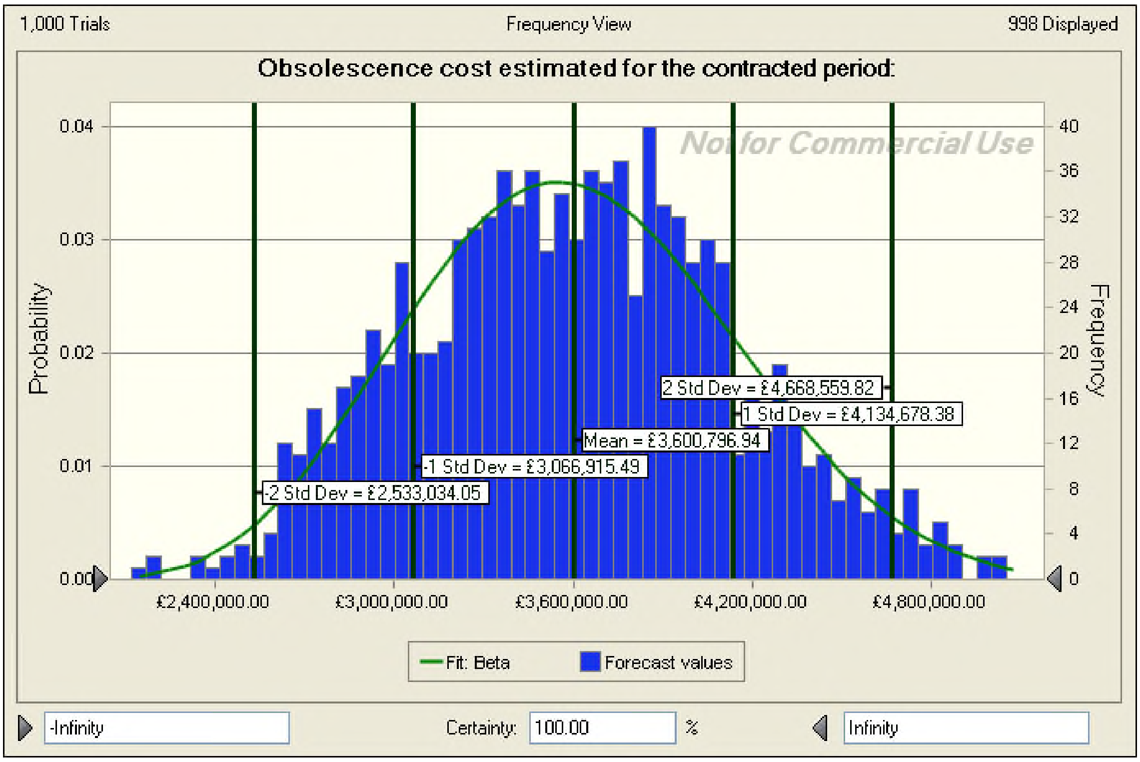


Figure 7-17 Output of EEE-FORCE after Running Monte Carlo Simulation (Case Study 5)

7.4.6 Case Study 6

This case study covers the obsolescence management for the support of a system in a maritime system of systems. It is still at the manufacture phase of the CADMID cycle, but the case study represents the support contract for the first five years of the in-service phase. This system has not been delivered yet but it is similar to another one that is already in service. This case study was carried out in collaboration with a Support Manager, a Supportability Engineer and a Engineering Manager with 12, 10 and 10 years of experience on obsolescence respectively (experts 2, 3 and 4 in Table 7-1). The inputs are summarised in Table 7-7.

Table 7-7 Summary of Inputs for Case Study 6

Number of Products	1
Contract Duration	5 years
Obsolescence Management Level	1
Type of Platform	Sea-based system
Coupling Level	Low
Package Density	Large
Level of Integration	Medium
Number of Components	37
Level of Information Available	- List of Components - Level of stock for 4 components - Historical data from similar system
Stock shared for components?	33 Yes, 4 No
Components Ignored	None
Probability of Run Out of Stock	3 (0% No) 28 (Medium)
Level of Complexity	19 Low, 13 Medium, 5 High
Requalification Testing Required	6
Probability of Becoming Obsolete	12 (0% No) 10 (Low) 13 (Medium) 1 (High) 1 (100% Yes)
Obsolescence Resolution Profiles	Default
Cost Metrics	Default
Clustering Factor	100%

As a result, the EEE-FORCE framework predicted a total of 1.63 obsolescence issues in low complexity components, 2.5 obsolescence issues in medium complexity components and 0.63 obsolescence issues in high complexity components during the contract period. It also estimated that the NRE cost of resolving those obsolescence issues will be £347.87k. The result of running the Monte Carlo Simulation is displayed in Figure 7-18. It shows that after running 1000 trials, a Weibull distribution represents the probability of the costs estimated. The mean (μ) of this distribution is £342.977k and the standard deviation (σ) is £25.87k. The three experts agreed that this estimate seems reasonable and realistic.

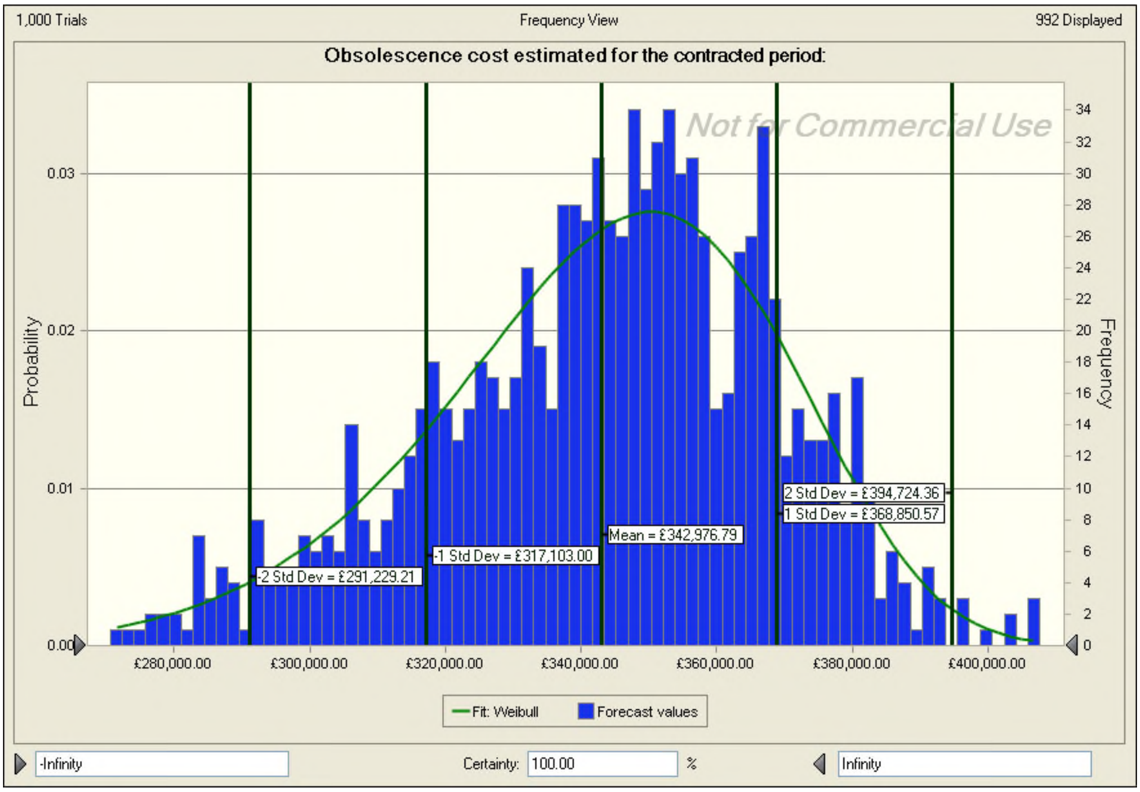


Figure 7-18 Output of EEE-FORCE after Running Monte Carlo Simulation (Case Study 6)

7.4.7 Case Study 7

This case study covers the obsolescence management for the support of a long-range radar in a maritime system of systems. It is still at the manufacture phase of the CADMID cycle, and hence, the information available is low. The case study represents the support contract for the first seven years of the in-service phase. This case study was carried out in collaboration with the same experts as the previous one (experts 2, 3 and 4 in Table 7-1). The inputs used are summarised in Table 7-8.

Table 7-8 Summary of Inputs for Case Study 7

Number of Products	13
Contract Duration	7 years
Obsolescence Management Level	1
Type of Platform	Sea-based system
Coupling Level	7 Low, 6 Medium, 0 High
Package Density	0 Very large, 1 Large, 10 Medium, 2 Small
Level of Integration	0 Very large, 1 Large, 5 Medium, 7 Small
Number of Components	391
Level of Information Available	- BoM is unavailable
Level of Complexity	279 Low, 82 Medium, 30 High
Number of Obsolete Components	38
Requalification Testing Required	7
Obsolescence Resolution Profiles	Default
Cost Metrics	Default
Clustering Factor	100%

As a result, the EEE-FORCE framework predicted a total of 25 obsolescence issues in low complexity components, 7 obsolescence issues in medium complexity components and 6 obsolescence issues in high complexity components during the contract period. It also estimated that the NRE cost of resolving those obsolescence issues will be £1.906m. The result of running the Monte Carlo Simulation is displayed in Figure 7-19. It shows that after running 1000 trials, a Weibull distribution represents the probability of the costs estimated. The mean (μ) of this distribution is £1.758m and the standard deviation (σ) is £199k. The three experts agreed that this estimate seems reasonable and realistic.

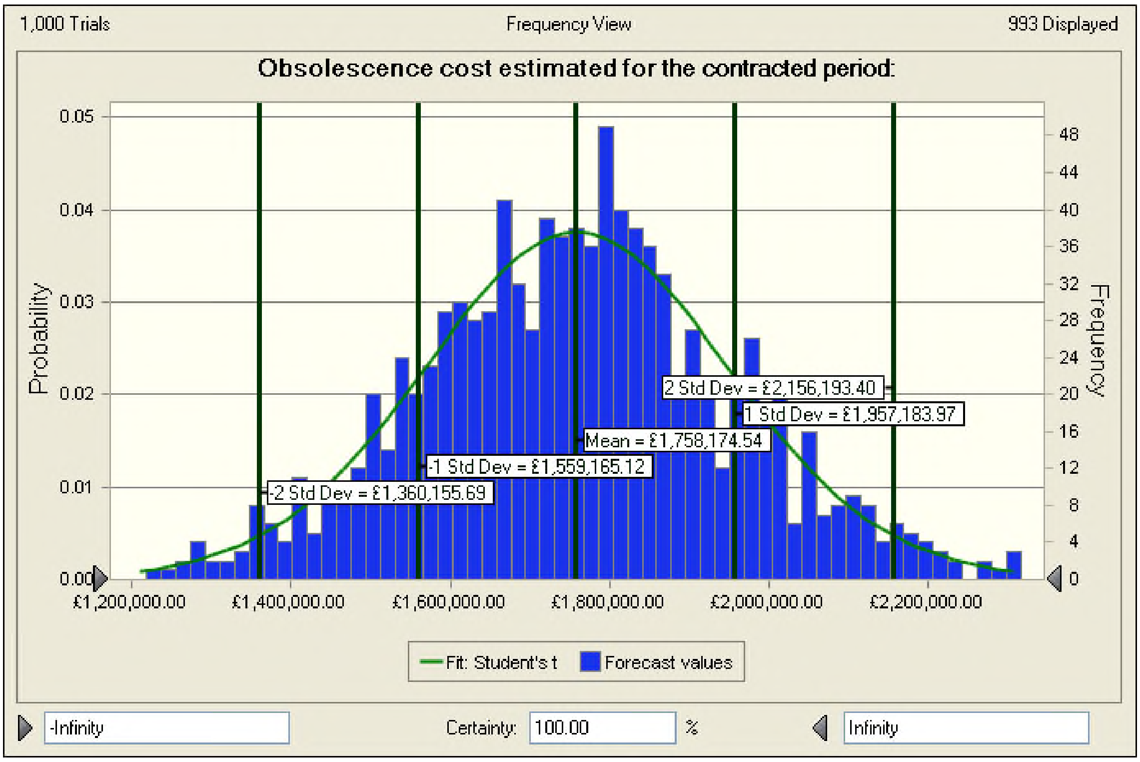


Figure 7-19 Output of EEE-FORCE after Running Monte Carlo Simulation (Case Study 7)

7.4.8 Cross-Case Study Analysis Synthesis

The quantitative results of the first five case studies carried out – those for which there are contractual figures available to compare – are summarised in Table 7-9. For all of them, the difference between the estimated cost (E) and the cost agreed in the contract at the engineering level (without inflation considerations) is on average 4.27%, and always lower than 10%. As a result of the verification and validation of the EEE-FORCE framework, a total of eight experts on obsolescence (1-8 in Table 7-1) from different organisations across the UK defence sector concur that the key formulae applied in this framework is valid and the outputs are consistent.

Table 7-9 Summary of Quantitative Results from Case Study

Case Study	Contract Duration	EEE-FORCE Estimate			Contractual Figure Agreed at the Engineering Level	Difference (%)
		Min. estimate (E-2SD)	Most Likely estimate (E)	Max. estimate (E+2SD)		
1-A	10years	£236k	£263k	£277k	£259k	+1.54%
1-B	Pre-contract	£33k	£43k	£52k	£45k	-4.44%
2-A	10years	£2.5m	£3.13m	£3.76m	(£2.4m–£3.7m) £3.05m	+2.62%
2-B	10years	£2.55m	£3.16m	£3.78m	(£2.4m–£3.7m) £3.05m	+3.61%
3	11years	£5.06m	£6.42m	£7.79m	£6.8m	-5.59%
4	5years	£1.62m	£1.86m	£2.1m	£1.7m	+9.41%
5	5years	£2.53m	£3.6m	£4.67m	£3.7m	-2.7%

SD – Standard Deviation

A cross-case study analysis and comparison has been carried out based on the responses that the eight experts (1-8 in Table 7-1) provided in their questionnaires during the interviews. The results are presented as follows.

- **LOGIC:**

The responses to the question "How logical is the cost estimating process for obsolescence?", as well as the scale used to capture them in the questionnaire, are presented in Table 7-10.

Table 7-10 How logical is the cost estimating process for obsolescence? - Ratings

1	2	3	4	5	6	7	8	9	10
Totally Invalid	Valid, with major deficiencies				Valid, with minor deficiencies				Totally valid

Experts	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	AVG
Score	8	8	7	10	10	8	10	7	**8.5**

The eight experts agree that the logic of the cost estimating process is valid, although some of them have identified minor deficiencies. Expert 2 indicates that there is a need to validate the framework on more case studies to test whether process covers all situations. Expert 3 suggests that some minor restructuring is recommended. Expert 6 highlights that the correct assignment of product and component, as well as the application of complexity levels and integration levels, is not intuitive. Expert 7 argues that the degree of sensitivity of the coupling level and package density is not clearly described. Finally, expert 8 finds difficult to identify which items are driving the cost and when they are due to be obsolete.

The responses to the question “Is the framework suitable for the bid stage?”, as well as the scale used to capture them in the questionnaire, are presented in Table 7-11.

Table 7-11 Is the framework suitable for the bid stage? - Ratings

1	2	3	4	5	6	7	8	9	10
Totally unsuitable	Suitable, with major deficiencies				Suitable, with minor deficiencies				Totally suitable

Experts	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	**AVG**
Score	8	7	10	10	10	9	7	8	**8.63**

The eight experts agree that the framework is suitable for the bid stage, although some of them have identified minor deficiencies. Expert 2 indicates that there is a need to test calibration of tool to gain confidence in quantitative results. Expert 6 highlights the suitability of the STEP-3B approach for the bid stage, whereas the STEP-3A approach is more suitable for a pre-contract scenario. Experts 7 and 8 concur with this, arguing that the time to input data with checks for accuracy and the time required to bespeak the model to suit the actual system is significant and could be an issue for fast-turnaround bids. However, this can be resolved by integrating the tool with the sources of information of the company.

The experts discussed the stages of the CADMID cycle in which the EEE-FORCE framework can be used. Experts 2, 6 and 8 agree that it could be used at any stage in the CADMID cycle. However, expert 3 argues that it can be used at all stages from Assessment onwards but not at the Concept stage, as there may not be sufficient information. Experts 4, 5 and 7 agree that it could only be used at the Development, Manufacture and In-service stages. Finally, expert 1 regards that it can only be used during the Manufacture and In-service stages.

- **GENERALISABILITY:**

The eight experts agree that the EEE-FORCE framework is suitable across the defence sector, including land, maritime and aerospace applications. They also agree that it can be applied for any high-value commercial application that involves high technology and long sustainment periods. Experts 7 and 8 pointed out that the framework needs to be tailored for each project, dependent on customer and specific contractual needs. They also commended the fact that the framework is flexible to allow tailoring easily. Experts 9 and 10, who deal with obsolescence in the nuclear and railway sectors respectively, agree that the EEE-FORCE framework is definitely suitable in these sectors and any other sector involving high-value equipment, high technology and long sustainment periods.

- **BENEFITS OF USING THE FRAMEWORK:**

Experts 1, 2 and 8 agree that the EEE-FORCE framework can provide an early estimate for obsolescence management costs before much detail is available as to engineering design (e.g. bill of materials). This could be very beneficial on projects for which the design is not frozen yet. Experts 1, 3, 5 and 6 highlighted that this framework provides a consistent way of illustrating obsolescence between the customer, prime contractor and suppliers. This common understanding allows parties to discuss obsolescence risk transfer. Additionally, experts 4, 6 and 7 agree that the framework can provide "what-if" scenarios to allow differing levels of support to the bid. This allows deciding the most cost-effective way to manage obsolescence. It gives a "menu" of levels of support for the customer to be offered at the bidding stage.

All the experts agree that the EEE-FORCE framework should be owned by the Obsolescence Management Team at the organisation level. Expert 1 argues that at a higher level, the ownership should stay with the MoD to preserve the common understanding across all parties, centralising and coordinating any further modifications and enhancements.

- **LIMITATIONS OF THE FRAMEWORK:**

Experts 1, 3, 6 and 7 agree that the EEE-FORCE framework user requires a good understanding about obsolescence, the support project and the product/components relationship, as well as access to the BoM and predictive data. The user also needs to have a good understanding about the framework to ensure consistency in use. Experts 1 and 2 highlighted that this framework requires good calibration against the organisation's past performance to gain confidence of its accuracy. Furthermore, experts 4, 7 and 8 agree that the framework can be time-consuming to populate, especially when defining bespoke ORPs is required. Additionally, expert 5 indicated that as a result of having the framework implemented as an Excel-based tool, it can become easily corrupted by incorrectly manipulating data.

Experts 1 and 5 highlight the opportunity that this framework provides to cascade the cost for obsolescence down the supply chain, now that the costs can be agreed; to save costs for spares buy; and to make accurate analysis based on assumptions and known data using a consistent costs model. However, experts 2, 6 and 7 express their concerns about the usage of this framework. Firstly, the fact that prime contractors may not be interested in cascading the obsolescence management down the supply chain. Secondly, persuading suppliers to share information needed to use the framework can be challenging. Finally, the fact that different users may misuse the tool and obtain widely varying cost estimates for equipment and systems that are essentially similar, or even equivalent.

- **USABILITY OF THE SOFTWARE PROTOTYPE:**

The experts identified the four main strongest features of the software prototype:

- Structured logical layout, straightforward navigation, clarity of approach, easy to follow and understand (Experts 1, 2, 5 and 8).
- Excel-based - no training required (Experts 3 and 4).
- Takes account of a wide range of variables (Expert 6).
- Customisable (Expert 7).

They also identified the weakest features:

- Some very busy screens can make it look complicated (Expert 1).
- More validation may be required (Expert 2).
- Need for a user guide that defines properly the concepts (Experts 3, 4, 6 and 8).
- Time consuming, especially due to the amount of manual input required for large programs (Experts 4, 7 and 8).
- Pasting data may corrupt the tool's operation (Expert 5).

The assessment of the intuitiveness of the software prototype, as well as the scale used to capture it in the questionnaire, is presented in Table 7-12. It shows that all the experts concur that the software prototype is quite intuitive.

Table 7-12 Is the software prototype intuitive? - Ratings

1	2	3	4	5	6	7	8	9	10
Counter-intuitive	Low intuitive				Quite intuitive				Very intuitive

Experts	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	AVG
Score	7	7	9	8	8	7	8	9	**7.88**

Six of the experts agree that the software prototype provide enough initial information. However, experts 2 and 7 disagree arguing that the user manual is required, especially to understand the degrees of sensitivity of variables.

The time required to populate the tool for a case study was uneven for the participating experts. Experts 2, 3, 4, 5 and 6 required less than four hours, whereas expert 8 required about 40 hours and expert 7 required 1 to 3 weeks, depending on project size.

All the experts agree that the terminology and concepts used in this framework are consistent and also that the key cost drivers are considered in this cost estimating framework. All of them also agree that the list of resolution techniques indicated in the framework is comprehensive and that the tool is flexible enough to adapt to the different levels of information available. Seven of them agree that the "coupling level" and "package density" concepts are valid. Expert 6 differs arguing that they appear somewhat academic and difficult to equate to real life situations. Seven of the experts also think that this framework is suitable for the pre-contract stage, although experts 7 and 8 argue that for this purpose a more detailed approach would be applied.

- **ASSUMPTIONS:**

The experts assessed whether each of the assumptions made in the framework are realistic. There are five assumptions.

a. Assumption 1: Any component is not expected to become obsolete more than once during the contracted period.

   Four experts (2, 3, 4 and 7) agree with the validity of this assumption, arguing that this approximation might lead to second-order errors, which are not significant. Along these lines, expert 7 explains that this assumption can be tolerated as the number of instances would be very low. However, the other four experts differ arguing that it may happen for long contracts as the life cycle of some components is becoming very short. Therefore, the validity of this assumption depends on the contract length and type of component.

b. Assumption 2: An obsolescence issue will only contribute to costs for the contract if the level of stock for that item is not enough to cover the contracted period.

   Seven experts agree with the validity of this assumption. Only expert 7 differs with them, indicating that storage costs for LTB need to be considered, especially if controlled environments are used (e.g. dry nitrogen stores).

c. Assumption 3: All the fleet is enhanced during mid-life upgrades.

   Four experts (2, 3, 7 and 8) agree with the validity of this assumption. However, the other four experts differ arguing that it not always happens.

d. Assumption 4: Emulation, Minor and Major Redesigns may resolve several obsolescence issues simultaneously. The "clustering" factor represents the number of redesigns that would be applied to resolve 100 obsolescence issues requiring a redesign.

   All the experts agree with the validity of this assumption. However, expert 3 indicates that for small systems this may not be possible, and expert 2 is concerned that this can be a rather subjective input that drastically affects output.

e. Assumption 5: The obsolescence resolution profiles mainly depend on the level of complexity and the level of proactiveness in managing obsolescence.

   All the experts agree with the validity of this assumption.

- **RESULTS:**

The feedback received from each expert after evaluating the output of the prototype, after populating it with information from the case studies, is summarised as follows in Table 7-13.

Table 7-13 Evaluation of the Output of Software Prototype by Experts

Experts	Feedback
Expert 2	Tool is capable of sensible cost predictions if inputs are manipulated interactively; experience needs to be built-up in how to set inputs sensibly against given project scenarios.
Expert 3	Cost initially considered too high mitigation methods. Revised and more realistic answer provided.
Expert 4	With minor adjustments to input data sheet model performed well and produced an answer.
Expert 5	Contract: The tool produced results within +/-£2k against absolute figures against an agreed contract. Absolute based on number of Years-to-End-of-Life predictions on BoM. Model uses percent risk based on specific criteria more accurate based on stock and complexity. Pre-contract: Costs estimated by tool within 5-10% of those calculated and actually presented to the customer. Good confidence in figure calculated by tool.
Expert 6	When comparative inputs were achieved, both the 3A and the 3B processes gave similar output, and comparable with in-house tool results.
Experts 7 and 8	The first run of the tool produced a very-high figure, due to incorrect coupling/package density definitions. It took several attempts to refine the input, to gain understanding of sensitivities. Once understood, results seem consistent with history.

The evaluation that each expert made of the repeatability of the prototype after populating it with the same information from the case study is summarised as follows in Table 7-14.

Table 7-14 Evaluation of the Repeatability of Software Prototype by Experts

Experts	Feedback
Experts 2, 3 and 4	Changing the data changed the answer so performed well.
Expert 5	Contract: Definition of parameters in organisation to ensure output was repeatable. Pre-contract: Due to consistent approach and automation of calculations - repeatability considered - high level of confidence.
Expert 6	Same inputs give same outputs.
Experts 7 and 8	Provided all tool variables used are the same, full repeatability achieved. Changing coupling/package level or profiles, requalification, etc had large impact on repeatability.

The evaluation that each expert made of the sensitivity/robustness of the prototype after populating it with information from the case studies is summarised as follows in Table 7-15.

Table 7-15 Sensitivity Analysis of Software Prototype by Experts

Experts	Feedback
Expert 2	Too sensitive to clustering input.
Expert 3	Allowed cost revisions.
Expert 4	Good.
Expert 5	Contract: No problems found after initial issues overcome. Pre-contract: Some additional data added that was not necessarily required - did not have any adverse effect on the tool operation - high level of confidence.
Expert 6	Considerable output variations are obtained by selecting the resolution, rather than following the profiles provided
Expert 7	Some aspects of sensitivity are not obvious and should be spelt out more clearly. The high sensitivity of the model makes that small differences in the assessment of integration level/complexity will have big implications on costs.
Expert 8	Some cell formats should be protected to avoid wrong entries (e.g. dates).

All the experts agree that the cost estimating framework is fit for the purpose from which it has been developed. However, experts 3 and 7 highlight the importance making sure that the user fully understands the tool and its sensitivities. Expert 5 explains that it provides detailed analysis; ability to customise results and pre-contract negotiation is enhanced with accurate resolution costs. Additionally, he argues that the output is simple to understand, consistent in approach and only requires limited info for a valid output.

All the experts agree that the Monte Carlo simulation applied is suitable to incorporate uncertainty to the cost estimate. Expert 5 indicates that it gives a mean value and upper and lower limit that could be used as the boundaries during contract negotiation. Moreover, expert 6 highlights that it provides a good measure of uncertainty.

Finally, all the experts have verified and validated the key formulae and architecture used in this framework.

7.5 Summary

In this Chapter, the implementation, verification and validation of the EEE-FORCE framework was presented. A total of seven case studies with seven obsolescence experts across four different organisations were carried out for this purpose, as well as qualitative validation with three more experts from other organisations.

In Section 7.2, the research methodology followed for the validation of the EEE-FORCE framework was presented. It included a detailed description of the experts that participated.

In Section 7.3, the author described the implementation of the EEE-FORCE framework into a tool using MS Excel and Visual Basic for Applications (VBA), detailing the structure of the tool and the data required at each step.

Section 7.4 presented the each of the seven case studies in detail, and subsequently provided a cross-case study analysis synthesis based on the responses that the experts gave to the questionnaire used during the case study sessions.

The next Chapter describes the implementation of the M-FORCE framework in an Excel-based tool and its subsequent validation by means of six case studies with current projects across the defence, aerospace and shipping industry.

THIS PAGE IS INTENTIONALLY LEFT BLANK

Chapter 8

8 VERIFICATION AND VALIDATION OF M-FORCE

8.1 Introduction

In the previous Chapter, the implementation, verification and validation of the “Electronic, Electrical and Electromechanical - Framework for Obsolescence Robust Cost Estimation” (EEE-FORCE) has been described. The purpose of this Chapter is to describe the implementation, verification and validation of the “Materials - Framework for Obsolescence Robust Cost Estimation” (M-FORCE). It has been implemented in an Excel-based tool and subsequently validated by means of six case studies with current projects across the defence, aerospace and shipping industry. Two of the case studies were related to the aerospace domain, one to the naval domain and three to the ammunition domain.

In Section 8.2, the research methodology followed for the validation of the M-FORCE framework in the aerospace, naval and ammunition domains, is presented. It includes a detailed description of the experts that participated.

In Section 8.3, the author describes the implementation of the M-FORCE framework into a tool using MS Excel and Visual Basic for Applications (VBA), detailing the structure of the tool and the data required at each step.

Section 8.4 presents each of the three case studies in the aerospace/naval domain in detail, and subsequently provides a cross-case study analysis synthesis based on the responses that the experts gave to the questionnaire used during the case study sessions. Section 8.5 is analogous to the previous section, but focused on the three case studies carried out in the ammunition domain.

8.2 Detailed Research Methodology for Case Studies

For the development of each case study, a copy of the tool was sent to the experts who were going to participate (their details are shown in Table 8-1). By means of a WebEx teleconference, the characteristics of the tool were explained to each of the participants, together with a demonstration of the usage of the tool using dummy data. Any questions that the participants had about the tool or the framework were clarified during this session. After this, the experts were in a position to start inputting the required data to the tool from a current project. In the case that the experts had any questions or doubts while doing this, they were able to contact the researcher by telephone to clarify them. Once the tool was populated with the relevant data, a 5- to 6-hour meeting was arranged with the researcher and the experts to run the tool, to discuss the outcomes and to fill in a validation questionnaire (see Appendices A.9 and A.10) assessing the results of the case study. Examples of the questions are shown as follows.

- Is the logic (process/rationale) to build the cost estimate valid?
- Is the framework suitable for the bid stage?
- Is this cost estimating framework truly generalisable to different defence and aerospace platforms?
- What are the potential limitations and challenges in using the tool?
- Evaluation of the output of the tool after populating it with information from the case study

The responses were analysed by identifying similarities, differences and unique responses across the different participants. The outcomes from this analysis are summarised further along in this Chapter.

Table 8-1 Experts that Participated in M-FORCE Validation

Expert Number	Organisation	Role	Domain of Expertise	Years of Experience on Obsolescence
1	ORG_J	Materials Engineer	Aerospace	10
2	ORG_J	Obsolescence Manager	Aerospace	4
3	ORG_D	Materials Engineer	Aerospace	30
4	ORG_E	Obsolescence Manager	Naval	5
5	ORG_E	Materials Engineer	Naval	10
6	ORG_F	Obsolescence Manager	Ammunition	3
7	ORG_F	Obsolescence Technician	Ammunition	2

8.3 M-FORCE Implementation and Verification

The M-FORCE framework was implemented into a tool using MS Excel and Visual Basic for Applications (VBA). The tool is structured according to the process described for the M-FORCE framework in Chapter 6. The sequence of tabs is as follows, including the data required at each step.

1. Cover.

   This is the front page of the tool, showing the logo and the developer's name. Due to the differences in the cost estimation process between ammunition and air platforms, two buttons – AIR and AMMUNITION – are included in this menu so that the user will be taken to a different (but analogous) set of tabs for each of them.

2. Instructions.

   This tab provides a link to the user manual, as well as a summary of the key instructions required to use this tool, including the scope, the definition of key concepts and the data input process. This set of instruction has been customised for the aerospace and ammunition domains in two different tabs.

3. STEP 1: User Information.

   The user's name and the date of use of the tool are recorded in this tab. This allows having traceability about when the tool has been applied to each particular project and who has input the data or made amendments.

4. STEP 2: System/Products Information.

   This tab has been customised for the aerospace and ammunition domains in two different tabs. In both of them it is requested to input the project name, the duration support contract and indicate whether the list of components/materials is available or not. For the ammunition domain, the following inputs are also required.

   - Select the type of platform.
     - Large Calibre Ammunition (Artillery, Tank, Mortar)
     - Medium Calibre Ammunition (20-40mm)
     - Small Calibre Ammunition (5.5-7.62mm)
   - Indicate the life cycle of materials and uncertainty in these values (default values are provided).
     - Long Life Cycle (Metallic, Non Metallic parts, Energetic Components)
     - Medium Life Cycle (Energetic Materials)
     - Short Life Cycle (Other)

   Once STEP 2 is populated, if the list of components/materials is available, the user will be sent to STEP 3A, and to STEP 3B otherwise.

5. STEP 3A: Detailed Component Information (BoM).

   This tab has been customised for the aerospace and ammunition domains in two different tabs. In both cases, it is requested to input the list of components/materials used in the system. In the aerospace tab, it is required to assess each component/material in terms of: the level of complexity, the level of criticality, the level of integration and the probability of becoming obsolete during the contracted period. However, in the ammunition tab, only the type of material is required, as the other parameters are correlated to this variable and the type of platform.

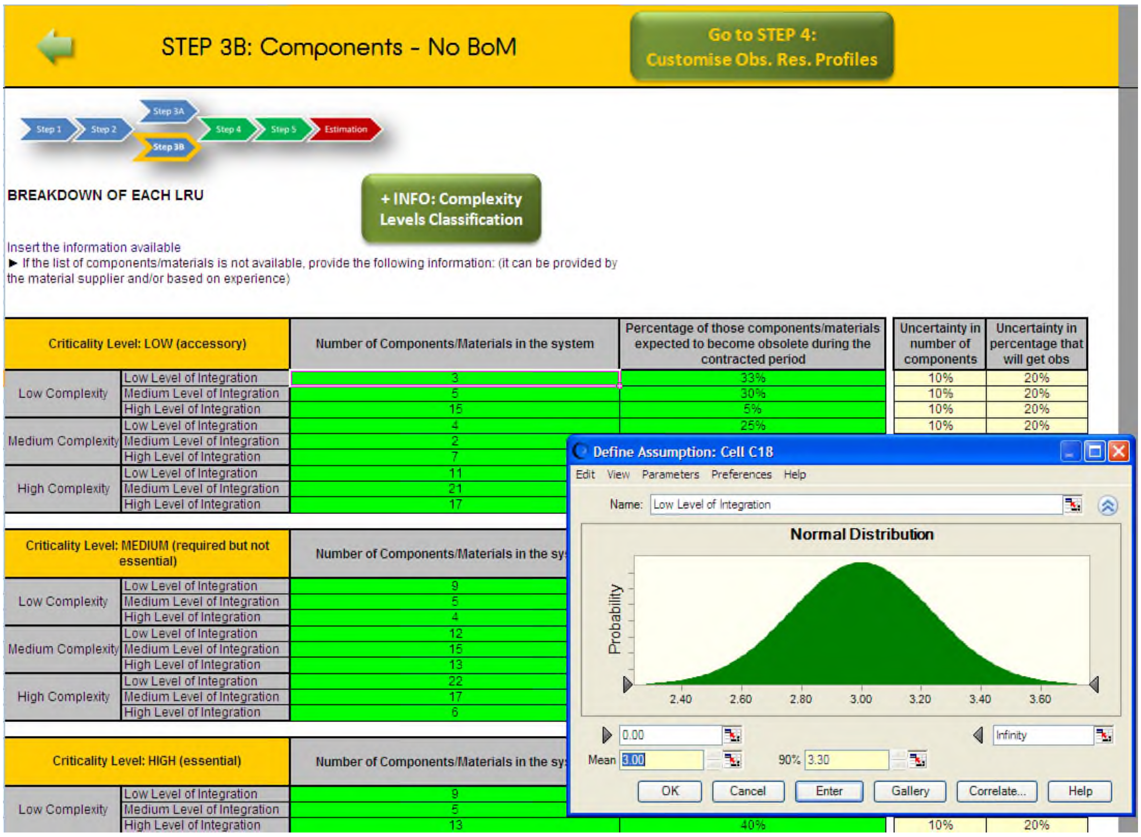


Figure 8-1 M-FORCE Input Form STEP 3B in Aerospace Domain

6. STEP 3B: Component Information Based on Expert Judgement.

This tab has been customised for the aerospace and ammunition domains in two different tabs. In this tab, the user should input the information related to the components of the products for which detailed information is not available. In the aerospace tab (Figure 8-1), expert judgement shall be applied to estimate the number of components/materials contained in the system for each level of criticality, each level of complexity, and each level of integration. It is also required to estimate how many of them are expected to become obsolete during the contracted period. The user can also specify the level of uncertainty for each input. In the ammunition tab, expert judgement shall be applied to estimate the number of components/materials contained in the system for each type of component/material. Likewise, the user can also specify the level of uncertainty for each input.

7. STEP 4: Obsolescence Resolution Profiles (ORP).
   This tab is only applicable to the aerospace domain. The Obsolescence Resolution Profile (ORP) resulting from the study explained in Chapter 6 is provided in this step, so that the user has the possibility to modify it if necessary.

8. STEP 5: Obsolescence Cost Metrics (OCM).
   This tab has been customised for the aerospace and ammunition domains in two different tabs. The aerospace tab includes the weight matrix described in Chapter 6, and allows the user to modify the values if necessary. The user will also have to input a calibration point that enables turning the weight matrix into a cost metrics table. The level of uncertainty for the value of the calibration point is also required. A snapshot of this tab is shown in Figure 8-2, where the table at the top is the weight matrix and the table at the bottom represents the obsolescence cost metrics. Between the two tables there are the results of the pairwise comparison between cost drivers and the different levels in each of them. A change in these values will automatically modify the values in the weight matrix and hence the values in the obsolescence cost metrics. The calibration point used represents the NRE cost of resolving an obsolescence issue with the following characteristics: low level of complexity, low level of criticality, low level of integration and resolved finding a FFF replacement with low effort.

   The ammunition tab includes a database with 23 entries that represent the possible types of obsolescence issues according to the following parameters.

- Type of Platform
- Type of Material
- Level of Criticality
- Level of Complexity
- Level of Integration
- Resolution Approach

For each entry it is specified the most likely NRE cost of resolving the obsolescence issue and its probability, as explained in Chapter 6. The user has the possibility to customise this database if necessary.

Cost Estimation

WEIGHT MATRIX FOR AIR PLA

	COMPLEXITY	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIU
	CRITICALITY	LOW	LOW	LOW	MEDIUM	MEDIUM	MEDIUM	HIGH	HIGH	HIGH	LOW	LOW	LOW	MEDIUM	MEDIU
	INTEGRATION	LOW	MEDIUM	HIGH	LOW	MEDIUM	HIGH	LOW	MEDIUM	HIGH	LOW	MEDIUM	HIGH	LOW	MEDIU
RESOLUTION	FFF REPLACEMENT - LOW EFFORT	42.7	140	171	104	341	416	137	450	550	167	547	668	406	1331
	FFF REPLACEMENT - HIGH EFFORT	85.4	280	342	208	681	831	275	901	1099	334	1095	1336	812	2663
	MINOR REDESIGN	891	2920	3564	2167	7104	8669	2866	9393	11462	3483	11416	13931	8472	2776
	MEDIUM REDESIGN	1202	3940	4809	2924	9585	11697	3866	12673	15466	4699	15404	18798	11431	3746

COMPLEXITY	LOW	MEDIUM	HIGH
	3.142857	12.28571	18.85714

CRITICALITY	LOW	MEDIUM	HIGH
	5.285714	12.85714	17

INTEGRATION	LOW	MEDIUM	HIGH
	2.571429	8.428571	10.28571

RESOLUTION	FFF REPLACEMENT - LOW EFFORT	1
	FFF REPLACEMENT - HIGH EFFORT	2
	MINOR REDESIGN	20.85714
	MEDIUM REDESIGN	28.14286

COST	COMPLEXITY	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	MEDIUM
	CRITICALITY	LOW	LOW	LOW	MEDIUM	MEDIUM	MEDIUM	HIGH	HIGH	HIGH	LOW
	INTEGRATION	LOW	MEDIUM	HIGH	LOW	MEDIUM	HIGH	LOW	MEDIUM	HIGH	LOW
RESOLUTION	FFF REPLACEMENT - LOW EFFORT	£500	£1,639	£2,000	£1,216	£3,986	£4,865	£1,608	£5,271	£6,432	£1,955
	FFF REPLACEMENT - HIGH EFFORT	£1,000	£3,278	£4,000	£2,432	£7,973	£9,730	£3,216	£10,542	£12,865	£3,909
	MINOR REDESIGN	£10,429	£34,183	£41,714	£25,367	£83,147	£101,467	£33,541	£109,938	£134,162	£40,766
	MEDIUM REDESIGN	£14,071	£46,123	£56,286	£34,228	£112,191	£136,911	£45,257	£148,342	£181,027	£55,006

Calibration Reference: Lowest case=500£	500
Uncertainty (%)	10%
Conversion Factor (weight into cost)	11.70489

Figure 8-2 Weight Matrix and Obsolescence Cost Metrics for the Aerospace Domain

9. Results.
   Once the previous steps have been followed, the NRE cost of obsolescence can be automatically estimated by clicking the "Calculate Cost Estimation" button. In order to apply the Monte Carlo simulation to take uncertainty into account and get as a result a cost distribution, an add-on to MS Excel called Crystal Ball is applied. The user only has to click the "Start" button from the Crystal Ball ribbon, and the simulation will start. Once the simulation has finished, the final distribution of cost will be shown and the user can do a statistical analysis of it and/or print a report of it.

Macros have been implemented in the development of this tool to facilitate the navigation across the tabs (steps), making it more user-friendly. The algorithms used in this framework are detailed in Appendix D. They have been verified in collaboration with a professor of Cranfield University, who has more than ten years experience in cost engineering and modelling, and amended accordingly. This process took place prior to starting the case studies for validation.

The assumptions made for the implementation of this framework are indicated as follows.

- Assumption 1: The level of complexity, level of criticality and level of integration are not correlated.
- Assumption 2: A calibration data point can be applied to derive the spectrum of cost metrics based on the "weight matrix".
- Assumption 3: The Obsolescence Management Level does not have a significant impact on the NRE cost of resolving obsolescence issues for materials.
- Assumption 4: The cost of materials obsolescence is independent from EEE components obsolescence.
- Assumption 5: The cost of materials obsolescence is independent from software obsolescence.

These assumptions were included in the questionnaire used in the validation process, so the experts were able to further assess their validity.

8.4 M-FORCE Validation for the Aerospace Domain

The M-FORCE framework has been validated for the aerospace domain by applying it to two case studies from two different companies in the UK defence and aerospace sector. Additionally, a third case study with a different organisation in the shipping industry was carried out to verify that this framework can also be applied to the naval domain. A description of each case study is provided as follows.

8.4.1 Case Study 1: Airframe of Military Aircraft

This case study covers the obsolescence management for the support of the airframe of a large military aircraft for ten years. It is currently at the manufacturing phase of the CADMID cycle. The list of specified materials for this case study is fully available. This case study has been chosen due to the availability of this information and because it represents a good example of the application of the proposed framework.

This case study was carried out in collaboration with the Materials Engineer and the Obsolescence Manager of the prime contractor, who have 10 and 4 years of experience on managing materials obsolescence respectively (experts 1 and 2 in Table 8-1). The inputs are summarised in Table 8-2.

Table 8-2 Summary of Inputs for Case Study 1 (Aerospace Domain)

Number of Components/Materials	353
Contract Duration	10 years
Type of Platform	Aerospace
Number of Components/Materials for each Level of Complexity	- Low: 174 - Medium: 163 - High: 16
Number of Components/Materials for each Level of Criticality	- Low: 93 - Medium: 243 - High: 17
Number of Components/Materials for each Level of Integration	- Low: 205 - Medium: 129

	- High: 19
Number of Components/Materials for each Level of Probability of becoming obsolete during the contracted period	- Low: 278 - Medium: 65 - High: 10
Level of Information Available	Specified Materials/Components List
Obsolescence Resolution Profile	Default
Weight Matrix	Default
Calibration Point	£500
Uncertainty in Calibration Point	10%

As a result, the M-FORCE framework estimated that the NRE cost of resolving the obsolescence issues during the support period will be £3.79m. The result of running the Monte Carlo Simulation is displayed in Figure 8-3. It shows that after running 1000 trials, a gamma distribution represents the probability of the costs estimated. The mean (μ) of this distribution is £3.798m and the standard deviation (σ) is £305k.

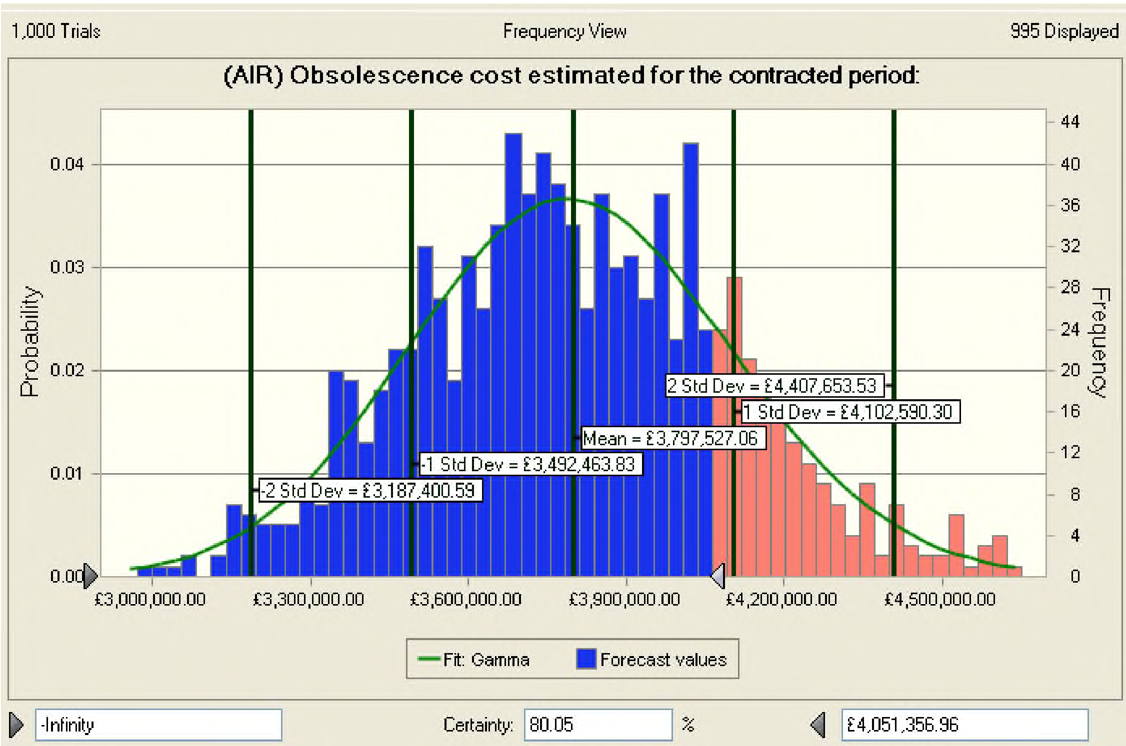


Figure 8-3 Output of M-FORCE after Running Monte Carlo Simulation in Case Study 1 (Aerospace Domain)

The results could not be compared with real figures because the case study is on a real project still at the Manufacturing stage in the CADMID cycle. However, the results were analysed by the two experts, concluding that the cost estimated "looks a bit lower than expected".

8.4.2 Case Study 2: Printed Circuit Board (PCB)

This case study covers the obsolescence management for the support of a printed circuit board (PCB) populated construction with military specified connectors and finished to housing. The BoM for this case study is fully available. The support contract duration is 15 years. The case study was carried out in collaboration with the Obsolescence Manager of the subcontractor, who has 30 years of experience on managing materials obsolescence (expert 3 in Table 8-1). The inputs are summarised in Table 8-3.

Table 8-3 Summary of Inputs for Case Study 2 (Aerospace Domain)

Number of Components/Materials	12
Contract Duration	15 years
Type of Platform	Aerospace
Number of Components/Materials for each Level of Complexity	- Low: 5 - Medium: 5 - High: 2
Number of Components/Materials for each Level of Criticality	- Low: 5 - Medium: 6 - High: 1
Number of Components/Materials for each Level of Integration	- Low: 0 - Medium: 12 - High: 0
Number of Components/Materials for each Level of Probability of becoming obsolete during the contracted period	- Low: 4 - Medium: 3 - High: 5
Level of Information Available	Specified Materials/Components List
Obsolescence Resolution Profile	Bespoke
Weight Matrix	Default

Calibration Point	£50
Uncertainty in Calibration Point	10%

The Obsolescence Resolution Profiles were customised to represent the current practice in this project, as shown in Figure 8-4.

AIR PLATFORM	COMPLEXITY LEVEL		
	Low	Medium	High
FFF replacement - Low effort	55.0%	40.0%	25.0%
FFF replacement - High effort	20.0%	25.0%	30.0%
Minor Redesign	15.0%	20.0%	25.0%
Medium Redesign	10.0%	15.0%	20.0%
TOTAL	100.0%	100.0%	100.0%

Figure 8-4 Bespoke Obsolescence Resolution Profiles for Case Study 2 (Aerospace Domain)

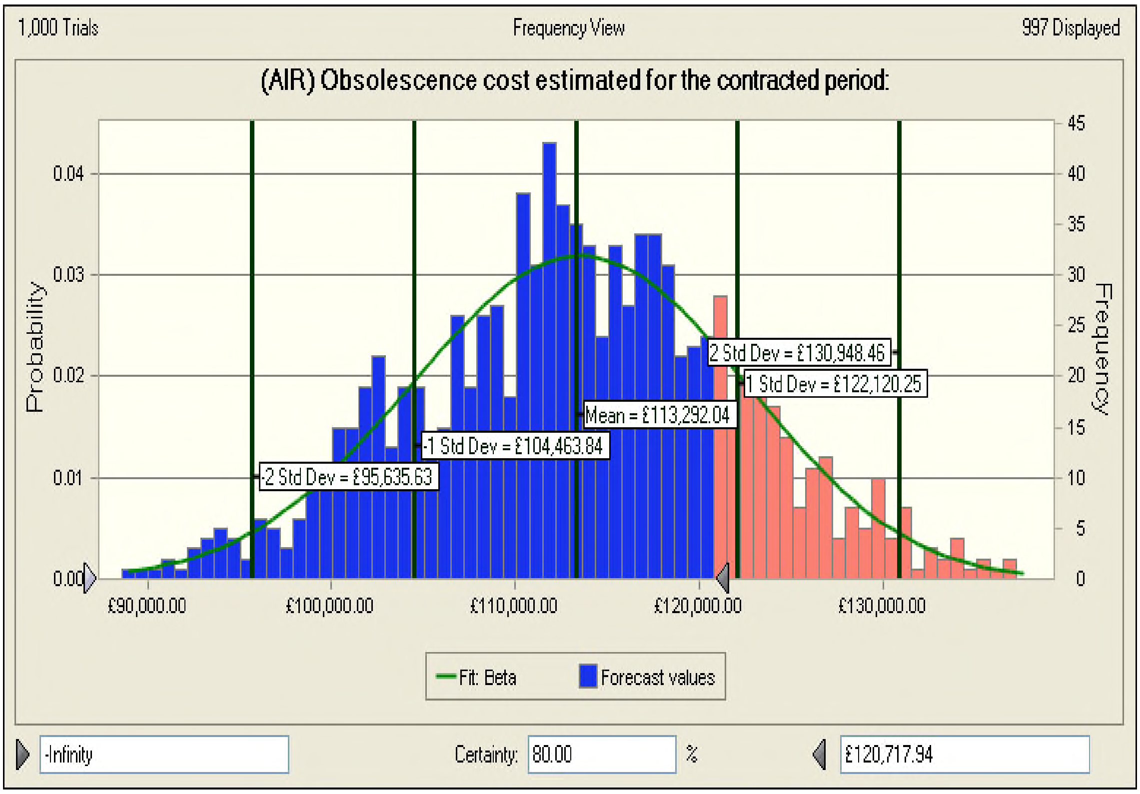


Figure 8-5 Output of M-FORCE after Running Monte Carlo Simulation in Case Study 2 (Aerospace Domain)

As a result, the M-FORCE framework estimated that the NRE cost of resolving materials obsolescence issues will be £113,455. The result of running the Monte Carlo Simulation is displayed in Figure 8-5. It shows that after running 1000 trials, a beta distribution represents the probability of the costs estimated. The mean (μ) of this distribution is £113,292 and the standard deviation (σ) is £8,828. After analysing the results of the M-FORCE, the expert that participated in this case study stated that it “resulted in numbers that have been estimated from past case studies and real past events”.

8.4.3 Case Study 3

This case study covers the obsolescence management for the support of a marine gas turbine engine, used for civil applications, during 25 years. Full detail of the list of materials/components is available. The project is currently commencing the in-service phase of the CADMID cycle. The case study was carried out in collaboration with an Obsolescence Manager and a Materials Engineer, who have five and ten years of experience on managing obsolescence respectively (experts 4 and 5 in Table 8-1). The inputs are summarised in Table 8-4.

Table 8-4 Summary of Inputs for Case Study 3 (Maritime Domain)

Number of Components/Materials	21
Contract Duration	25 years
Type of Platform	Maritime
Number of Components/Materials for each Level of Complexity	- Low: 5 - Medium: 6 - High: 10
Number of Components/Materials for each Level of Criticality	- Low: 0 - Medium: 0 - High: 21
Number of Components/Materials for each Level of Integration	- Low: 0 - Medium: 12 - High: 9
Number of Components/Materials for each Level of Probability of	- Low: 11

becoming obsolete during the contracted period	- Medium: 9 - High: 1
Level of Information Available	Specified Materials/Components List
Obsolescence Resolution Profile	Default
Weight Matrix	Default
Calibration Point	£ 2000
Uncertainty in Calibration Point	10%

As a result, the M-FORCE framework estimated that the NRE cost of resolving the materials obsolescence issues will be £10.697m. In this case study, the Monte Carlo Simulation was run twice, changing the number of trials, to assess how this parameter influences the results. Figure 8-6 shows that after running 1,000 trials, a beta distribution represents the probability of the costs estimated. The mean (μ) of this distribution is £10.103m and the standard deviation (σ) is £795k. Figure 8-7 shows that after running 10,000 trials, a lognormal distribution represents the probability of the costs estimated. The mean (μ) of this distribution is £10.127m and the standard deviation (σ) is £789k.

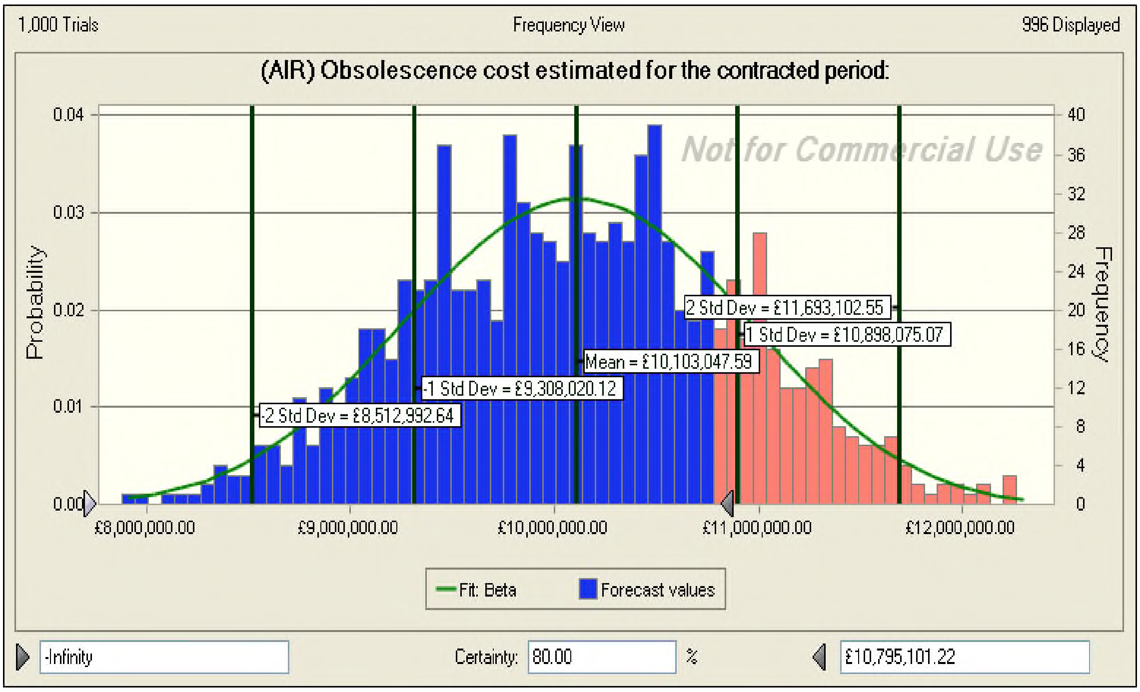


Figure 8-6 Output of M-FORCE after Running Monte Carlo Simulation for Case Study 3 (Maritime Domain) – 1,000 trials

A comparison between the results of the two Monte Carlo Simulations shows that, although the type of curve that best fits the distribution changes from a Beta to a Lognormal, the mean (μ) and the standard deviation (σ) do not change significantly from one to another. This shows that running the Monte Carlo Simulation for 1,000 trials is enough to achieve good results.

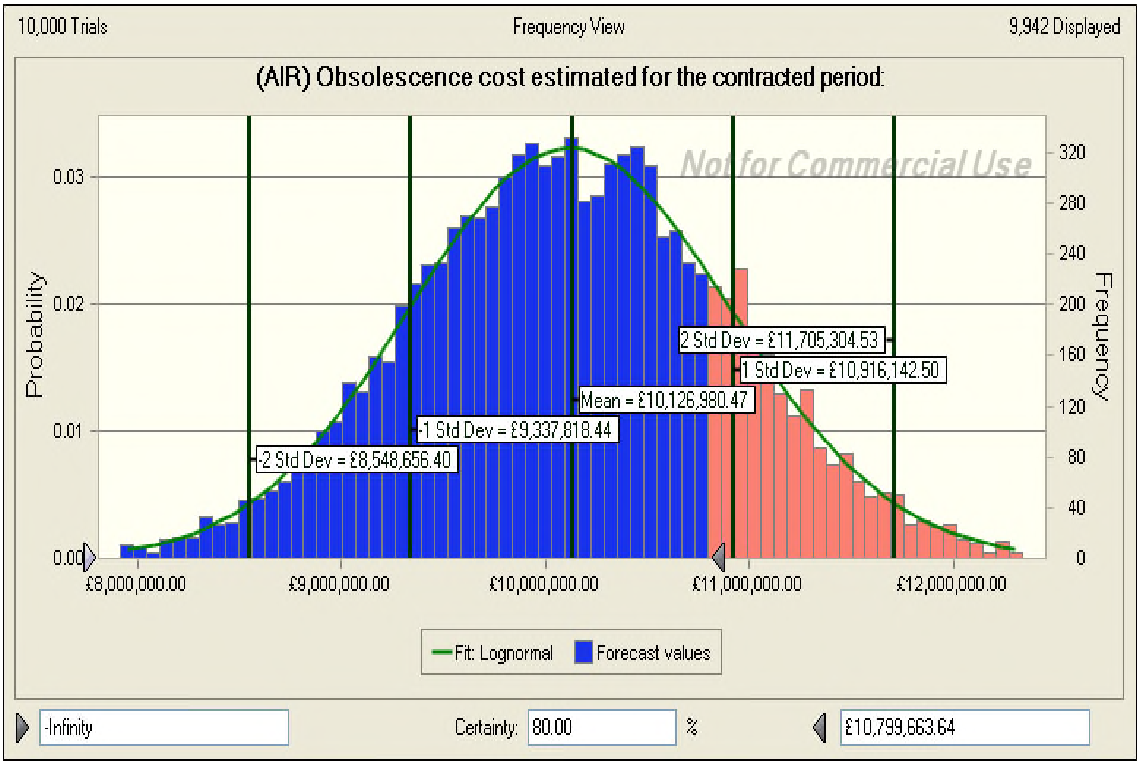


Figure 8-7 Output of M-FORCE after Running Monte Carlo Simulation for Case Study 3 (Maritime Domain) – 10,000 trials

After analysing the results of the M-FORCE for this case study, the two experts concurred that the estimation is what they expected. Furthermore, the uncertainty expected by the experts around that figure was ±£1m, which is consistent with the resulting standard deviation (£789k).

This case study shows that the M-FORCE customised for the aerospace domain has potential to be applied in the maritime domain.

8.4.4 Cross-Case Study Analysis Synthesis

A cross-case study analysis and comparison has been carried out based on the responses that the five experts (1-5 in Table 8-1) provided in their questionnaires during the interviews. The results are presented as follows.

- **LOGIC:**

The responses to the question "How logical is the cost estimating process for obsolescence?", as well as the scale used to capture them in the questionnaire, are presented in Table 8-5.

Table 8-5 How logical is the cost estimating process for obsolescence? - Ratings

1	2	3	4	5	6	7	8	9	10
Totally Invalid	Valid, with major deficiencies				Valid, with minor deficiencies				Totally valid

Experts	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	AVG
Score	8	8	7	7	7	**7.4**

The five experts agree that the logic of the cost estimating process is valid, although they have identified minor deficiencies. Experts 1 and 2 indicate that this framework provides a simplification of the complexity of materials obsolescence. Expert 3 expresses that the default relative weightings of resolution seem a bit low. Experts 4 and 5 highlight that the process is valid for the maritime domain, but it would be better to have just an input sheet.

The responses to the question "Is the framework suitable for the bid stage?", as well as the scale used to capture them in the questionnaire, are presented in Table 8-6.

Table 8-6 Is the framework suitable for the bid stage? - Ratings

1	2	3	4	5	6	7	8	9	10
Totally unsuitable	Suitable, with major deficiencies				Suitable, with minor deficiencies				Totally suitable

Experts	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	AVG
Score	8	8	8	6	7	**7.4**

The five experts agree that the framework is suitable for the bid stage, although they have identified minor deficiencies. Experts 1 and 2 highlight that it is based on experience rather than real data. Expert 3 argues that it may need slight modifications for other specific product range.

- **GENERALISABILITY:**

The five experts agree that the M-FORCE framework is suitable for defence and civil aerospace applications, as well as maritime. They also agree that it can be easily calibrated to be applied to any type of support project in those domains. Additionally, they all concur that the list of resolution techniques indicated in the framework is complete.

- **BENEFITS OF USING THE FRAMEWORK:**

Experts 1, 2, 4 and 5 argue that this framework provides a standard process to estimate, based on data rather than just guessing, the cost of obsolescence and supports contracting for availability. This very useful at the bidding stage, so that it gives confidence on the figures negotiated for these contracts. They highlight that it provides repeatable results with clearly defined inputs and outputs. In addition, expert 3 indicates that it also allows investigation of alternatives and anticipated legislative changes to be examined.

The experts discussed the stages of the CADMID cycle in which the M-FORCE framework can be used. While experts 4 and 5 agree that it could be used at any stage in the CADMID cycle, experts 1, 2 and 3 argue that it can be only be used at DMI stages, because at the Concept stage there may not be sufficient information.

There is a lack of consensus among the experts about who should own the tool in the organisation. Expert 1 states that it should be owned by the project bid team, whereas expert 3 argues that it should be shared between Materials Engineer and Product Manager. Experts 2, 4 and 5 agree that it should be owned by the engineering team, and the output should go to the commercial team.

- **LIMITATIONS OF THE FRAMEWORK:**

Experts 1 and 2 highlight that the user of this framework requires technical knowledge about materials and about the platform, so that the commercial team, for instance, cannot use it. Moreover, experts 3, 4 and 5 agree that the M-FORCE needs to be fully tested before full reliance is ascribed and it can get accepted across the business. Experts 4 and 5 also indicate that the assessment should be done for different contract durations simultaneously, so it eases scenarios analysis.

- **USABILITY OF THE SOFTWARE PROTOTYPE:**

Experts 1 and 2 emphasise that the flexibility of this framework to adapt to different levels of data available is one of its strongest features. Likewise, experts 4 and 5 highlight that the tool is easy to use and easy to explain as a key strength. In addition, expert 3 stresses the ability that the framework provides to cost obsolescence versus legislative changes. However, experts 1 and 2 indicate that the lack of materials obsolescence forecasting tools, in sharp contrast with the tools available for EEE components, results in this framework relying on expert judgement from the user.

The assessment of the intuitiveness of the software prototype, as well as the scale used to capture it in the questionnaire, is presented in Table 8-7. It shows that all the experts concur that the software prototype is quite intuitive.

Table 8-7 Is the software prototype intuitive? - Ratings

1	2	3	4	5	6	7	8	9	10
Counter-intuitive	Low intuitive				Quite intuitive				Very intuitive

Experts	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	**AVG**
Score	7	7	7	8	8	**7.4**

All the experts agree the following points about the framework:

- The terminology and concepts used are consistent.
- The key cost drivers are considered.

- It is flexible enough to adapt to the different levels of information available. Although, expert 4 argues that it is good enough at assembly level, but it needs to be more flexible for low-level items. Therefore, it would be useful to generalise the low risk components and provide more detail for key components, combining STEP3A and STEP3B.
- The materials complexity classification defined is valid. Although, expert 4 argues that non-standard manufacturing techniques and low number of suppliers should be in high complexity.
- The materials criticality classification defined in the tool is valid.

- **ASSUMPTIONS:**

All of them agree as well with the validity of the following assumptions:

- The level of complexity, level of criticality and level of integration are not correlated.
- A calibration data point can be applied to derive the spectrum of cost metrics based on the “weight matrix”.
- The Obsolescence Management Level does not have a significant impact on the NRE cost of resolving obsolescence issues for materials.
- The cost of materials obsolescence is independent from EEE components obsolescence.
- The cost of materials obsolescence is independent from software obsolescence.

- **RESULTS:**

All the experts agree that the cost estimating framework is accurate enough for the purpose from which it has been developed. Indeed, expert 3 reasserts that it offers him a good analysis of obsolescence into materials. However, experts 1 and 2 warn that the accuracy will highly depend on the availability of the data and how reliable it is.

All the experts also agree that the Monte Carlo simulation applied is suitable to incorporate uncertainty to the cost estimate. Indeed, expert 3 reasserts that this simulation technique is becoming an industry standard. As an enhancement in the framework, experts 4 and 5 indicate that it would be good to indicate the uncertainty on the probability of becoming obsolete in STEP 3A.

Finally, all the experts have verified and validated the key formulae and architecture used in this framework.

8.5 M-FORCE Validation for the Ammunition Domain

The M-FORCE framework has been validated for the ammunition domain by applying it to three case studies in the UK defence sector. Due to the fact that these case studies are related to projects which are still at early stages in the CADMID cycle, the assessment of the outcomes of the M-FORCE was based on expert judgement. These case studies were carried out in collaboration with experts 6 and 7 in Table 8-1. A description of each case study is provided as follows.

8.5.1 Case Study 1

This case study covers the obsolescence management for the support of Small Calibre Ammunition during 10 years. The BoM is fully available. The inputs are summarised in Table 8-8.

Table 8-8 Summary of Inputs for Case Study 1 (ammunition domain)

Number of Components/Materials	54
Contract Duration	10 years
Type of Platform	Small Calibre Ammunition
Life Cycle of Materials	- Long: 25 years - Medium: 12.5 years - Short: 5 years
Uncertainty for Life Cycle of Materials	- Long: 1 year - Medium: 1 year - Short: 1 year
Types of Number of Components/Materials for each Level of Integration	- Metallic: 19 - Non Metallic parts: 0 - Energetic Components: 3

	- Energetic Materials: 6 - Others: 26
Cost Metrics and Probability Database	Default
Uncertainty in Cost Metrics	10%

As a result, the M-FORCE framework estimated that the NRE cost of resolving materials obsolescence issues will be £852,401. The result of running the Monte Carlo Simulation is displayed in Figure 8-8. It shows that after running 1000 trials, a beta distribution represents the probability of the costs estimated. The mean (μ) of this distribution is £854.34k and the standard deviation (σ) is £38,575. The experts agree that this estimate is reasonable, based on likely costs on annual basis for Small Calibre Ammunition obsolescence. Although the output looks reasonable, there is no sufficient data on past obsolescence costs to confirm the accuracy of the output.

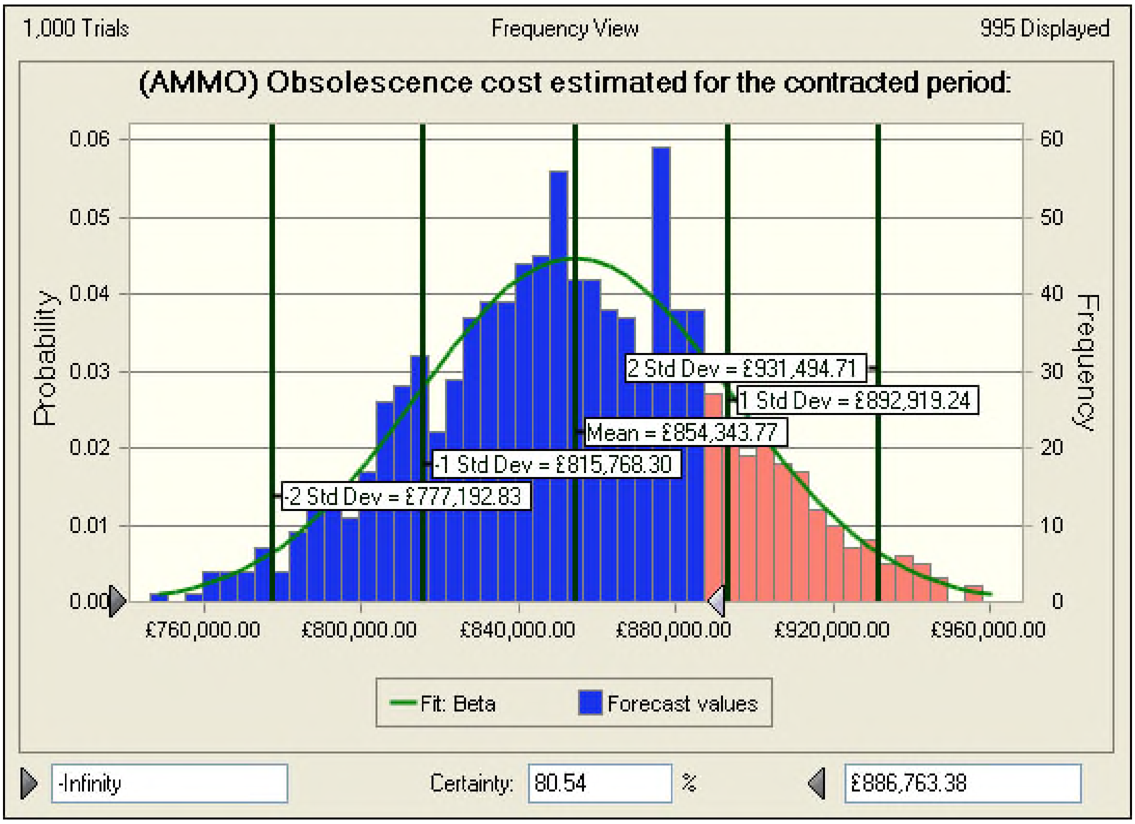


Figure 8-8 Output of M-FORCE after Running Monte Carlo Simulation for Case Study 1 (ammunition domain)

8.5.2 Case Study 2

This case study covers the obsolescence management for the support of Medium Calibre Ammunition for three years. This represents a recent design (less than 6 years design) in regular manufacture (annual deliveries). The inputs are summarised in Table 8-9.

Table 8-9 Summary of Inputs for Case Study 2 (ammunition domain)

Number of Components/Materials	32
Contract Duration	3 years
Type of Platform	Medium Calibre Ammunition
Life Cycle of Materials	- Long: 25 years - Medium: 12.5 years - Short: 5 years
Uncertainty for Life Cycle of Materials	- Long: 1 year - Medium: 1 year - Short: 1 year
Types of Number of Components/Materials for each Level of Integration	- Metallic: 5 - Non Metallic parts: 2 - Energetic Components: 1 - Energetic Materials: 2 - Others: 22
Cost Metrics and Probability Database	Default
Uncertainty in Cost Metrics	10%

As a result, the M-FORCE framework estimated that the NRE cost of resolving materials obsolescence issues will be £402,367. The result of running the Monte Carlo Simulation is displayed in Figure 8-9. It shows that after running 1000 trials, a max extreme distribution represents the probability of the costs estimated. The mean (μ) of this distribution is £408,184 and the standard deviation (σ) is £40,240. The experts agree that the costs estimated are higher than expected. It has been identified the need to factor in age of design and frequency of manufacture, as both affect obsolescence risk and likely costs.

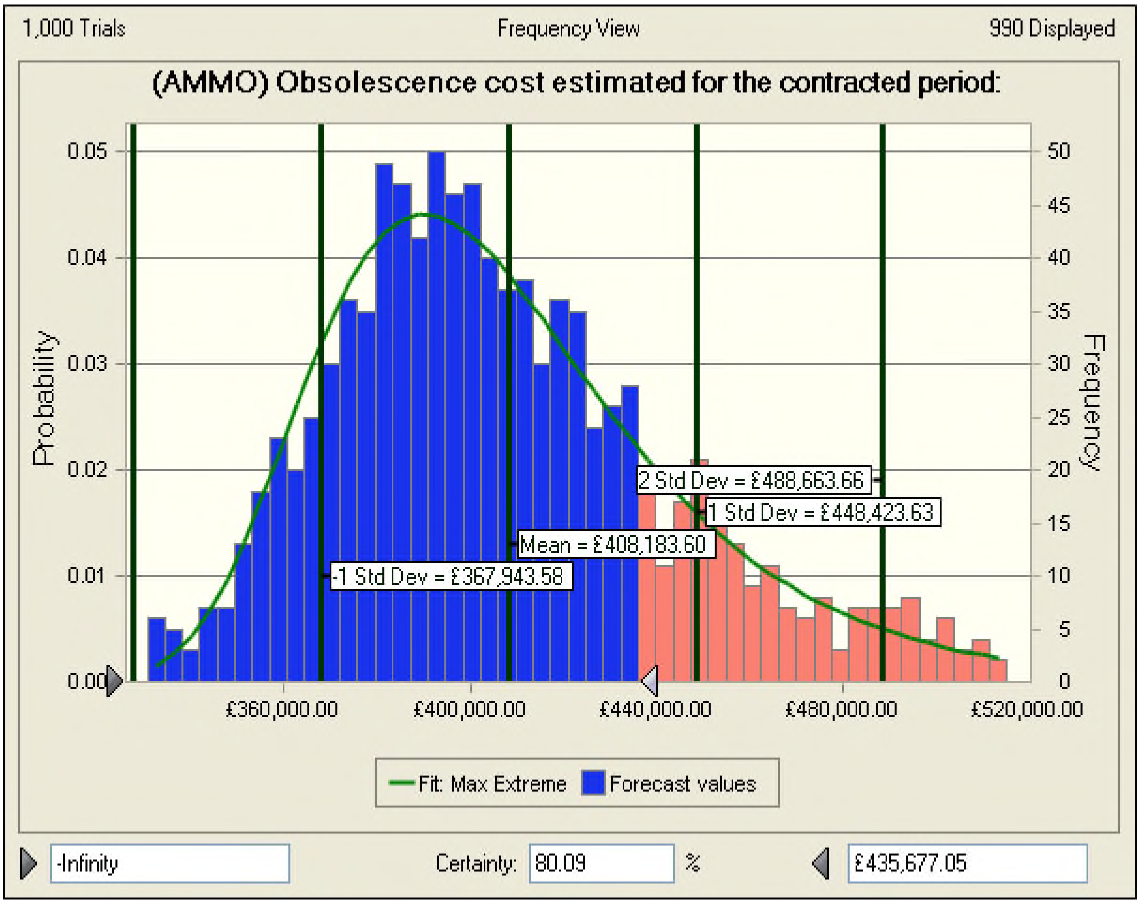


Figure 8-9 Output of M-FORCE after Running Monte Carlo Simulation for Case Study 2 (ammunition domain)

8.5.3 Case Study 3

This case study covers the obsolescence management for the support of Large Calibre Ammunition for three years. This represents an old design (more than 30 years design) in regular manufacture (annual deliveries). The inputs are summarised in Table 8-10.

Table 8-10 Summary of Inputs for Case Study 3 (ammunition domain)

Number of Components/Materials	26
Contract Duration	3 years
Type of Platform	Large Calibre Ammunition
Life Cycle of Materials	- Long: 25 years - Medium: 12.5 years - Short: 5 years
Uncertainty for Life Cycle of Materials	- Long: 1 year - Medium: 1 year - Short: 1 year
Types of Number of Components/Materials for each Level of Integration	- Metallic: 5 - Non Metallic parts: 4 - Energetic Components: 0 - Energetic Materials: 2 - Others: 15
Cost Metrics and Probability Database	Default
Uncertainty in Cost Metrics	10%

As a result, the M-FORCE framework estimated that the NRE cost of resolving materials obsolescence issues will be £605,352. The result of running the Monte Carlo Simulation is displayed in Figure 8-10. It shows that after running 1000 trials, a lognormal distribution represents the probability of the costs estimated. The mean (μ) of this distribution is £612,376 and the standard deviation (σ) is £38,034. The experts agree that the costs estimated are higher than expected. Similarly to the previous case study, it has been identified the need to factor in age of design and regularity of manufacture, as both affect obsolescence risk and likely costs.

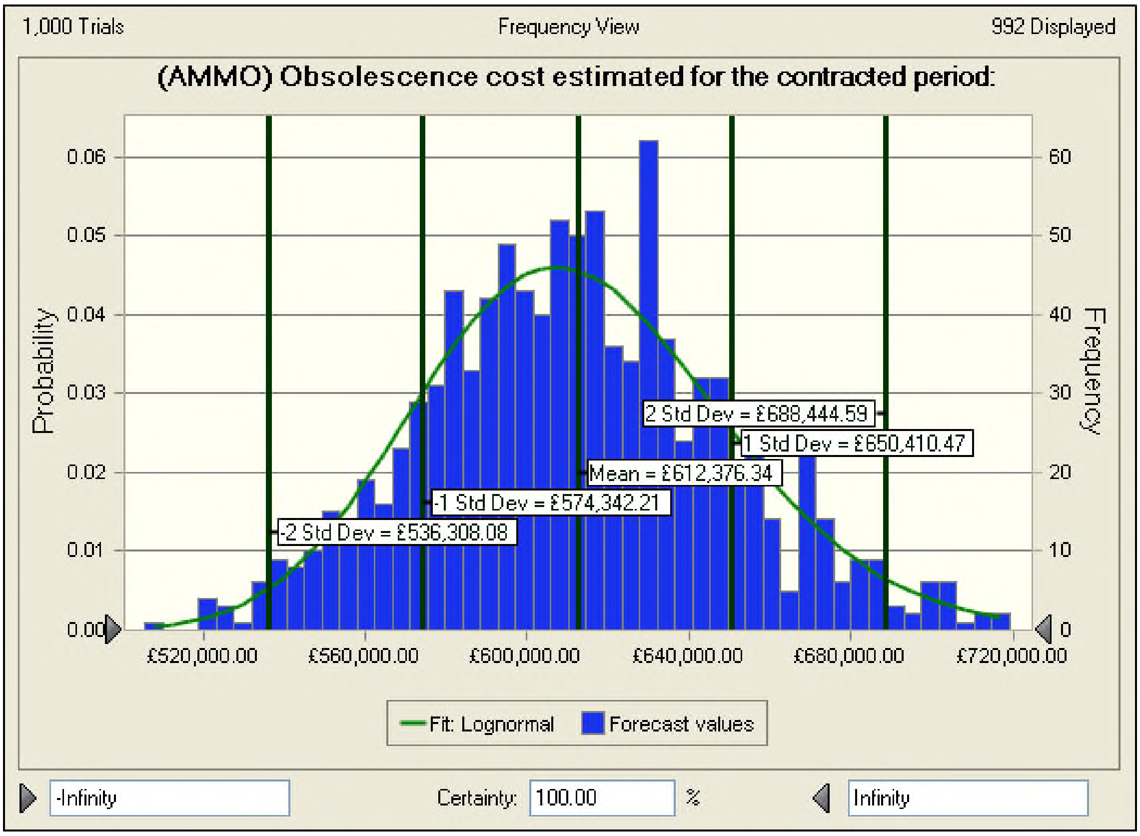


Figure 8-10 Output of M-FORCE after Running Monte Carlo Simulation for Case Study 3 (ammunition domain)

8.5.4 Cross-Case Study Analysis Synthesis

The two experts (6 and 7 in Table 8-1) that participated in the three case studies provided their joint feedback after discussion during the interviews. This type of experts is rare in the companies, which hindered the validation process. The results were captured in a questionnaire and are presented as follows.

- **LOGIC:**

The two experts agree that the logic of the cost estimating process is valid (8 out of 10), although they have identified as a minor deficiency the fact that there is duplication of materials in common natures. Both experts also agree that the framework is suitable for the bid stage (8 out of 10), although they have identified as a minor deficiency the fact that there is a need to confirm the output against reality figures/costs, which are not available at present.

- **GENERALISABILITY:**

Both experts agree that the M-FORCE framework is truly generalisable to different defence and aerospace platforms and it can be easily calibrated. Additionally, they concur that the list of resolution techniques indicated in the framework is complete.

- **BENEFITS OF USING THE FRAMEWORK:**

The two experts consider that this framework benefits a bidding team by providing an estimate on potential obsolescence costs in support contracts. They agree that it can be used at different stages of the CADMID cycle, such as supporting mitigation strategy development in design phase and providing early cost estimates using component count in STEP 3B at concept stage. Additionally, they agree that the tool should be owned by the obsolescence group/engineers.

- **LIMITATIONS OF THE FRAMEWORK:**

Experts 6 and 7 highlight the need to ensure duplicate materials used in other ammunition are taken into account before use. They indicate that a limitation of the framework is that it relies on accuracy of data used.

- **USABILITY OF THE SOFTWARE PROTOTYPE:**

Both experts agree that the strongest features of the framework are: clear layout, easy to navigate and easy to follow instructions. However, the fact that there are many tabs, including those related to the aerospace domain, can be confusing for the user. In addition, they agree that the software prototype is quite intuitive (9 out of 10).

Both experts agree the following points about the framework:

- The terminology and concepts used are consistent.
- The key cost drivers are considered.

- It is flexible enough to adapt to the different levels of information available.
- The materials complexity classification defined is valid.
- The materials criticality classification defined in the tool is valid.

- **ASSUMPTIONS:**

Both of them agree as well with the validity of the following assumptions:

- The level of complexity, level of criticality and level of integration are not correlated.
- A calibration data point can be applied to derive the spectrum of cost metrics based on the “weight matrix”.
- The Obsolescence Management Level does not have a significant impact on the NRE cost of resolving obsolescence issues for materials.
- The cost of materials obsolescence is independent from EEE components obsolescence.
- The cost of materials obsolescence is independent from software obsolescence.

- **RESULTS:**

The experts consider that the uncertainty in the output is related to the fact that qualification cost for an alternative material may vary because specific requirements for various ammunition natures are likely to vary with the use of the material.

The results of the sensitivity analysis for the tool are that it is not very sensitive to change. Change to input data did not significantly change the output cost result.

Finally, all the experts have verified and validated the key formulae and architecture used in this framework.

8.6 Summary

In this Chapter, the implementation, verification and validation of the M-FORCE framework was presented. A total of six case studies with seven obsolescence experts across four different organisations were carried out for this purpose.

In Section 8.2, the research methodology followed for the validation of the M-FORCE framework was presented. It included a detailed description of the experts that participated.

In Section 8.3, the author described the implementation of the M-FORCE framework into a tool using MS Excel and Visual Basic for Applications (VBA), detailing the structure of the tool and the data required at each step.

Section 8.4 presented in detail each of the three case studies applied for the validation of the M-FORCE for the aerospace domain, and subsequently provided a cross-case study analysis synthesis based on the responses that the experts gave to the questionnaire used during the case study sessions. The third case study, which represents a naval application, was carried out to test if the framework is generalisable and suitable for the maritime domain.

Section 8.5 presented in detail each of the three case studies applied for the validation of the M-FORCE for the ammunition domain, and subsequently provided a cross-case study analysis synthesis based on the responses that the experts gave to the questionnaire used during the case study sessions.

The next Chapter provides the discussion and conclusions of this Thesis.

Chapter 9

9 DISCUSSION AND CONCLUSIONS

9.1 Introduction

In Chapters 5 and 6, the development of the proposed methodologies for the estimation of NRE costs of hardware (EEE components and materials) obsolescence was presented. This development was based on the observations that emerged from Chapters 2 and 4. In Chapters 7 and 8, the framework, which consists of two distinct parts: a) EEE-FORCE for EEE components obsolescence, and, b) M-FORCE for materials obsolescence; was validated by applying it to a total of 13 case studies with the collaborating organisations.

The aim of this Chapter is to provide a synopsis of the research findings and further discuss their implications to the relevant fields. Additionally, the conclusions drawn from this thesis are presented in this Chapter.

In Section 9.2, a summary and further discussion of the key research findings described in this thesis is presented, taking each area of the thesis in turn. In Section 9.3, the quality, generalisability and applicability of the research findings is discussed. In Section 9.4, the author emphasises the main contributions of this research. Section 9.5 identifies the limitations of this study. In Section 9.6, the author suggests areas for future research in the light of this thesis. Finally, an account of how the research findings fulfilled the research objectives is presented in Section 9.7.

9.2 Discussion of Key Research Findings

A discussion of the key research findings and observations is presented in this Section. The sequence followed represents the structure in which this thesis has been presented.

9.2.1 Literature Review

The review of literature covered the two main areas of this research: obsolescence and cost estimation. In regard to obsolescence, this review revealed that the research on this topic is growing; especially in the military and aerospace sectors because obsolescence is increasingly becoming an important issue for sustainment-dominated systems. This review also revealed that most of the research described in the literature makes an attempt to determine: how to reduce the risks of future component obsolescence; how to react to occurrences of component obsolescence; and, how to anticipate occurrences of component obsolescence. The main focus in literature has been on EEE components obsolescence, disregarding other types of obsolescence such as software and materials obsolescence. Indeed, as it was confirmed in Chapter 4, very few organisations in the defence industry are managing and costing software obsolescence. Thus, there is a lack of understanding about the concept of software obsolescence and how it can be managed and mitigated.

In spite of the existence of an extensive literature in the area of obsolescence management for EEE components, it was observed a lack of definition of the terms ‘mitigation strategies’ and ‘resolution approaches’, and frequently they are used interchangeably in literature. The author observed that the two terms are conceptually different, and hence, they need to be defined properly, clarifying the differences between them.

In the US and UK, different obsolescence cost metrics have been developed. However, it has been identified a need to revalidate them and identify the key cost drivers involved. This would allow the selection of the most cost effective solution, making cost-avoidance analysis and the assessment of the impact of obsolescence on whole life cycle costs. Furthermore, it has been observed that there is a lack of understanding about the NRE cost involved in resolving obsolescence issues for hardware, including EEE components and materials, during support contracts.

From the literature review carried out in the area of cost estimating, it can be concluded that none of the existing Maintenance Cost Estimation Models takes into account the cost related to obsolescence. In addition, the main commercial and non-commercial tools available at present have been systematically analysed and compared as part of the literature review. None of the models described in literature addresses directly the problem of estimating the cost of obsolescence except for the MOCA tool and R2T2, which apply obsolescence cost estimation in order to identify the most cost-effective plan for design refresh. Further research on these two tools revealed that they are not suitable for the cost estimation of obsolescence at the bidding stage. Additionally, none of the tools/models existing in the literature addresses the problem of managing materials obsolescence, and particularly estimating the costs related to these issues.

9.2.2 Research Methodology

As described in Chapter 3, the research methodology followed is primarily qualitative. The main weaknesses of this approach are the potential bias from the participants as well as from the researcher, which may jeopardise the validity and reliability of the results. Therefore, the author has endeavoured to ensure that the bias has been mitigated and the results are trustworthy. One of the measures taken to mitigate the bias was to follow a systematic process, combining different data collection methods. The author used face-to-face interviews, WebEx meetings, workshops and collection of companies' documentation, reports and publications. The information captures from different sources was triangulated to minimise bias. Moreover, the author triangulated the data collected by means of semi-structured interviews with different experts from different organisations. In addition, the questionnaires used in this research have always been piloted with a subject expert to ensure its quality and applicability. Likewise, the research protocol has been continuously reviewed and refined throughout the research process.

In order to reduce the researcher's bias, after capturing and analysing the data from different sources, the author prepared reports summarising the key findings and showed them to the participants for feedback. That measure reduced the risk of possible misinterpretations of the data collected on the part of the researcher.

The author realised that his membership to the Component Obsolescence Group (COG) granted him access to numerous obsolescence experts from across industry. That set the appropriate circumstances for deploying the Delphi method as part of the research for overcoming the lack of appropriate historical data.

9.2.3 Cost Estimation and Obsolescence Management Current Practice

The author, after conducting multiple face-to-face interviews with experts from different industrial organisations and triangulating it with official documents, managed to capture the current practice in different topics. These are: the cost estimation process at bidding stage for defence contracts; the obsolescence management practice for EEE components, materials and software; the contractual agreements for obsolescence management; and the obsolescence cost estimation practice in industry.

It was identified that currently in the defence sector the support contracts are evolving towards Availability Contracts, as they provide a win-win situation for both the customer and the contractor, improving readiness and availability of the system. Nevertheless, this transition implies the transfer of risks, such as obsolescence, from the customer to the contractor. It implies that the cost of obsolescence needs to be estimated at the bidding stage and agreed during the contract negotiation. However, the research has brought to light a lack of understanding about the NRE cost involved in resolving obsolescence issues for EEE components during support contracts. It has also been observed that there is a general lack of standard procedures for the cost estimation of obsolescence across all the industrial collaborators.

Obsolescence Cost Metrics developed in the past by the UK MoD and the US DoD received criticism from many experts in industry. It was highlighted that they can be improved by taking into account other cost factors apart from the resolution approach applied. By means of this study, other key cost drivers were identified and their contribution to costs was assessed.

The current efforts in dealing with obsolescence are mainly focused on EEE components while software obsolescence is disregarded and not managed at all. The main problem related to software obsolescence is that it is generally ignored within the defence and aerospace sector and usually it is not included in the Obsolescence Management Plan (OMP) or just briefly mentioned without providing a detailed strategy to manage it. Apart from the lack of awareness, there is a lack of tools to assist in the software obsolescence management such as obsolescence monitoring tools (analogous to those used for EEE components, described in Chapter 2) which makes difficult the forecast of software obsolescence issues. These facts show the lack of maturity of this subject, which makes unfeasible at this point the development of a framework for the cost estimation of software obsolescence at the bidding stage for support contracts. Along these lines, the current interest of the sponsoring organisations was solely focused on the cost estimation of hardware obsolescence, though they acknowledge that software obsolescence will require more attention in the future.

9.2.4 EEE-FORCE and M-FORCE Cost Estimation Process

A clear distinction between the terms “mitigation strategies” and “resolution approaches” was made in this research. Subsequently, a set of definitions for the obsolescence resolution approaches was developed as a result of the consensus reached at a workshop with obsolescence experts from across the

British defence and aerospace sector. Additionally, the concepts of “complexity” for materials and EEE components, and the “Obsolescence Management Levels of Proactiveness” were developed.

As mentioned in the previous Section, it has been identified that existing obsolescence cost metrics take the resolution approach as the only cost driver. However, there are other factors that may have an impact on the NRE cost of resolving an obsolescence issue. In this study it has been identified that the key additional cost drivers are the type of platform, the need for requalification testing and the level of integration, which depends upon the coupling level and the package density. This finding provided the basis for the development of the Obsolescence Cost Metrics (OCM).

By means of the interactions with industry, it was identified that the probability of using a resolution approach to tackle an obsolescence issue for an EEE component depends mainly on these two parameters: the level of complexity of the obsolete component and the level of proactiveness deployed to manage obsolescence. This finding provided the basis for the development of the Obsolescence Resolution Profiles (ORPs).

9.2.5 EEE-FORCE and M-FORCE Development and Validation

EEE-FORCE

The EEE-FORCE framework has been validated in collaboration with eight experts on obsolescence by applying it to seven case studies across four different companies in the UK defence sector. For the analysis of five of the case studies, the output provided by the EEE-FORCE framework was compared with the cost estimated at the engineering level, which provides the basis for the price agreed with the customer when signing the contract, after including the profit margins and inflation considerations. For all of them, the difference between the estimated cost (E) and the cost agreed in the contract at the engineering level (without inflation considerations) is on average 4.27%, and always lower than 10%. For the two remaining case studies, as they are still at early stages in the CADMID cycle, the assessment of the outcomes of the EEE-FORCE was based on expert judgement. As a result of these case studies, the eight experts concur that the key formulae applied in this framework is valid and the outputs are consistent.

This is a robust framework because much consideration has been made in the development, combining validation with experts and continuous enhancements. As a result, this framework incorporates features such as a rigorous risk assessment, the clustering factor, and the alternative obsolescence resolution profiles that can be applied when the system is reaching the end of its in-service phase. It also takes into account the uncertainty in the inputs and applies the Monte Carlo simulation to bring it into the cost estimate. The framework can be applied to any long-term project, predicting cost at least at the same level of accuracy as the in-house developed model existing in some companies.

All the experts that participated in the validation of this framework agreed that it is very flexible for two reasons. First, it adapts to any level of information available, which enables the user to apply it at different stages of the CADMID cycle. This provides a key advantage over cost estimating approaches designed for early stages (e.g. parametric) or when detailed information is available (e.g. bottom-up), because it provides continuity in the estimates and allows for refinement as more data becomes available. Second, the framework has been designed in a way that the user can easily customise it, by modifying the cost metrics and the ORP.

In terms of the generalisability of the EEE-FORCE framework, the eight experts agree that it is suitable across the defence sector, including land, maritime and aerospace applications. They also agree that it can potentially be applied for any high-value commercial application that involves high technology and long sustainment periods.

M-FORCE

The M-FORCE framework has been validated in collaboration with seven experts on obsolescence by applying it to six case studies across four different companies in the UK defence, aerospace and naval sectors. Two of the case studies tested the applicability of the framework for the aerospace domain. Another case study showed that the M-FORCE customised for the aerospace domain is generalisable and suitable for the maritime domain as well. The other three case studies proved the validity of the framework for the ammunition domain.

All the experts agree that this framework is flexible to adapt to different levels of data available, and it is easy to use and easy to explain. They also consider that this framework benefits a bidding team by providing a structured process to produce an estimate on potential materials obsolescence costs in support contracts.

9.3 Quality, Generalisability and Applicability of Research Findings

In this Section, the author discusses the quality and generalisability of the research findings. Their applicability in an industrial environment is also explored.

9.3.1 Quality of Research Findings

Throughout the research, the author made every effort to ensure that the whole process followed to capture information and analyse the results was carried out in a thorough and systematic manner. Regarding the case studies, the time available for the researcher was the main limitation. Therefore, proactive measures were taken to overcome this issue. For instance, the researcher arranged the meetings/workshops for the case studies well in advance to ensure the availability of the experts. The research protocol was sent to the experts in advance and a demonstration of the framework was provided by means of WebEx to the experts prior to the case study. A copy of the prototype was also distributed so that the experts can familiarise themselves with it and start populating it with the data related to the case study. During that time, the experts had the possibility of contacting the researcher by telephone or email to clarify any doubt.

The research outputs were qualitatively and quantitatively validated by experts in different domains. The qualitative validation involved the verification of the framework's structure and formulae. Additionally, the opinions of the experts about the suitability of the framework were elicited by means of a questionnaire. The qualitative validation was performed in those case studies for which the actual cost of obsolescence or an estimate agreed in the support contract is available. It involved the comparison of the framework's outputs with this figure. The overall conclusion that can be drawn from the results of the validation is that the framework is fit for purpose and the estimates that it produces are reasonable.

The author has endeavoured to maintain a high level of reliability regarding the methods used to reach the research findings. This was achieved by means of developing a formal research strategy and combining different data collection methods, including the use of semi-structured questionnaires. Triangulation of data acquired from different sources was performed, whenever possible.

9.3.2 Generalisability of Research Findings

The proposed framework has been developed primarily for the defence and aerospace sectors, and has been demonstrated to be applicable to such domain. Nevertheless, the experts that participated in the validation agree that it can potentially be applied to other domains. For instance, interviews with obsolescence experts in the nuclear and railway sectors have indicated that there are big similarities for any sustainment-dominated system, whose support is usually contracted following Product-Service System (PSS) business models. Therefore, the EEE-FORCE framework has potential to be used for this type of systems, regardless of the sector in which it is considered.

The five experts that participated in the validation of the M-FORCE framework for the aerospace domain agree that the framework is suitable for defence and civil aerospace applications, as well as maritime. This opinion is underpinned by the case studies carried out in those domains. They also agree that it can be easily calibrated to be applied to any type of support project in those domains, by adjusting the obsolescence cost metrics and the ORPs. Additionally, the two experts that validated the M-FORCE framework for the ammunition domain concur that it is truly generalisable to different defence and aerospace platforms.

9.3.3 Applicability of Research Findings

In this Section, the applicability of the research findings in industry and their potential impact on the business as a result of being implemented are discussed. Particularly, the adoption and implementation of the framework across industry in the defence sector is discussed.

Any industrial setting that fits the boundaries of the research context can easily implement both, the EEE-FORCE and the M-FORCE. At the bidding stage of a support contract that includes the risk of obsolescence, the framework can be used to assist the cost estimator in forecasting the NRE costs of resolving obsolescence issues for hardware, including materials and EEE components.

Although the motivation for estimating the cost of obsolescence is originated in the PSS business model, such as availability contracts, this framework is applicable to any type of support contract.

If this framework becomes the industry standard, which is the intention of the MoD, its use is particularly beneficial during the contract negotiation. The reason is that it provides a common understanding for both parties, the customer and the support provider. This framework is favoured for this purpose because organisations from across the supply chain and the customer have collaborated on its development. That helped to ensure that the resulting framework is unbiased, and all the organisations are keen on embracing it.

One of the main characteristics of this framework is its flexibility to adapt to any level of information available. Therefore, it ensures the continuity of the cost estimation approach used throughout the CADMID cycle. The framework is also flexible in terms of customisation. The fact that it can be easily customised by any organisation willing to use their own historical information provides an incentive to adopt this framework, instead of having to develop a tailored one.

The framework can be primarily used for negotiating the support contract between the customer and the prime contractor. However, its use is not restricted to this scenario. As the risk of obsolescence is transferred from the customer to prime contractor, it can also be cascaded by the prime contractor down the supply chain. Therefore, the framework can be used to negotiate the cost of managing obsolescence for a subsystem between the prime contractor and a supplier.

The author believes that if the framework becomes an industry standard, it should be owned by the MoD. They will preserve the common understanding across all parties, centralising and coordinating any further modifications and enhancements. Based on the feedback received from the obsolescence experts, the author believes that, within each organisation, the ownership the framework should stay with a functional group of obsolescence managers, so they can customise, adapt and apply to any project where it is required. The user of this framework must have knowledge about obsolescence and the system that will be supported in the contract.

9.3.3.1 Usage of the Framework at the Bidding Process

The generic bidding process for defence contracts was described in Chapter 4. As shown in Figure 9-1, the level of effort that the contractor will put before the invitation to tender (ITT) is released is considerably lower than after this point. Taking into account that during that initial period the level of information available is very low, the contractor will only be able to prepare a rough cost estimate with high levels of uncertainty built-in. The STEP 3B in the framework has been conceptualised to address this need, during this phase.

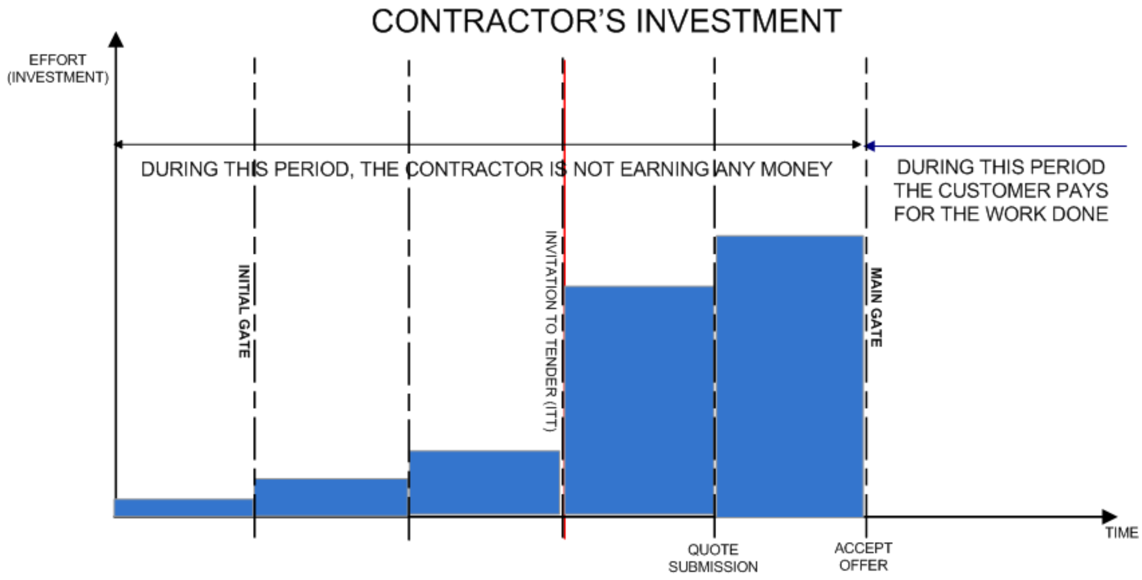


Figure 9-1 Contractor's Effort during the Bidding Process

As the Main Gate approaches, more data will become available and more effort the contractor is willing to put into estimating accurately the cost of obsolescence. This is the ideal scenario to apply the STEP 3A of the framework, which takes more detailed information and in turn produces a more reliable cost estimate.

The fact that the framework accepts combining partial information input from STEP 3A and STEP 3B, enables the usage of this framework throughout the whole bidding process. The advantage of using only one framework for the cost estimation is that it provides a gradual transition during the bidding process as more information becomes available.

9.4 Key Research Contributions

This research has significantly contributed to increase the understanding about obsolescence in EEE components, materials and software. It has introduced novel concepts regarding obsolescence management that enabled the development of a novel framework for the estimation of the NRE cost of solving existing obsolescence issues at the bidding stage and through the life of the contract. This framework was subsequently implemented within the EEE-FORCE and M-FORCE tools.

The key contributions of this research are summarised as follows:

- This research identified through literature that obsolescence is increasingly becoming an important issue for sustainment-dominated systems, and consequently, the research on EEE components obsolescence is growing. However, it has been identified a lack of research on materials obsolescence and especially on software obsolescence. In fact, there is a lack of understanding about the concept of software obsolescence and how it can be managed and mitigated. In addition, it has been identified a lack of understanding about the NRE cost involved in resolving obsolescence issues for hardware, including EEE components and materials, during support contracts.
- This research clarified the concept of software obsolescence and identified strategies to mitigate it.
- This research identified the key cost drivers for EEE components and materials obsolescence. This finding was essential for the subsequent development of the obsolescence cost metrics for EEE components and the weight matrix for materials. It also contributed new knowledge by formulating the concepts of component complexity, component criticality, level of integration and level of proactiveness to manage obsolescence.
- This research identified the key parameters that determine the probability of using each resolution approach to tackle an obsolescence issue. This finding was essential for the subsequent development of the Obsolescence Resolution Profiles (ORP).
- As a result of the research findings, a novel framework was developed to provide a systematic approach to estimate the NRE cost of resolving obsolescence issues at the bidding stage and through the life of the contract in EEE components and materials. It addresses an unfulfilled need triggered by the current move towards contracting for availability, where the obsolescence risk is cascaded down the supply chain.

9.5 Research Limitations

In this Section, the limitations of this research are presented. These limitations can be related to the research methodology followed, the cost estimation process proposed in the framework and the framework development and validation.

9.5.1 Research Methodology

As it was explained in Chapter 3, the qualitative nature of this research makes it prone to possible bias and problems with validity and reliability. In previous Sections the author explained the measures taken to overcome these weaknesses. However, one of the major issues is the difficulty to replicate the results, in contrast to quantitative research.

A limitation was identified in the analysis of the data collected during the first phase. Due to the qualitative nature of the research, the filtering and collating of information collected may be prone to subjective interpretation. In order to reduce this potential bias, the author produced reports summarising the results of the analysis and presented them back to the participants for feedback and validation.

A large amount of the author’s knowledge about obsolescence, industrial practice and common issues was gain through informal discussions with many obsolescence experts during the COG quarterly meetings. These meetings were a rich source of information but were not properly recorded. Nonetheless, the researcher arranged formal interviews with those experts who were willing to collaborate and provide further information that can be useful for the research project.

Prolonged involvement of the researcher, such as spending months at the research sponsors’ premises, may increase researcher bias, as it was explained in Chapter 3. However, the researcher never stayed at the sponsors’ premises for more than two consecutive days due to the lack of experts’ availability and time limitation, which contributed to avoid this problem. On the other hand, this entailed the need to ensure that the case studies were conducted properly. In this effort, the following measures were taken: 1) careful proactive planning of the case studies, collaborating with the experts to ensure that they have a good understanding about the requirements for the case studies; 2) involvement of the author in the case study selection to ensure that they are suitable; 3) Use of multiple sources of data collection, maintaining notes and evidences, and audio-recording most of the interviews/workshops (whenever it was possible); and 4) setting up debriefing sessions with the experts to capture their feedback and comments on the resulting findings.

9.5.2 EEE-FORCE and M-FORCE Cost Estimation Process

A set of assumptions have been made in the development of this framework, which may be a possible limitation for its usage. The first one is that this framework is meant to be used for the NRE cost estimation of resolving the obsolescence issues that arise during a support contract, assuming that no technology refresh or capability upgrades take place in this period. Additionally, it is assumed that all the fleet is enhanced during midlife upgrades. Another assumption made is that any component is not expected to become obsolete more than once during the contracted period. In reality, this assumption is only valid when the obsolescence issue is tackled using long-term solution such as LTB or redesigns; whereas the usage of short-term solutions such as alternates or equivalents may result on several obsolescence issues. It is regarded that an obsolescence issue will only contribute to costs for the contract if the level of stock for that item is not enough to cover the contracted period. Emulation, Minor and Major Redesigns may resolve several obsolescence issues simultaneously, and the clustering factor is used to represent this fact.

A limitation of this framework is the fact that the cost of money is not taken into account. For this purpose, it is not enough to predict the number of obsolescence issues during the contracted period, but also it is necessary to forecast when each obsolescence issue will happen. The EEE-FORCE framework estimates the cost of obsolescence at the engineering level and this is why the year on year escalation of cost due to inflation is not taken into account. Concepts such as net present value (NPV) and inflation will need to be taken into account for further enhancements of this framework in order to convert the cost estimate into a price for the contract.

The experts highlighted from the sensitivity analysis performed that the EEE-FORCE is highly sensitive to changes in parameters such as the level of integration. Therefore, a limitation is that the framework has to be used by an expert on obsolescence with good understanding of the system, to avoid misjudgements in the inputs.

9.5.3 EEE-FORCE and M-FORCE Development and Validation

The concepts and data used for the development of the EEE-FORCE framework are derived from discussions, workshops and interviews with experts in obsolescence rather than from historical data, due to its unavailability. However, the usage of a systematic research methodology, combining the Delphi method and the Critical Incident technique, overcame the problem of basing the research on expert judgement rather than on actual data. It is expected that the appropriate storage of historical data related to obsolescence across different projects may enable in the future the refinement of the figures and concepts generated in this framework.

Two limitations have been identified in the application of the Delphi method for the development of the Obsolescence Resolution Profiles:

- Low sample size. Only 38 experts participated in the first round and 33 in the second round of the Delphi study. In the first round each expert provided data related to a particular level of OM, as shown in Table 9-1. Therefore, it can be argued that the level of uncertainty is high, especially for OM levels 1 and 2 due to the reduced sample size. However, the 33 experts that participated on the second round validated the figures for all the OM levels.
- Experts from across the UK defence sector participated on the study. Many experts have different backgrounds and the fact that they work at different levels of the supply chain (e.g. customers, system integrators,

manufacturers, suppliers, authorised aftermarket) results in them having different points of view about the resolution of obsolescence issues.

Table 9-1 Number of Experts Participating on the First Round of the Delphi Study for each Obsolescence Management Level

OBSOLESCENCE MANAGEMENT LEVEL	*NUMBER OF EXPERTS*
OM 1	5
OM 2	3
OM 3	8
OM 4	10
OM 5	12

These limitations have been addressed by incorporating the trends refinement phase to the research process. It ensured that the results were coherent and rectified deviations resulting from these limitations.

A set of cost metrics has been derived from the study, based on the expertise of 21 obsolescence managers and support engineers from seven different organisations. The validity of this study can be jeopardized by the fact that no actual cost data has been gathered and analysed, relying on expert opinion, and hence, increasing the risk of subjective and biased results. This has been mitigated by following a systematic research methodology, bringing in the study obsolescence experts from different organizations and different points of view, and refining the results with key experts from different companies. It is necessary to highlight that the metrics are based on resolution of an isolated obsolescence occurrence and that no attempt is made here to estimate system obsolescence costs. Finally, the parameterisation and normalisation of the cost metrics allows their usage for any currency and any financial year, as they are unaffected by inflation. It is suggested that in the future, these obsolescence cost metrics can be revalidated using actual cost data, as it would increase their reliability.

From the ten experts that participated in the validation of the EEE-FORCE, five of them also participated on its development and refinement. This could cause bias since their views were taken into account for the development of the framework. However, other five experts from different organisations, who were not involved at the development stage, participated in the validation as well. In the case of the M-FORCE, three experts out of seven participated in the validation but not in the development of the framework.

For the validation of the framework, the ideal approach for each case study would be to compare the actual management costs of a completed program to the costs predicted by the framework. However, the industrial collaborators have provided data for ongoing projects. Therefore it would be necessary to wait for five or ten years to be able to make the comparison with the actual cost. The reason why the validation has not been done using data from past projects is that the data regarding the obsolescence cost is not usually stored in a systematic way, and hence it would be extremely laborious and expensive to get it done. This is why sponsoring companies were not keen on collecting this data. Nevertheless, most of the comparisons in the validation were done against actual cost figures estimated using in-house models at the engineering level, which provided the basis for the price agreed in the contract after incorporating the inflation and profit margin. These in-house models are kept confidential by each company but have been already validated by MoD cost estimating experts.

9.6 Future Research

Several activities are suggested as further work to build on the results of this study. The first one is to revalidate the obsolescence cost metrics using actual cost data. This is not an easy task due to the lack of historical data for obsolescence cost. When data exists, it is usually scattered across different parts of an organisation, resulting in costly and time consuming activities to retrieve. This could be overcome by implementing across the defence sector a standard way to systematically store this data, so that it can be easily retrieved. Within the factors considered in the cost metrics, the length of contract has not been taken into account. However, contract length will have an impact on the

NRE cost of a last-time buy (LTB) due to storage and periodic testing costs. Further work is required to incorporate the storage cost to the cost metrics. Additionally, it was concluded at the workshop that the platform type is only applied if requalification is required. However, further research should confirm whether the platform type does affect the cost metrics when no requalification testing is required. Additional further investigation could refine the platform types and determine whether for example there is any variance between costs for land-based in military, industrial and consumer environments.

The representation of the decision process by which an expert practitioner assesses the impact of the level of integration needs further investigation. For example, the additional factors that practitioners typically consider, their weighting, and degree of independence or correlation may need to be modelled by an expert system.

Future research should be focused on the development of a model for the cost estimation of software obsolescence, as well as tools for monitoring, managing and predicting software obsolescence issues. Additionally, it is required to explore the correlation between hardware and software obsolescence due to the high level of interdependencies between them.

Finally, it is suggested that future research on this framework may address the limitations of the current version, including those discussed in the previous section, making the framework more robust and reliable. The M-FORCE framework may be tested and customised for other domains different from marine, aerospace and ammunition.

9.7 Conclusions

The purpose of this Section is to show how the aim and objectives of this thesis, defined in Chapter 3, have been achieved.

The **first objective** was to understand the current practice and state of the art in obsolescence and cost estimation. Based on the review of literature and information gathered from multiple organisations in the UK defence and aerospace sector, the author revealed that:

- The research on obsolescence is growing, and is especially focused on EEE components. Most of the research described in the literature makes an attempt to determine: how to reduce the risks of future component obsolescence; how to react to occurrences of component obsolescence; and, how to anticipate occurrences of component obsolescence.
- It was observed a lack of research on materials and software obsolescence.
- None of the existing maintenance cost estimation models takes into account the cost related to obsolescence.
- It was identified that currently in the defence sector the support contracts are evolving towards Availability Contracts. This transition implies the transfer of risks, such as obsolescence, from the customer to the contractor. Therefore, the cost of obsolescence needs to be estimated at the bidding stage and agreed during the contract negotiation.
- There is a lack of understanding about the NRE cost involved in resolving obsolescence issues for EEE components during support contracts. It has also been observed that there is a general lack of standard procedures for the cost estimation of obsolescence across all the industrial collaborators.

The **second objective** was to clarify the concept of software obsolescence, investigate the possible mitigation strategies and determine the key challenges to estimate the cost of software obsolescence. The author identified that:

- The nature of software obsolescence is different from materials or EEE components obsolescence because it is not affected by degradation (and hence does not require replacement) and can be easily replicated. The essence of obsolescence is that it prevents from maintaining and supporting the system. Therefore, the software obsolescence prevents the software from being maintained accordingly.

- Software obsolescence can happen in three different areas: skills, COTS software and media.
- Software obsolescence can happen in both, the development environment and the target environment. The characteristics and impact that an obsolescence issue may have on each environment may be different.
- The main problem related to software obsolescence is that it is generally disregarded and not managed at all in industry due to the lack of maturity of this topic. Apart from the lack of awareness, there is a lack of tools to assist in the software obsolescence management such as obsolescence monitoring tools, which makes difficult the forecast of software obsolescence issues.
- At the moment, no organisation is able to make robust cost estimations for software obsolescence. In the future, a cost model should be developed at system level, so both the software and hardware obsolescence are concurrently considered, taking into account the interactions between them.
- The author has identified a set of mitigation strategies to reduce the risk of software obsolescence (Section 4.4.4).
- The author has identified the key challenges to estimate the cost of software obsolescence (Section 4.4.5).

The **third objective** was to identify the key obsolescence cost drivers for resolving hardware obsolescence issues. The author identified that:

- There are four key obsolescence cost drivers for EEE components obsolescence: 1) the resolution approach applied to resolve the obsolescence issue; 2) the type of platform; 3) whether requalification testing is required, which depends upon the level of safety/criticality of the obsolete component, the required level of reliability and whether any legislative approvals apply; and 4) the level of Integration of the obsolete item, which depends upon the package density and the coupling level.

- There are four key obsolescence cost drivers for materials obsolescence: 1) the complexity level; 2) the criticality level; 3) the integration level; and 4) the type of resolution approach.

The **fourth objective** was to develop a systematic approach to predict the NRE cost of resolving hardware obsolescence issues, including EEE components and materials obsolescence. The author achieved this objective by:

- Carrying out the Obsolescence Resolution Profiles (ORP) study to determine the probability of using each resolution approach to tackle an obsolescence issue (Section 5.5).
- Carrying out the Obsolescence Cost Metrics (OCM) study to revalidate the existing obsolescence cost metrics and identify the key obsolescence cost drivers (Section 5.6).
- Proposing a method that combines the information available about the system and support contract with the ORP and OCM to predict the NRE cost of resolving hardware obsolescence issues.
- Iteratively refining the propose method in collaboration with experts from different organisations.
- Carrying out a pairwise comparison with materials obsolescence experts to develop the weight matrix, which is the basis for the cost estimation when using the M-FORCE in the aerospace domain (Section 6.5.1).
- Identifying the correlations between the cost drivers for materials obsolescence in the ammunition domain. That enabled the development of materials obsolescence cost metrics for ammunition (Section 6.5.2).

The **fifth objective** was to verify and validate the systematic approach developed using detailed case studies. To achieve this objective, the author:

- Implemented the EEE-FORCE and M-FORCE frameworks into tools using MS Excel and Visual Basic for Applications (VBA).
- Verified the architecture and formulae of the frameworks in collaboration with experts from academia and industry.
- Validated the EEE-FORCE framework by applying it to seven case studies across four different companies in the UK defence sector. A total of ten obsolescence experts from industry participated.
- Validated the M-FORCE framework in collaboration with seven experts on obsolescence by applying it to six case studies across four different companies in the UK defence, aerospace and naval sectors. Two of the case studies tested the applicability of the framework for the aerospace domain. Another case study showed that the M-FORCE customised for the aerospace domain is generalisable and suitable for the maritime domain as well. The other three case studies proved the validity of the framework for the ammunition domain.

In summary, the thesis has achieved the stated aim and objectives by demonstrating that the NRE cost of hardware obsolescence can be systematically estimated at the bidding stage for support contracts.

THIS PAGE IS INTENTIONALLY LEFT BLANK

REFERENCES

AACE (1990), *Standard Cost Engineering Terminology. AACE Recommended Practices and Standards.*

AACE (2006). *AACE International's Recommended Practice 11R-88, Required Skills and Knowledge of Cost Engineering*. http://www.aacei.org/about/whatIsCE.shtml (accessed 25th August 2010)

Adams, C. (2005). Getting a Handle on COTS Obsolescence, *Avionics Magazine*, (available online http://www.aviationtoday.com/av/categories/military/887.html) (accessed on 19th January 2011).

Aderoba, A. (1997). A generalised cost-estimation model for job shops. *International Journal of Production Economics,* 53(3), pp. 257-263.

Andrade, M. C., Pessanha Filho, R. C., Espozel, A. M., Maia, L. O. A. and Qassim, R. Y. (1999). Activity-based costing for production learning-Persistence, transfer and turnover. *International Journal of Production Economics,* 62(3), pp. 175-180.

ARINC (1999). *Resolution Cost Factors for Diminishing Manufacturing Sources and Material Shortages - Final Report*, February, 1999. Prepared for Defense Microelectronics Activity (DMEA). (available online at www.dmea.osd.mil/docs/resolution_cost_factors.pdf, last accessed on 19th January 2011)

Avramenko, Y. and Kraslawski, A. (2006). Similarity concept for case-based design in process engineering. *Computers & Chemical Engineering,* 30(3), pp. 548-557.

Baca, M. (2005). The third dimension in obsolescence management. *Military & Aerospace Electronics*, pp. 15-18. (available online http://mae.pennnet.com/articles/article_display.cfm?article_id=236302) (accessed on 19th January 2011).

Baines, T.S., Lightfoot, H.W., Evans, S., Neely, A., Greenough, R., Peppard, J., Roy, R., Shehab, E., Braganza, A., Tiwari, A., Alcock, J.R., Angus, J.P., Bastl, M., Cousens, A., Irving, P., Johnson, M., Kingston, J., Lockett, H., Martinez, V., Michele, P., Tranfield, D., Walton, I.M., and Wilson, H. (2007). State-of-the-art in product-service systems, *Proc. IMechE Part B: J. Engineering Manufacture*, 221, pp.1543–1552.

Barton, D.L. and Chawla, P. (2003). Designing systems for future obsolescence. *Digital Avionics Systems Conference, 2003. DASC '03*, vol.2, pp. 10.C.2-101-11, 12-16 Oct. 2003, IEEE, Indianapolis, IN, USA

Battersby, C. (2008). *The Counterfeit Electronic Components Minefield: A Guide to understanding and avoiding Counterfeit Components*. 1st ed., COG International Ltd., UK.

Behrend, S., Jasch, C., Kortmap, J., Hrauda, G., Firzner, R., and Velte, D. (2003). *Eco-Service Development Reinventing Supply and Demand in the European Union*, Greenleaf: Sheffield.

Ben-Arieh, D. and Qian, L. (2003). Activity-based cost management for design and development stage. *International Journal of Production Economics,* 83(2), pp. 169-183.

Blackman, I. and Rogowski, R. (2008). *The Obsolescence Tools Minefield: A Guide to Availability Monitoring*. 1st ed., COG International Ltd., UK.

Boehm, B. W. (1981). *Software Engineering Economics.* 1st ed, Prentice Hall PTR Upper Saddle River, New York.

Boons, A. (1998), Product costing for complex manufacturing systems, *International Journal of Production Economics,* 55(3), pp. 241-255.

Bosworth, M.T. (1995), *Solution Selling: Creating Buyers in Difficult Selling Markets*. McGraw-Hill, New York, NY.

Bowman, R.A. and Schmee, J. (2001). Pricing and managing a maintenance contract for a fleet of aircraft engines. *Simulation*, 76(2), pp. 69-77. DOI: 10.1177/003754970107600202.

Bradley, M. and Dawson, R. (1999). Whole Life Cost: The Future Trend in Software Development. *Software Quality Journal*, 8(2), pp. 121-131.

Bray, O. H. and Garcia, M. L. (1997). Technology roadmapping: the integration of strategic and technology planning for competitiveness. *PICMET '97*, 27-31 July 1997, IEEE, Portland, OR, USA, pp. 25-28.

Brewin, A. (2005). *The Pb-free Minefield: A Guide to Mitigating Risk during the Transition to RoHS Compliance*. 1st ed., COG International Ltd., UK.

Brezet, J.C. et al. (2001). *The design of eco-efficient services; method, tools and review of the case study based 'designing eco-efficient services' project*. Ministry of VROM-Delft University of Technology.

Burns, R. (2000). *Introduction to research methods*. Sage Publications Limited, London.

Cavalieri, S., Maccarrone, P. and Pinto, R. (2004). Parametric vs. neural network models for the estimation of production costs: a case study in the automotive industry. *International Journal of Production Economics,* 91(2), pp. 165-177.

Cheung, W. M., Marsh, R., Newnes, L. B., Mileham, A. R. and Lanham, J. D. (2009). Standards and inference of design information in through life costing of innovative defence electronic products. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 223(2), pp. 169–181. ISSN 0954-4054, DOI: 10.1243/09544054JEM1315.

COG (2010). *Component Obsolescence Group webpage* www.cog.org.uk (accessed on 15th December 2010)

Condra, L. (1999). *Combating Electronic Component Obsolescence by Using Common Processes for Defense and Commercial Aerospace Electronics*. IECQ-CMC Avionics Working Group1, NDIA Paper document, September 1999.

Cook, M. (2004). Understanding the potential opportunities provided by service-orientated concepts to improve resource productivity. In Tracy Bhamra, Bernard Hon. *Design and Manufacture for Sustainable Development 2004*. John Wiley and Sons. pp. 125. ISBN 1860584705.

Craig, R. W. (2002). A methodology for addressing support equipment obsolescence. *Aerospace and Electronic Systems Magazine, IEEE*, 17(5), pp. 20-25.

Creswell J. W., (1998). *Qualitative Inquiry and Research Design: Choosing among five traditions*. SAGE Publications Inc., USA.

Cutler, T.R. (2006). *Cost Management Platforms for New Product Introduction*, Manufacturing.Net - June 21, 2006. http://www.manufacturing.net/article.aspx?id=5148&menuid=264 (accessed on 19th January 2011).

Datta, P.P. and Roy, R. (2009). Cost Modelling Techniques for Availability Type Service Support Contracts: a Literature Review and Empirical Study. *Proceedings of the 1st CIRP IPS2 Conference*, Cranfield, pp. 216–223.

Datta, P.P. and Roy, R. (2010). Cost modelling techniques for availability type service support contracts: A literature review and empirical study. *CIRP Journal of Manufacturing Science and Technology*, 3(2), Industrial Product-Service Systems - IPS2, 2010, pp. 142-157, ISSN 1755-5817, DOI: 10.1016/j.cirpj.2010.07.003.

Day, E. and Fox, R.J. (1985). Extended Warranties, Service Contracts, and Maintenance Agreements—A Marketing Opportunity?. *Journal of Consumer Marketing*, 2(4), pp.77–86.

Denzin, N.K. and Lincoln, Y.S. (1998). *Collecting and Interpreting Qualitative Materials.* Sage Publications, California.

DIS (2005). *Defence Industrial Strategy: Defence White Paper (Cm 6697)*, 2005. Ministry of Defence. Date last updated: 21st Jan 2010. http://www.mod.uk/DefenceInternet/AboutDefence/CorporatePublications/PolicyStrategyandPlanning/DefenceIndustrialStrategy/DefenceIndustrialStrategyDefenceWhitePapercm6697.htm (accessed on 27th September 2010)

DoD (2003). *The DoD Shelf-Life Program - Shelf-Life Management Manual – Definitions*. DoD4140.27-M / DLAJ-373/ May 5, 2003.

DoD (2005). *V-22 Obsolescence Management Plan*. Department of Defense (DOD), Department of the Navy (DON), United States Air Force communities, U.S. (available online https://acc.dau.mil/GetAttachment.aspx?id=46246&pname=file&aid=13738&lang=en-US) (accessed on 19th January 2011).

Dowling, T. (2000). *Planning For Change with a Holistic View of the System. Strategies to Mitigate Obsolescence in Defense Systems Using Commercial Components*. vol. 22, pp. 23-25 October 2000, Budapest, Hungary, RTO MP-072.

Dowling, T. (2004). Technology insertion and obsolescence. *Journal of Defence Science*, 9(3), pp. 151-155.

Duverlie, P. and Castelain, J. M. (1999). Cost Estimation During Design Step: Parametric Method versus Case Based Reasoning Method. *The International Journal of Advanced Manufacturing Technology,* 15(12), pp. 895-906.

Easterby-Smith, M., Thorpe, R. and Lowe, A., (2002). *Management Research: An Introduction*. 2nd Edition, SAGE publications, London.

Eisenhardt, K.M. (1989). Building theories from case study research. *Academy of Management Review*, Vol. 14, pp. 532–550

Evans, D. K., Lanham, J. D. and Marsh, R. (2006). *Cost Estimation Method Selection: Matching User Requirements and Knowledge Availability to Methods*. Systems Engineering and Estimation for Decision Support (SEEDS) Group, University of West of England, Bristol, UK.

Farineau, T., Rabenasolo, B., Castelain, J. M., Meyer, Y. and Duverlie, P. (2001). Use of Parametric Models in an Economic Evaluation Step During the Design Phase. *The International Journal of Advanced Manufacturing Technology,* 17(2), pp. 79-86.

Feldman, K. and Sandborn, P. (2007). Integrating Technology Obsolescence Considerations into Product Design Planning. *Proceedings of the ASME 2007 International Design Engineering Conferences & Computers and Information in Engineering Conference*, Sept. 2007, Las Vegas, NV.

Feng, D., Sandborn, P. and Singh, P. (2007). *Optimizing Lifetime Buy Quantities to Minimize Lifecycle Cost*. MSc Thesis, University of Maryland, (available online http://www.lib.umd.edu/drum/bitstream/1903/6740/1/umi-umd-4217.pdf) (accessed on 19th January 2011).

Flaherty, N. (2005). New parts for old. *IEE Review*, 51(1), pp. 34-37.

Flanagan, J.C. (1954). The critical incident technique. *Psychological bulletin*, 51(4), July 1954, pp. 327-358.

Flick, U. (2002). *An Introduction to Qualitative Research*. Sage Publications Ltd., London.

Fontana, A. and Frey, J. H. (1998). *Interviewing: the art of science*. In: *Collecting and interpreting qualitative materials*, Edited by Denzin N. K. and Lincoln Y. S. Sage, California.

Francis, L. (2006). Tackling obsolescence. *Electronics Weekly*, no. 2235, pp. 20-21.

Frank, B. and Morgan, R. L. (2007). Obsolescence mitigation and management of electronics test equipment. *Autotestcon, 2007 IEEE*, pp. 527-536.

Galliers, R. (1992). *Choosing information systems research approaches. Information Systems Research: Issues, Methods and Practical Guidelines*, Blackwell Science.

Galorath (2008). *SEER-H*. Available at: http://www.galorath.com (accessed 12th June 2008).

GAO (2009). *GAO Cost Estimating and Assessment Guide - Best Practices for Developing and Managing Capital Program Costs (GAO-09-3SP). U.S. Government Accountability Office*. Available online at www.gao.gov/new.items/d093sp.pdf (accessed on 19th January 2011)

Gerson, K. and Horowitz, R. (2002). *Observation and interviewing: options and choices in qualitative research*. In: *Qualitative research in action*, Edited by May T. Sage, London.

Goffin, K. (1999). Customer support: a cross-industry study of distribution channels and strategies. *International Journal of Physical Distribution & Logistics Management*, 29(6), pp. 374-97.

Greene, J. C. & Caracelli, V. J. (eds) (1997). *Advances in Mixed-Method Evaluation: The Challenges and Benefits of Integrating Diverse Paradigms*. San Francisco: Jossey-Bass Publishers.

Grisham, T. (2009). The Delphi technique: a method for testing complex and multifaceted topics. *International Journal of Managing Projects in Business*, 2(1), pp. 112-130.

Guajardo, J. A., Cohen, M. A., Netessine, S. and Kim, S.-H. (2010). *Impact of performance-based contracting on product reliability: An empirical analysis*. Available online at http://www.som.yale.edu/faculty/sangkim/PBC-Reliability-Empirical.pdf (accessed on 27th January 2011)

Gummesson E., (1991). *Qualitative Methods in Management Research*. Sage Publications, USA.

Heilala, J., Montonen, J. and Väätäinen, O. (2008). Life cycle and unit-cost analysis for modular reconfigurable flexible light assembly systems. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 222(10), pp. 1289–1299. DOI:10.1243/09544054JEM1034.

Herald, T. and Seibel, J. (2004). *Technology Management Forecasting and Predictions for System of Interest Analysis*. MARC, INCOSE, Reston, VA, pp. 1-14.

Herald, T., Verma, D. and Lechler, T. (2007). A Model Proposal to Forecast System Baseline Evolution due to Obsolescence through System Operation. *Proceedings of 5th Annual Conference on Systems Engineering Research*, Hoboken, New Jersey, 14-16 March.

Herald, T., Verma, D., Lubert, C. and Cloutier, R. (2008). An obsolescence management framework for system baseline evolution-Perspectives through the system life cycle. *Systems Engineering*, 12(1), pp. 1-20.

Hicks, B. J. (2002).Cost estimation for standard components and systems in the early phases of the design process. *Journal of Engineering Design,* 13(4), pp. 271-292.

Hitt, E. F. and Schmidt, J. (1998). Technology obsolescence (TO) impact on future costs. *Digital Avionics Systems Conference, 17th DASC*, 31 Oct – 7 Nov. The AIAA/IEEE/SAE, vol. 1, no. A33, pp. 1-7.

H'mida, F., Martin, P. and Vernadat, F. (2006). Cost estimation in mechanical production: The Cost Entity approach applied to integrated product engineering. *International journal of production economics,* 103(1), pp. 17-35.

Hollnagel, E., (2003). *Handbook of cognitive task design*. Lawrence Erlbaum, Mahwah (NJ).

Hoppin, T. (2002). Strategies for mitigating risk related to the obsolescence of HP 8566/68 spectrum analyzers in ATE systems. *AUTOTESTCON Proceedings IEEE*, pp. 608-620. DOI:10.1109/AUTEST.2002.1047943.

Howard, M. A., (2002). Component obsolescence – It's not just for electronics anymore. *Proc.FAA/DoD/NASA Aging Aircraft Conference*, San Francisco, CA, 16-19 Sept. 2002.

Hughes, R. T. (1996). Expert judgement as an estimating method. *Information and Software Technology,* 38(2), pp. 67-75.

Humphrey, D., Condra, L., Pendse, N., Das, D., Wilkinson, C. and Pecht, M. G. (2000). An avionics guide to uprating of electronic parts. *IEEE Transactions on Components and Packaging. Technologies*, 23(3), pp. 595-599.

Humphreys, K. K. and Wellman, P. (1995). *Basic Cost Engineering*. 3rd ed, MARCEL DEKKER INC, UK.

IEC 62402:2007 - Obsolescence Management - Application Guide.

ISPA (2008). *International Society of Parametric Analysts - Parametric Estimating Handbook*, Fourth Edition. Available at: http://www.ispa-cost.org/ISPA_PEH_4th_ed_Final.pdf (accessed on 19th January 2011).

Jankowicz, A.D. (1995). *Business Research Projects.* Chapman and Hall, London.

Jian, L. and Hong-fu, Z. (2004). The predictive models of maintenance costs for a civil airplane. *Proceedings of the Institution of Mechanical Engineers*, vol. 218, pp. 347- 351.

Johnsen, T.; Howard, M.; Miemczyk, J. (2009). UK defence change and the impact on supply relationships. *Supply Chain Management: An International Journal*, 14(4), 2009, pp. 270-279(10). DOI:10.1108/13598540910970108.

Johnson, P. and Harris, D. (2002). *Qualitative and quantitative issues in research design*, in: Partington, D. (2002). *Essential Skills for Management Research*. Sage Publications, London, UK, pp. 99-116.

Jones, G. (2001). *Developing a Systematic and Consistent Approach to Engineering Prototype Cost Estimating.* (MSc Thesis), Cranfield University, UK.

Josias, C., Terpenny, J. P. and McLean, K. J. (2004). Component obsolescence risk assessment. *Proceedings of the 2004 Industrial Engineering Research Conference (IERC)*, 15–19 May.

Kanda, Y. and Nakagami, Y. (2006). *What is Product-Service Systems (PSS)? – A review on PSS researches and relevant policies*. IGES Kansai Research Centre – white paper, available at: http://enviroscope.iges.or.jp/modules/envirolib/upload/469/attach/report08.pdf (accessed on 27th January 2011)

Kaplan, R.S. and Cooper, R. (1998). *Cost and Effect: Using Integrated Cost Systems to Drive Profitability and Performance*. Harvard Business School Press, Boston, MA.

Kapletia, D. and Probert, D. (2010). Migrating from products to solutions: An exploration of system support in the UK defense industry. *Industrial Marketing Management*, 39(4), Pages 582-592, May 2010, ISSN 0019-8501, DOI: 10.1016/j.indmarman.2009.03.013.

Keeney, R. L. and von Winterfeldt, D. (1988). Probabilities are useful to quantify expert judgments. *Reliability Engineering & System Safety*, 23(4), pp. 293–298. doi:10.1016/0951-8320(88)90041-5.

Kerr, C.I.V., Phaal, R. and Probert, D.R. (2008). Technology insertion in the defence industry: a primer. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 222(8). pp. 1009-1023. ISSN 0954-4054, 2041-2975. DOI: 10.1243/09544054JEM1080

Kingsman, B. G. and de Souza, A. A. (1997). A knowledge-based decision support system for cost estimation and pricing decisions in versatile manufacturing companies. *International Journal of Production Economics,*53(2), pp. 119-139.

Kirk, J.L. and Miller, M. (1986). *Reliability and Validity in Qualitative Research.* Sage, California.

Klinger, D. W., Stottler, R. and LeClair, S. R. (1992). Manufacturing application of case-based reasoning. *Aerospace and Electronics Conference, 1992 (NAECON 1992), Proceedings of the IEEE 1992 National*, vol. 3, pp. 855-859.

Koponen, H. (2002). *The Development of an Information Infrastructure for Cost Estimating in the Automotive Industry.* (MSc Thesis), Cranfield University, UK.

Kumar, R. (2005).*Research Methodology: A Step-by-Step Guide for Beginners*. Sage, 2005.

Kumar, R., Markeset, T. and Kumar, U. (2004). Maintenance of machinery: Negotiating service contracts in business-to-business marketing, *International Journal of Service Industry Management,* 15(4), pp.400–413.

Landeta, J. (2006). Current validity of the Delphi method in social sciences. *Technological Forecasting and Social Change*, 73(5), pp. 467-82.

Larsson, D. and Gunnarsson, J. (2001). A model to Predict Track Degradation Costs. *7th International Heavy Haul Conference*, Brisbane, pp. 437-444.

Leonard, J. V., Wolf, J. and Stolinski, R. (1988). Microcircuit parts obsolescence. *IEEE Region 5 Conference, 1988:'Spanning the Peaks of Electrotechnology'*, pp. 229-231.

Lere, J. C. (2000). Activity-based costing: a powerful tool for pricing. *Journal of Business & Industrial Marketing,* 15(1), pp. 23-33.

Lere, J. C. (2001). Your Product-costing System Seems to Be Broken-Now What?. *Industrial Marketing Management,* 30(7), pp. 587-598.

Ling, D. (2005). *Railway Renewal and Maintenance Cost Estimating*. (PhD Thesis), Cranfield University, UK.

Linstone, H. A. and Turoff, M. (1975). *The Delphi method: techniques and applications*. Addison-Wesley, London.

Livingston, H. (2000). GEB1: Diminishing Manufacturing Sources and Material Shortages (DMSMS) Management Practices. *Proceedings of the 2000 DMSMS Conference*, Jacksonville, Florida, 21-25 August.

Luke, J., Bittorie, J. W., Cannon, W. J. and Haldeman, D. G. (1999). Replacement strategy for aging avionics computers. *Aerospace and Electronic Systems Magazine, IEEE*, 14(3), pp. 7-11.

Madisetti, V., Jung, Y., Khan, M., Kim, J. and Finnessy, T. (2000). On upgrading legacy electronics systems: methodology, enabling technologies and tools.

VHDL International Users Forum Fall Workshop, 2000. Proceedings, 18 – 20 Oct., Orlando, FL, USA, pp. 7-14.

Manor, D. (2006). Addressing the Instrument Obsolescence Problem-Options and Solutions. *Autotestcon, 2006. IEEE Systems Readiness Technology Conference*, 18-21 Sept, Anaheim, CA, USA, pp. 426-430.

Marion, R. L. (2001). Mitigating COTS obsolescence in military test. *AUTOTESTCON Proceedings, 2001. IEEE Systems Readiness Technology Conference*, pp. 746-756. DOI: 10.1109/AUTEST.2001.949458

Marshall, C. and Rossman, G. B. (1989). *Designing qualitative research*. Sage, California.

Mathieu, V. (2001). Product services: from a service supporting the product to a service supporting the client. *Journal of Business & Industrial Marketing*, 16(1), pp. 39-58.

Maxwell, J. A., (2002). *Understanding and Validity in qualitative research*, in: Huberman, A. M. and Miles, M. B. (2002). *The qualitative researcher's companion*. SAGE Publications Inc., USA.

Meier, H., Roy, R. and Seliger, G. (2010) Industrial Product-Service Systems - IPS2. *CIRP Annals – Manufacturing Technology*. 59(2), pp. 607-627.

Merola, L. (2006). The COTS software obsolescence threat. *Fifth International Conference on Commercial-off-the-Shelf (COTS)-Based Software Systems*, 2006. San Diego, CA.

Meyer, A., Pretorius, L. and Pretorius, J. H. C. (2003). A management approach to component obsolescence in the military electronic support environment. *South African Journal of Industrial Engineering*, 14(2), pp. 121-136.

Meyer, A., Pretorius, L., Pretorius, J. H. C. (2004). A model to manage electronic component obsolescence for complex or long life systems.

Engineering Management Conference, 2004 Proceedings. 2004 IEEE International, vol. 3, pp. 1303-1309. DOI:10.1109/ IEMC.2004.14089

MoD (2004). *Ministry of defence component obsolescence resolution cost metrics study*. QinetiQ and ARINC, UK. Available at: www.aof.mod.uk/aofcontent/tactical/engineering/downloads/om_resolution_metrics_2004.pdf (accessed on 19th January 2011).

MoD (2006). *Enabling Acquisition Change - An examination of the Ministry of Defence's ability to undertake Through Life Capability Management*. UK Ministry of Defence (MoD) report, June 2006. http://www.mod.uk/NR/rdonlyres/10D1F054-A940-4EC6-AA21-D295FFEB6E8A/0/mod_brochure_hr.pdf (accessed on 24th November 2010)

Mont, O. (2004). *Product-service systems: Panacea or myth.* (Doctoral Dissertation thesis), The International Institute for Industrial Environmental Economics (IIIEE), Lund University: Lund, Sweden.

Mont, O. K. (2002). Clarifying the concept of product–service system. *Journal of Cleaner Production*, 10(3), pp. 237-245.

MTI (2008a). *Advanced Component Obsolescence Management (AVCOM) is a registered trademark for a component-level bill of material obsolescence forecasting and analysis tool*. Available at: http://thedmsmscompany.com/avcom.asp (accessed 12th June 2008).

MTI (2008b). *OASIS is a registered trademark for a web-based component-level bill of material obsolescence monitoring tool*. Available at: http://thedmsmscompany.com/oasis.asp (accessed 12th June 2008).

NASA (2004). *Cost Estimating Handbook, 2004*. http://ceh.nasa.gov/webhelpfiles/Cost_Estimating_Handbook_NASA_2004.htm (accessed on 19th January 2011).

NATO (2009). *Code of Practice for Life Cycle Costing (RTO-TR-SAS-069). NATO Research and Technology Organisation*. September 2009. Available online at http://ftp.rta.nato.int/public//PubFullText/RTO/TR/RTO-TR-SAS-069///$$TR-SAS-069-ALL.pdf (accessed on 19th January 2011).

Neal, T. M. (2004). Obsolescence replacement-applied technology. *AUTOTESTCON 2004 Proceedings*, 20-23 Sept., pp. 58-61.

Negrini, D., Kettle, A., Sheppard, L., Mills, G.H., Edbrooke, D.L., (2004). The cost of a hospital ward in Europe: Is there a methodology available to accurately measure the costs?. *Journal of Health Organization and Management*, 18(3), pp.195–206

Ng, I.C.L. and Nudurupati, S.S. (2010). Outcome-based service contracts in the defence industry – mitigating the challenges. *Journal of Service Management*, 21(5), pp.656–674

Niazi, A., Dai, J. S., Balabani, S. and Seneviratne, L. (2006). Product Cost Estimation: Technique Classification and Methodology Review. *Journal of Manufacturing Science and Engineering,* 128(2), pp. 563-575.

Oblad, R.P. (1999). Achieving robust interchangeability of test assets in ATE systems, AUTOTESTCON '99. IEEE Systems Readiness Technology Conference, IEEE, pp. 687-698. DOI:10.1109/AUTEST.1999.800443.

Okoli C. and Pawlowski S.D. (2004). The Delphi Method as a research tool: An example, design considerations and applications. *Information & Management*. 42(1), pp. 15-29. DOI:10.1016/j.im.2003.11.002

Palacio Madariaga, A. (1999). *Cost Estimate and Risk Analysis in Manufacturing Processes.* (MSc Thesis), Cranfield University, UK.

PartMiner (2008). *CAPSXpert, CAPS BOM Manager & CAPS Forecast*. Available at: http://www.partminer.com (accessed 12th June 2008).

Pecht, M. and Humphrey, D. (2006). Uprating of electronic parts to address obsolescence. *Microelectronics International*, 23(2), pp. 32-36.

Pecht, M. G. and Das, D. (2000). Electronic part life cycle. *IEEE Transactions on Components and Packaging Technologies*, 23(1), pp. 190-192. DOI:10.1109/6144.833060.

Perera, H. S. C., Nagarur, N. and Tabucanon, M. T. (1999). Component part standardization: A way to reduce the life-cycle costs of products. *International Journal of Production Economics*, 60-61, 20 April 1999, pp. 109-116, ISSN 0925-5273, DOI: 10.1016/S0925-5273(98)00179-0.

Petersen, L. (2000). The Use of Commercial Components in Defense Equipment to Mitigate Obsolescence. A Contradiction in Itself? *RTO SCI Symposium on Strategies to Mitigate Obsolescence in Defense Systems Using Commercial Components*, Budapest, Hungary, 23-25 October 2000, RTO MP-072.

Pope, S. M., Elliott, J. R. and Turbini, L. J. (1998). Designing for technological obsolescence and discontinuous change: an evaluation of three successional electronic products. *Electronics and the Environment, 1998. ISEE-1998. Proceedings of the 1998 IEEE International Symposium on*, 4-6 May 1998, Oak Brook, IL , USA, pp. 280-286. ISSN: 1095-2020. DOI:10.1109/ISEE.1998.675072

Porter, G. Z. (1998). *An Economic Method for Evaluating Electronic Component Obsolescence Solutions*. Boeing, Company White Paper.

PRICE Systems (2008). *TruePlanning*, available at: http://www.pricesystems.com (accessed 12th June 2008).

QinetiQ (2008). *Q-Star™*. Available at: http://www.qtec.us (accessed 12th June 2008).

Rahman, A. and Chattopadhyay, G. (2008). Cost estimation for maintenance contracts for complex asset/equipment. *The IEEE International Conference on Industrial Engineering and Engineering Management*, 8th - 11th December, 2008, Singapore, pp.1355-1358.

Redling, T. J. (2004). Considerations for upgrading aging military avionics systems with state-of-the-art technology. *The 23rd Digital Avionics Systems Conference, 2004. DASC 04*. 24-28 Oct., vol. 2, pp. 7.D.1- 7.1-7.

Robson C. (2002). *Real World Research: A Resource for Social Scientists and Practitioner-Researchers*. Blackwell Publishers Ltd., UK.

Romero Rojo, F. J. (2007). *Cost estimating process improvement within a manufacturing environment*. (MSc Thesis), Cranfield University, UK.

Rowe, G. and Wright, G. (1999). The Delphi Technique as a Forecasting Tool: Issues and Analysis. *International Journal of Forecasting*, 15(4), pp. 353–375.

Roy, R. (2003). Cost engineering: why, what and how?. *Decision Engineering Report Series.* Issue 1, Cranfield University, UK, 18-September 2003.

Roy, R. and Cheruvu, K. (2009). A competitive framework for Industrial Product Service Systems. *International Journal of Internet Manufacturing and Services, Special Issue on Product Service Solutions in Life-Cycle Activities*. 2(1), pp. 4–29.

Roy, R. and Sackett, P. (2003). *Cost Engineering: The Practice and the Future*. 3rd ed, CASA/SME BLUE BOOK SERIES, USA.

Roy, R., Kelvesjo, S., Forsberg, S. and Rush, C. (2001). Quantitative and qualitative cost estimating for engineering design. *Journal of Engineering Design,* 12(2), pp. 147-162.

Rumney, G. A., (2007). *The Software Obsolescence Minefield: A Guide for Supporting Software and Electronic Information*. 1st ed., COG International Ltd., UK.

Rush, C. and Roy, R. (2001). Expert judgement in cost estimating: Modelling the reasoning process. *Concurrent Engineering,* 9(4), pp. 271-284.

Sandborn, P. (2004). Beyond reactive thinking—We should be developing proactive approaches to obsolescence management tool. *DMSMS Center of Excellence Newsletter*, 2(4), July 2004.

Sandborn, P. (2007a). Designing for Technology Obsolescence Management. *Proceedings of the 2007 Industrial Engineering Research Conference*, 19-23 May 2007, Nashville, TN.

Sandborn, P. (2007b). Software Obsolescence - Complicating the Part and Technology Obsolescence Management Problem. *IEEE Transactions on Components and Packaging Technologies*, 30(4), pp. 886-888.

Sandborn, P. and Plunkett, G. (2006). The Other Half of the DMSMS Problem - Software Obsolescence. *DMSMS Knowledge Sharing Portal Newsletter*, 4(4), pp. 3-11.

Sandborn, P. and Singh, P. (2002). Electronic Part Obsolescence Driven Design Refresh Optimization. *Proc. FAA/DoD/NASA Aging Aircraft Conference*, September 2002, San Francisco, CA.

Sandborn, P., Mauro, F. and Knox, R. (2005). A Data Mining Based Approach to Electronic Part Obsolescence Forecasting. *Proceedings of the 2005 DMSMS Conference*, 11-15 April, Nashville, TN.

Sandborn, P., Mauro, F. and Knox, R. (2007). A data mining based approach to electronic part obsolescence forecasting. *2007 IEEE Transactions on Components and Packaging Technologies,* 30(3), pp. 397-401.

Sandborn, P., Prabhakar, V. and Ahmad, O. (2010). Forecasting electronic part procurement lifetimes to enable the management of DMSMS obsolescence. *Microelectronics Reliability*, In Press, Available online 3 September 2010, ISSN 0026-2714, DOI: 10.1016/j.microrel.2010.08.005.

Shehab, E. and Abdalla, H. (2002). An Intelligent Knowledge-Based System for Product Cost Modelling. *The International Journal of Advanced Manufacturing Technology,* 19(1), pp. 49-65.

Shehab, E. M. and Abdalla, H. S. (2001). Manufacturing cost modelling for concurrent product development. *Robotics and Computer Integrated Manufacturing,* 17(4), pp. 341-353.

Shepperd, M. and Schofield, C. (1997). Estimating Software Project Effort Using Analogies. *IEEE Transactions on Software Engineering,* 23(12), pp. 736-743.

Shuman, L. L. (2002). *Cost-Benefit Analysis Tools for Avionics Parts Obsolescence*. Research Report AU/ACSC/02-103/2002-04, Air Command and Staff College, Air University, Maxwell Air Force Base, Alabama.

Singh, P. and Sandborn, P. (2005). Forecasting technology insertion concurrent with design refresh planning for COTS-based electronic systems. *Reliability and Maintainability Symposium, 2005 Proceedings Annual*, pp. 349-354.

Singh, P. and Sandborn, P. (2006). Obsolescence Driven Design Refresh Planning for Sustainment-Dominated Systems. *The Engineering Economist*, 51(2), pp. 115-139.

Singh, P., Sandborn, P., Geiser, T. and Lorenson, D. (2004). Electronic part obsolescence driven design refresh planning*. International Journal of Agile Manufacturing*, 7(1), pp. 23-32.

Singh, P., Sandborn, P., Lorenson, D. and Geiser, T. (2002). Determining Optimum Redesign Plans for Avionics Based on Electronic Part Obsolescence Forecasts. *Proc. World Aviation Congress*, November 2002, Phoenix, AZ, SAE International.

Sjoberg, E. S. and Harkness, L. L. (1996). Integrated circuit obsolescence and its impact on technology insertion definition for military avionics systems. *Aerospace and Electronics Conference, 1996. NAECON 1996., Proceedings of the IEEE 1996 National*, vol. 2, pp. 792 - 799.

Skulmoski, G.J., Hartman F.T. and Krahn, J., (2007). The Delphi method for graduate research. *Journal of Information Technology Education*, 6(1), pp. 1-21.

Software Development Environment (SDE), available at: http://en.wikipedia.org/wiki/Software_development_environment (last accessed on 5/11/09).

Solomon, R., Sandborn, P. and Pecht, M. (2000). Electronic part life cycle concepts and obsolescence forecasting. *Components and Packaging Technologies, IEEE Transactions on [see also Components, Packaging and Manufacturing Technology, Part A: Packaging Technologies, IEEE Transactions on]*, 23(4), pp. 707-717. DOI:10.1109/ 6144.888857

Stein, P. and Wadey, S. (2008). *Technology Partnership in Defence - Mantaining a cutting edge for planning and investing in Defence R&D*. A Report by the National Defence Industries Council - Research & Development Group (NDIC RDG). UK Ministry of Defence (MoD), Sept 08.

Steinmetz, W. R. and Ashmore, D. P. (1997). *Risk Based Analysis of Urban Public Life Cycle Costs*. London, Railway Technology strategy Centre, Imperial College.

Stelling, M. (2008). *Automated Cost and Customer Based Business Process Reengineering in the Service Sector*. (PhD Thesis), Cranfield University, UK.

Stewart, R. D. and Wyskida, R. M. (1987). *Cost Estimator's Reference Manual.* 1st ed, Wiley-Interscience, New York / Toronto.

Stremersch, S., Wuyts, S. and Frambach, R.T. (2001). The purchasing of full-service contracts: an exploratory study within the industrial maintenance market. *Industrial Marketing Management*, vol. 30, pp. 1-12.

Tashakkori, A. and Teddlie, C. (2003). *Handbook of mixed methods in social & behavioral research*. SAGE, 2003. ISBN 0761920730, 9780761920731

Tomczykowski, W. J. (2003). A study on component obsolescence mitigation strategies and their impact on R&M. *Proceedings of Annual Conference on Reliability and Maintainability (RAMS)*, 27-30 Jan. 2003, IEEE, Tampa, FL, USA, pp. 332-338.

Torresen, J. and Lovland, T. A. (2007). Parts Obsolescence Challenges for the Electronics Industry. *Design and Diagnostics of Electronic Circuits and Systems, 2007. DDECS'07. IEEE*, 11-13 April, pp. 1-4.

Total Parts Plus (2008). *Parts Xpert & Parts Plus*. Available at: http://www.totalpartsplus.com (accessed 12th June 2008).

Trenchard, M. (2003). The obsolescence minefield. *IEE Review*, 49(9), pp. 29-29.

Tryling, D. P. (2007). Planning for obsolescence. *Electrical Apparatus*, 60(4), pp. 23-24.

Vant, J. A. (2002). A Life Cycle Cost Model for Prioritisation of Track Maintenance and Renewal. *Innovations for a Cost Effective Railway Track*. no. 2, pp. 20-25.

Veit. P. (2002). Track Maintenance Based on Life-Cycle Cost Calculations. *Innovations for a Cost Effective Railway Track*. no. 2, pp. 6-13.

Vitasek, K, Cothran, J, Geary, and Rutner, S. (2006). *Performance-Based Logistics: The Changing Landscape in Support Contracting*. University of Tennessee, white paper, June 2006. Available online at http://thecenter.utk.edu/images/Users/30/TheChangingLandscapeofSupportLogistics.pdf. (accessed on 26th January 2011)

Walsh, M. (2001). *Research Made Real*. Nelson Thornes Ltd.

Weaver, P. and Ford, M. (2003). ATE obsolescence solutions; costs and benefits [military equipment]. *AUTOTESTCON 2003. IEEE Systems Readiness Technology Conference Proceedings*, 22-25 Sept., pp. 623-628.

Webb, L.T. and Bil, C. (2010). Through-Life Support and the Aircraft Lifecycle. *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*. 4 - 7 January 2010, Orlando, Florida.

Westkamper, E., Niemann, J. and Dauensteiner, A. (2001). Economic and Ecological Aspects in Product Life Cycle Evaluation. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 215(5), pp. 673-681. ISSN 0954-4054, DOI:10.1243/0954405011518601.

Winchell, W. (1989). *Realistic Cost Estimating for Manufacturing*. 2nd ed, Society of Manufacturing Engineers, Publications Development Dept, UK.

Yin, R. K. (2009). *Case Study Research: Design and Methods*. Fourth Edition. SAGE Publications. California. ISBN 978-1-4129-6099-1

Zaring, O. (Ed.) (2001). *Creating Eco-Efficient Producer Services – Report of an EU Project*. Gothenburg Research Institute, Gothenburg.

Zio, E. (1996). On the use of the analytic hierarchy process in the aggregation of expert judgments. *Reliability Engineering and System Safety,* 53(2), pp. 127-138.

Zitron, J. (2006). Public-private partnership projects: Towards a model of contractor bidding decision-making. *Journal of Purchasing and Supply Management*, 12(2), March 2006, Pages 53-62, ISSN 1478-4092, DOI: 10.1016/j.pursup.2006.04.002.

Zoeteman, A. and Esveld, C. (1999). Evaluating track structures: life cycle cost analysis as a structured approach. *World Congress on Railway Research*, Tokyo.

THIS PAGE IS INTENTIONALLY LEFT BLANK

Appendix

A

APPENDIX A: QUESTIONNAIRES

APPENDIX A.1 Familiarisation Questionnaires

The three familiarisation questionnaires used during the introductory meetings with the industrial collaborator are shown as follows. The information collected during the initial meetings allowed refining the research protocol for the following ones.

PSS-Cost Project, Decision Engineering Centre, Cranfield University - Introductory Visit

FIRST FAMILIARISATION QUESTIONNAIRE

A) Capability/Availability Contracts

What criteria do use to select a capability/availability contract over others?

- What is the scope of time in the process of evaluating a project?
- What kind of methods/approaches do you use?

How do you measure the value (financial) in a contract proposal?

What is MDAL? How does it influence cost estimation?

What information do you hold on your suppliers e.g. their capabilities, their lead times?

What criteria's are used to define the quality of a supplier in capability/availability contracts?

How flexible are contracts that are accepted? (Delivery time, price, uncertainties and risks, contract termination…)

How long is the gap between the signing of capability/availability contract and the actual delivery of the contract?

On your contract, what are the particular features that make it a capability-/availability- based project?

- what is the duration of the project?
- what is the scope of time
- combination of product and service total responsibility.

What services are included in the capability/availability contract?

How do you agree pricing for capability/availability contract?

- what are the variables?

How do you define customer Value in a contract?

Could you please describe the business environment for each capability/availability contract? (What are the challenges, expectations, cost drivers, uncertainties and risks?)

How many capability/availability contracts do they put together per year? What is the rate of success? How long is the life of the capability/availability contract?

How long does it take to prepare for capability/availability contract, in terms of man days?

Do you have standard pro-formas for capability/availability contracts? If so what are they?

Which departments are distributed data concerning capability/availability contracts?

What level of interaction is there with suppliers prior to and during capability/availability contracts?

What structure do you have to satisfy customer requirements in capability/availability contracts?

What kind of relationship is there between product and service in the capability/availability contracts you have proposed?

B) Whole life cycle work breakdown structure and cost estimation

What is the cost breakdown structure of a capability/availability contract?

Do you prepare models to estimate costs? And, do you focus on each stage of the life cycle separately? If so, what are the cost drivers for each section?

What kind of models are you using to make estimations? Can you tell us specific examples of software that you use?

How do you check a quoted price level in a contract?

How do you compare estimates with actual results? How do you use this information to improve methods?

How do you categorize the life cycle of a capability/availability contract?

Would we be able to receive information on historic breakdown data of costs for capability/availability contracts?

What kind of data could we expect concerning capability contracts?

What kind of models are you using? Can you tell us specific examples of software that you use?

How do you predict costs at the bidding stage? How do you estimate cost of design?

Do you estimate costs for each stage of the life cycle separately? If so, what are the cost drivers for each section?

C) Obsolescence Modelling

What strategies are used to predict and mitigate obsolescence?

How do you incorporate obsolescence into cost models?

How do you predict obsolescence?

How do you define the mitigation strategy to tackle obsolescence?

How do you incorporate the cost related to the obsolescence mitigation to the WLCC?

Is there any business model in which the supplier is not in charge of tackling the obsolescence problems?

What methods are used to predict and mitigate obsolescence?

D) General

What is the information link between you and the supplier?

How are requirements communicated to suppliers? What risks are you transferring to the suppliers?

Why are you moving towards capability contracts over traditional Business Models?

Who takes responsibilities in each project?

Do you have historic data available on capability/availability contracts (cost breakdown?)

- If yes, is this data available for us?
- If not, is there someone with the knowledge for us to discuss with?

Which particular individuals should we contact concerning the capability/availability contracts?

Which particular individuals could we meet to learn about whole life cycle processes?

Which particular individuals should we interact concerning cost estimation?

Which particular individuals would be appropriate to discuss uncertainty and risk?

Which particular individuals measure obsolescence and technological maturity?

How do you come to an agreement that is fair to both parties?

PSS-Cost Project, Decision Engineering Centre, Cranfield University

Introductory Visit

SECOND FAMILIARISATION QUESTIONNAIRE

1. Scope of the estimate

SE.1.1 What is the scope of the estimate in programme terms, e.g. for United Kingdom MoD contracts? What stages of the CADMID/CADMIT cycle are included?

SE.1.2 What is the scope of the estimate in technical terms, e.g. coverage of interfaces, platform integration costs, evolutionary increments, in-service support?

SE.1.3 Are disposal costs considered within the life cycle cost considerations?

2. Programme Baseline

SE.2.1 Is there an agreed master data and assumptions list (MDAL) e.g. that supports translation of programme requirements into a defendable cost estimate?

3. Cost Breakdown Structure

CBS.3.1 Describe the CBS that you employ in availability contract?

CBS.3.2 Does the CBS for availability contracts differ from the CBS' of the past?

CBS.3.3 Has a cost breakdown structure (CBS) been agreed with the customer consistent with the level of detail that was (or will be) used to produce the estimate?

CBS.3.4 If a CBS is in use, where has it drilled-down (e.g. for de-risking) has the corresponding detail been added to the MDAL to support the audit process?

CBS.3.5 If a CBS is in use, is its scope and structure based on any particular standard (e.g. as mandated by the customer or to comply with legacy practices)?

CBS.3.6 If a CBS is in use, at what LCM stage was it first created and through which LCM stages is it intended to maintain it (e.g. to support cost metrics)?

4. Data Collection & Analysis

DCA.4.1 Where historical costs have been collected, what strategies have been used to analyze it (e.g. simple statistics, investigating anomalies, visualization?

- Where have you stored data, how easy is it to retrieve? (Using SAP?)

- What kind of data could we expect concerning availability contracts?

5. Method Selection

MS.5.1 What commercial or in-house tools are used to make estimates (e.g. parametric, simulation, optimisation, decision support, historical trends analysis)?

MS.5.2 What process assets (e.g. LCM, BMS) have you invoked in support of cost estimating, price build-up, managing uncertainty and risk, and phase reviews? (Risk Register?)
- Can you quote which ones you use or can you show us?

MS.5.3 What rationale was used to select the estimating method(s) for the programme (e.g. by analogy, expert opinion, extrapolation, parametric, or bottom-up)?

MS.5.4 Are there shortcomings in the available estimating methods that need to be addressed outside of the immediate project (e.g. cluster or functional level)?

MS.5.5 Where do we focus within a contract? Which areas should we concentrate on?

6. Whole life cycle cost estimation

WLCC.6.1 How does the WLC estimation process change when a WLC approach is taken?

WLCC.6.2 Which are the main cost drivers in availability contracts? (E.g. major 3)

WLCC.6.3 How do you compare estimates with the actual and how do you use this information to improve methods? (Do you use a CBS to calculate both estimates and actual e.g. EVM, CPI, SPI)

7. Availability Contract Process

CCP.7.1 How do you agree a price with the customer? (e.g. Competitive or single supplier)

CCP.7.2 Could you please describe the issues for each availability contract? (What are the challenges, expectations, cost drivers, uncertainties and risks?)

CCP.7.3 What has changed from delivering just a product to an availability contract in terms of customers' relations?

CCP.7.4 Do you have standard pro-formas for availability contracts? If so what are they?

CCP.7.5 What is the effort at the bidding stage? (e.g. hours)

PSS-Cost Project, Decision Engineering Centre, Cranfield University - Introductory Visit

THIRD FAMILIARISATION QUESTIONNAIRE

(1) Please describe the bid development process on a flow chart.
- Which people are involved in bidding process?
- Where does the cost estimation begin?
- How successful are you at following your own standards for bidding (level of standardization)?

(2) How is the cost estimation process at the bidding stage
- Which tools are used in cost estimation?
- Who are the stakeholders of estimates and how does their expectations influence the cost estimation at eh bid phase?
- At what level of quality are the estimates expected to be?
- What level of detail is reached at the bidding stage?

(3) Obsolescence
- What are the types and sources of obsolescence?
- What kind issues are there in selecting the types and source so obsolescence?
- How is obsolescence included to the costing?
- What are the challenges in incorporating obsolescence into cost estimation? How could this be improved?
- How is obsolescence estimated at the bidding stage?
- What issues are present in this process?
- How would you improve this process?
- What level of information about the project definition is available at the bidding stage so that could be used to analyse obsolescence?

- Which activities in-service stage get affected from obsolescence and why?
- How are cost drivers identified?
- In this project what are the cost drivers for obsolescence?
- Do you forecast obsolescence, and how?
- How do you define the mitigation strategy?
- What cost metrics are used?
- Who is in charge of costing obsolescence at the bidding stage? How is it done?
- What limitations do you feel you have in costing obsolescence?
- How do you mitigate obsolescence?
- What issues occur in mitigating obsolescence?
- How do you select the mitigation strategies? Could you please explain the logic behind the selection?
- What issues are present in this process? And how would you improve these issues?

APPENDIX A.2 Generic Obsolescence Capture Questionnaire

1. What is your role in the organisation?

A) Obsolescence Management:

2. Is there any standard policy for the management of obsolescence?
3. Do you use any tool for monitoring the 'health' of the components of a system in terms of obsolescence?
4. Do you forecast obsolescence issues? How?
5. Who is in charge of managing obsolescence and solving any obsolescence issue, the customer or the supplier? Who is responsible for the cost of it? Is there any case study that we can focus on?
6. Who decides what the most appropriate mitigation approach is to tackle an obsolescence issue? What are the drivers of this selection? Is it done in a reactive or proactive way?
7. Is it more expensive to deal with obsolescence in a reactive or proactive way? Explain
8. Do you plan the mitigation strategy at the early stages?

B) Cost Estimation of Obsolescence:

9. Who is in charge of doing the cost estimation of obsolescence at the bidding stage?
10. Do you take into account the cost related to obsolescence issues at the bidding stage?
11. How do you estimate the cost of obsolescence? What kind of technique do you use? (e.g. expert opinion, parametric, analogy-based, detailed,…)
12. What cost metrics are used?

13. What do you regard as are the key cost drivers for obsolescence?
14. How are cost drivers of obsolescence identified?
15. Do you compare estimates with the actual? How do you use this information to improve the estimating methods?
16. What limitations do you feel you have in costing obsolescence?
17. What are the challenges in incorporating obsolescence into cost estimation?
18. How would you improve this process?
19. What is the quality level expected for the estimates?
20. What are the types and sources of obsolescence? Which of them do you take into account for managing obsolescence?
21. Which activities in-service stage get affected from obsolescence and why?

C) Cost Estimation of Obsolescence:

22. At which stage of the CADMID cycle you develop the maintenance strategy?
23. What types of maintenance strategies to you consider and use?
24. How do you estimate the cost of maintenance? What kind of technique do you use? (e.g. expert opinion, parametric, analogy-based, detailed,…) Is it based on the type of maintenance strategy planned?
25. What do you regard as are the key cost drivers for maintenance?
26. Do you compare estimates with the actual? How do you use this information to improve the estimating methods?

D) General

27. Is there any expert or department focused on obsolescence management?

APPENDIX A.3 Software Obsolescence Capture Questionnaire

GENERAL:

1. What is your role in the organisation?
2. Years of experience

SOFTWARE OBSOLESCENCE:

3. What is the difference between Software Support and Software Obsolescence?
4. What are the main reasons for Software Obsolescence?
5. Is Software Obsolescence a major problem? What is the interaction with hardware?
6. Do you forecast obsolescence issues? How? (Technology roadmap)
7. Project decisions leading to Software Obsolescence vs. company policy. How is Software Obsolescence managed? At what level it is resolved? (e.g. upgrading software)
8. Do you plan in a project to upgrade the software?
9. Proactive or reactive?
10. What level of information is available? (e.g. databases, configuration management plan, “interaction map”)
11. Is there any mitigation strategy that can be applied to minimise the impact or probability of having a software obsolescence issue?
12. Who is in charge of managing obsolescence and solving any obsolescence issue, the customer or the supplier? Who is responsible for the cost of it?
13. Who decides what the most appropriate mitigation approach is to tackle an obsolescence issue? What are the drivers of this selection?
14. Is there any standard policy for the management of software obsolescence?
15. What do you regard as the key cost drivers for software obsolescence?
16. Do you estimate the cost of software obsolescence upfront? How?

APPENDIX A.4 Materials Obsolescence Capture Questionnaire

GENERAL:

1. What is your role in the organisation?
2. Years of experience

MATERIALS OBSOLESCENCE:

3. What are the main reasons why a material becomes obsolete?
4. What is the period since a new regulation is promulgated until a measure is taken to tackle materials obsolescence?
5. Do you forecast obsolescence issues? How?
6. Is it possible to foresee when (or how often) you will come across an obsolescence issue?
7. Is it possible to estimate the impact that an obsolescence issue will have on the system?
8. What are the possible resolution strategies that can be applied to resolve a material obsolescence issue?
9. Is there any mitigation strategy that can be applied to minimise the impact or probability of having a material obsolescence issue?
10. Who is in charge of managing obsolescence and solving any obsolescence issue, the customer or the supplier? Who is responsible for the cost of it? Is there any case study that we can focus on?
11. Who decides what the most appropriate mitigation approach is to tackle an obsolescence issue? What are the drivers of this selection? Is it done in a reactive or proactive way?
12. Is there any standard policy for the management of materials obsolescence?
13. What do you regard as the key cost drivers for materials obsolescence?

APPENDIX A.5 EEE-FORCE Development Questionnaire

Cranfield UNIVERSITY

PSS-Cost Project
Review Meeting at Abbey Wood, Bristol
Date: 20.01.2009

QUESTIONNAIRE

Aim: To capture industrial views on the logic, relevance, benefits and future development of the "obsolescence costing tool"

Name of respondent...

Question 1. Please tick a suitable box for the following questions.

a) Would an obsolescence costing tool be beneficial for the defence and aerospace industries at the bidding stage?

☐ Yes ☐ No ☐ Not sure

b) Relevance of the presented tool to your business.

Low	1	2	3	4	5	Hi
	☐	☐	☐	☐	☐	

Cranfield University, PSS-Cost Project, Decision Engineering Centre

Researcher: Francisco Javier Romero Rojo; Supervisors: Rajkumar Roy, Essam Shehab

Cranfield UNIVERSITY

Question 2. Please assess the benefits of the presented tool to industry. (Please add any other benefit you may consider)

BENEFITS OF THE TOOL	1(Low)	2	3	4	5(High)
Effective way to estimate obsolescence costs at the bidding stage	1(Low)	2	3	4	5(High)
It enables to identify obsolescence drivers	1(Low)	2	3	4	5(High)
It gives confidence to include obsolescence in contracts	1(Low)	2	3	4	5(High)
	1(Low)	2	3	4	5(High)
	1(Low)	2	3	4	5(High)
	1(Low)	2	3	4	5(High)
	1(Low)	2	3	4	5(High)
	1(Low)	2	3	4	5(High)
	1(Low)	2	3	4	5(High)
	1(Low)	2	3	4	5(High)

Cranfield University, PSS-Cost Project, Decision Engineering Centre

Researcher: Francisco Javier Romero Rojo; Supervisors: Rajkumar Roy, Essam Shehab

Cranfield UNIVERSITY

Question 3. Evaluate the need for the following improvements: (Please add any other improvement you may consider necessary)

IMPROVEMENTS	1(Low)	2	3	4	5(High)
Take into account the possibility of repairing a component and reusing it	1(Low)	2	3	4	5(High)
Make a distinction between consumable and repairable components	1(Low)	2	3	4	5(High)
Take into account new stock that may be purchased	1(Low)	2	3	4	5(High)
Take into account the possibility that some components may become obsolete more that once during the period	1(Low)	2	3	4	5(High)
Use of Monte-Carlo simulation to take uncertainty into account	1(Low)	2	3	4	5(High)
	1(Low)	2	3	4	5(High)
	1(Low)	2	3	4	5(High)
	1(Low)	2	3	4	5(High)
	1(Low)	2	3	4	5(High)

Cranfield University, PSS-Cost Project, Decision Engineering Centre

Researcher: Francisco Javier Romero Rojo; Supervisors: Rajkumar Roy, Essam Shehab

Cranfield UNIVERSITY

Question 4. Improvement for the obsolescence costing tool:

Please provide suggestions and strategies to make this tool adaptable to the situation in which the Bill of Materials (BoM) is not available

....

....

....

....

....

....

....

....

....

....

....

....

....

....

....

Cranfield University, PSS-Cost Project, Decision Engineering Centre

Researcher: Francisco Javier Romero Rojo; Supervisors: Rajkumar Roy, Essam Shehab

Cranfield UNIVERSITY

Question 5. Assumptions made in this tool:

a) Please assess the validity of the following assumptions made:

Assumptions	Valid	Invalid	If invalid, please justify
The period between design refreshes is 10 years			
All the components are regarded as consumables (once they fail they are scrapped rather than repaired)			
No new stock is purchased until it runs out			
The components cannot become obsolete more that once during the period			
Electronic components can be classified according to their level of complexity and each category will have a similar "obsolescence profile"			
The whole BoM is available			
The obsolescence date forecasted by the Obsolescence Monitoring tool is available			

Cranfield University, PSS-Cost Project, Decision Engineering Centre

Researcher: Francisco Javier Romero Rojo; Supervisors: Rajkumar Roy, Essam Shehab

Cranfield UNIVERSITY

b) Please suggest any other assumption that should be considered:

....

....

....

....

....

....

....

....

....

....

....

....

....

....

Thank you for your time, patience and contributions.

Cranfield University, PSS-Cost Project, Decision Engineering Centre

Researcher: Francisco Javier Romero Rojo; Supervisors: Rajkumar Roy, Essam Shehab

APPENDIX A.6 Questionnaire Delphi Study - Round 1

Aim: To capture the profiles of usage of each resolution approach to resolve obsolescence issues for different types of electronic components.

Name (optional):…..…........…………………………………………….

Organisation (optional):………..…………………………………………

Years of Experience:………………..…...………………………………

Question 1. Please evaluate the level of Obsolescence Management applied on your company.

Low						High
	1	2	3	4	5	

Question 2. Please assess the level of usage of each resolution approach for each level of complexity: (from 0 to 10; 0 represents that the resolution approach is not used at all; 10 represents that the resolution approach is used frequently)

<u>LOW COMPLEXITY</u>

RESOLUTION APPROACH	LEVEL OF USAGE										
Existing Stock	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Last Time Buy	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Cannibalisation	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
FFF Replacement	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Authorised Aftermarket	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Emulation	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Minor Redesign	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Major Redesign	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

MEDIUM COMPLEXITY

RESOLUTION APPROACH	LEVEL OF USAGE										
Existing Stock	0	1	2	3	4	5	6	7	8	9	10
Last Time Buy	0	1	2	3	4	5	6	7	8	9	10
Cannibalisation	0	1	2	3	4	5	6	7	8	9	10
FFF Replacement	0	1	2	3	4	5	6	7	8	9	10
Authorised Aftermarket	0	1	2	3	4	5	6	7	8	9	10
Emulation	0	1	2	3	4	5	6	7	8	9	10
Minor Redesign	0	1	2	3	4	5	6	7	8	9	10
Major Redesign	0	1	2	3	4	5	6	7	8	9	10

HIGH COMPLEXITY

RESOLUTION APPROACH	LEVEL OF USAGE										
Existing Stock	0	1	2	3	4	5	6	7	8	9	10
Last Time Buy	0	1	2	3	4	5	6	7	8	9	10
Cannibalisation	0	1	2	3	4	5	6	7	8	9	10
FFF Replacement	0	1	2	3	4	5	6	7	8	9	10
Authorised Aftermarket	0	1	2	3	4	5	6	7	8	9	10
Emulation	0	1	2	3	4	5	6	7	8	9	10
Minor Redesign	0	1	2	3	4	5	6	7	8	9	10
Major Redesign	0	1	2	3	4	5	6	7	8	9	10

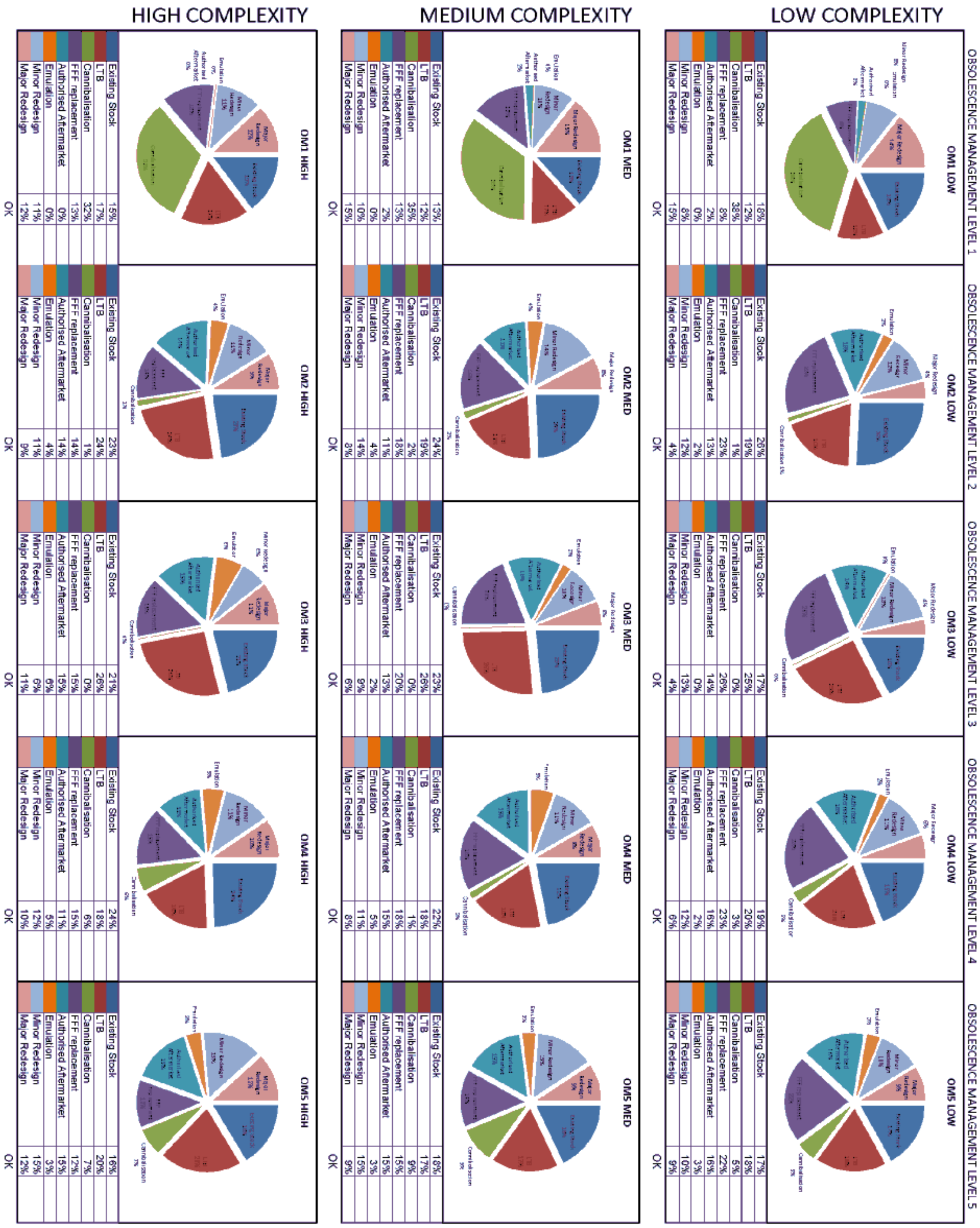
APPENDIX A.7 Questionnaire Delphi Study - Round 2

OBSOLESCENCE RESOLUTION PROFILES VALIDATION

Name (optional):..

Organisation (optional):...

Years of Experience:..



APPENDIX A.8 Validation EEE-FORCE Questionnaire

PSS-Cost Project

E[3]-FORCE FRAMEWORK VALIDATION QUESTIONNAIRE

GENERAL:

1. Name: ………………………………………………………………………………………….
2. Organisation: ………………………………………………………………………………….
3. Role: ....
4. Years of experience (on obsolescence):……………….……………………………

- **OVERVIEW OF THE CASE STUDY:**

5. Description of the case study (including years of contract and CADMID phase)

………………………………………………………………………………………………
………………………………………………………………………………………………
………………………………………………………………………………………………

6. Information available

………………………………………………………………………………………………
………………………………………………………………………………………………

- **LOGIC:**

7. How logical is the cost estimating process for obsolescence?

1	2	3	4	5	6	7	8	9	10
Totally Invalid	Valid, with major deficiencies				Valid, with minor deficiencies				Totally valid

If there are deficiencies please describe them: ………………………………………………..
………………………………………………………………………………………………

8. Is the framework suitable for the bid stage?

1	2	3	4	5	6	7	8	9	10
Totally unsuitable	Suitable, with major deficiencies				Suitable, with minor deficiencies				Totally suitable

If it is not totally suitable please explain why: ……………………………………………......……....
………………………………………………………………………………………………

Francisco J. Romero Rojo <f.romerorojo@cranfield.ac.uk>

Page 1 of 9

PSS-Cost Project

Cranfield UNIVERSITY

9. Can it be used at other stages of the CADMID cycle? Yes No

Please specify which:............................……………………………………………………………

- **GENERALISABILITY:**

10. Please comment on how generalisable the framework is within the defence sector

……………………………………………………………………………………………………

……………………………………………………………………………………………………

11. Please comment on how generalisable the framework is for other sectors (e.g. Nuclear)

……………………………………………………………………………………………………

……………………………………………………………………………………………………

- **BENEFITS OF USING THE FRAMEWORK:**

12. How could the tool benefit a bidding team?..

………………………………………………………………………………………………………

………………………………………………………………………………………………………

13. Who should own the tool in the organisation?...

………………………………………………………………………………………………………

- **LIMITATIONS OF THE FRAMEWORK:**

14. What are the potential limitations and challenges in using and implementing the tool?

………………………………………………………………………………………………………

………………………………………………………………………………………………………

15. What are the potential implications across the supply chain?

………………………………………………………………………………………………………

………………………………………………………………………………………………………

- **USABILITY OF THE SOFTWARE PROTOTYPE:**

16. Assessment of the usability of the tool

    a. What are the strongest features?..

    ………………………………………………………………………………………….

    b. What are the weakest features?..

    ………………………………………………………………………………………….

Francisco J. Romero Rojo <f.romerorojo@cranfield.ac.uk>

Page 2 of 9

c. Is it intuitive?

1	2	3	4	5	6	7	8	9	10
Counter-intuitive	Low intuitive				Quite intuitive				Very intuitive

d. Does the tool provide enough initial information? Yes No

If not, please explain:..

17. Time required to populate the tool for a case study ....

....

18. Are the terminology and concepts used in this framework consistent? Yes No

19. If not, please explain:..

20. Are the key cost drivers considered in this cost estimating framework? Yes No

If not, please explain:..

21. Is the list of resolution techniques indicated in the framework comprehensive?

Yes No

If not, please indicate the missing resolution techniques:..

....

22. Is the tool flexible enough to adapt to the different levels of information available?

(e.g. Step 3A for detailed information and Step 3B for high-level information) Yes No

If not, please explain:..

23. Are the "coupling level" and "package density" concepts valid? Yes No

If not, please explain:..

24. Is this tool suitable for the pre-contract stage? (solve the existing obsolescence issues before starting the support contract) Yes No

If not, please explain:..

25. Are the assumptions made realistic?

a. Any component is not expected to become obsolete more than once during the contracted period. Yes No

If not, please explain:..

....

PSS-Cost Project

Cranfield UNIVERSITY

b. An obsolescence issue will only contribute to costs for the contract if the level of stock for that item is not enough to cover the contracted period. Yes No
If not, please explain:...
....

c. All the fleet is enhanced during mid-life upgrades. Yes No
If not, please explain:...
....

d. Emulation, Minor and Major Redesigns may solve several obsolescence issues simultaneously. The "clustering" factor represents the number of redesigns that would be applied to solve 100 obsolescence issues requiring a redesign.
Yes No
If not, please explain:...
....

e. The obsolescence resolution profiles mainly depend on the level of complexity and the level of proactiveness in managing obsolescence. Yes No
If not, please explain:...
....

- **RESULTS:**

26. Evaluation of the output of the tool after populating it with information from the case study...
....
....

27. Evaluation of the repeatability of the tool after populating it with the same information from the case study...
....
....

Francisco J. Romero Rojo <f.romerorojo@cranfield.ac.uk>

Page 4 of 9

28. Evaluation of the sensitivity/robustness of the tool after populating it with information from the case study (sensitivity analysis)..
....
....

29. Is the cost estimating framework fit for the purpose from which it has been developed?
    Yes No
    Please explain: ....
    ....
    ....

30. Is the Montecarlo simulation applied suitable to incorporate uncertainty to the cost estimate? Yes No
    Please explain: ....
    ....
    ....

- **KEY FORMULAE:**

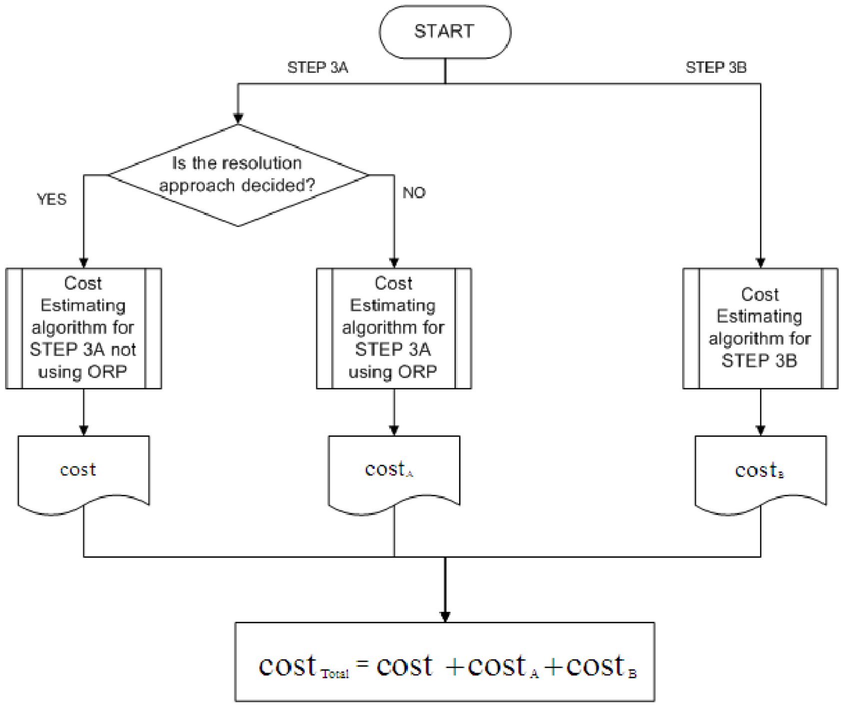
31. Are the key formulae and flowchart valid? Yes No
    Please explain: ....
    ....
    ....
    ....
    ....
    ....
    ....

Francisco J. Romero Rojo <f.romerorojo@cranfield.ac.uk>

PSS-Cost Project

Cranfield UNIVERSITY

Obsolescence Cost Estimation



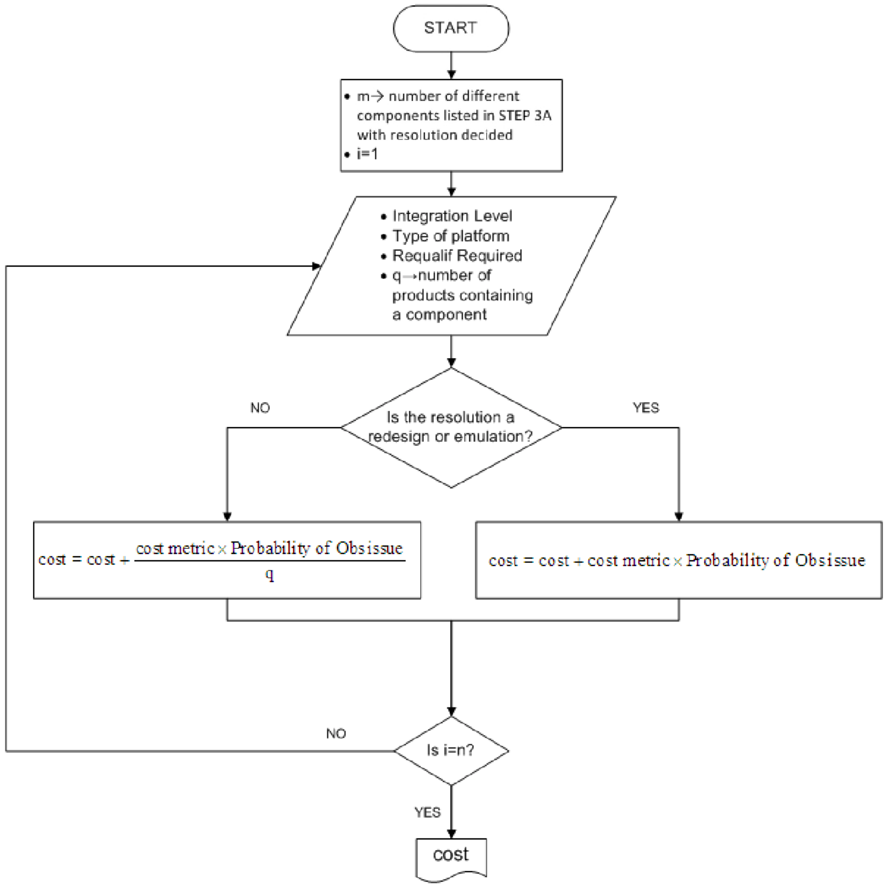
Francisco J. Romero Rojo <f.romerorojo@cranfield.ac.uk>

Page 6 of 9

PSS-Cost Project

Cranfield UNIVERSITY

Cost Estimating Algorithm for STEP 3A When Resolution Approach is Decided

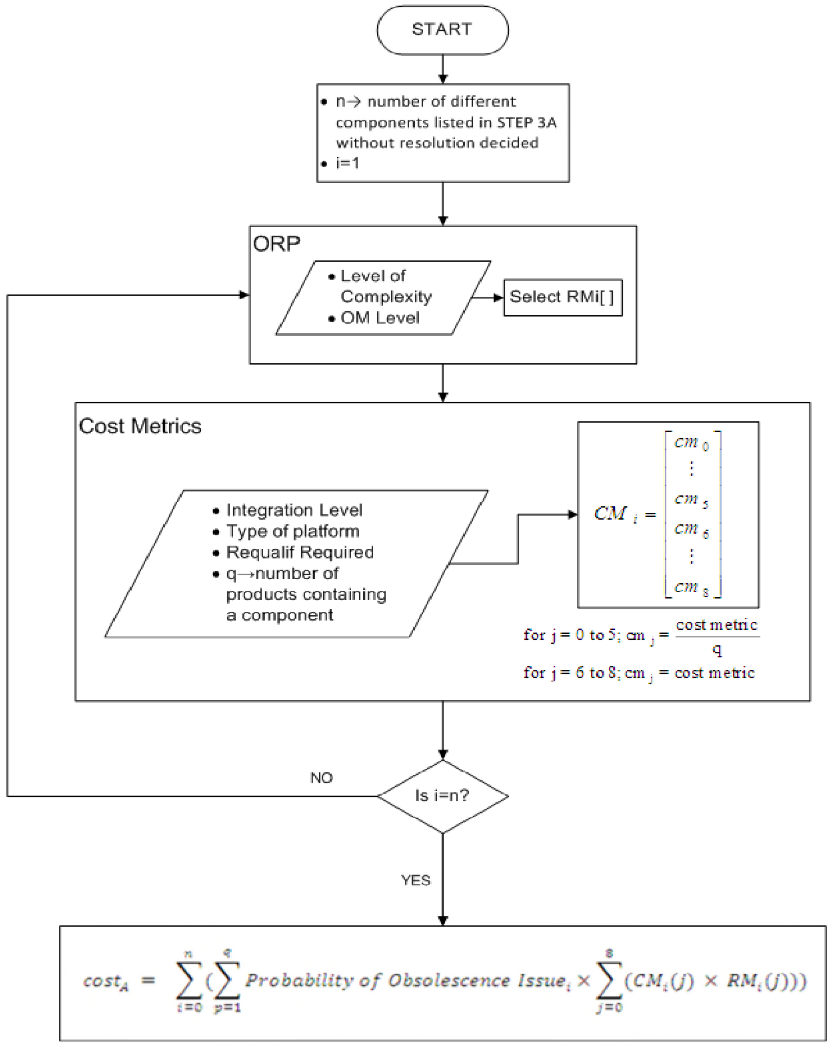


Francisco J. Romero Rojo <f.romerorojo@cranfield.ac.uk>

Page 7 of 9

PSS-Cost Project

Cost Estimating Algorithm for STEP 3A
Using Obsolescence Resolution Profiles (ORP)



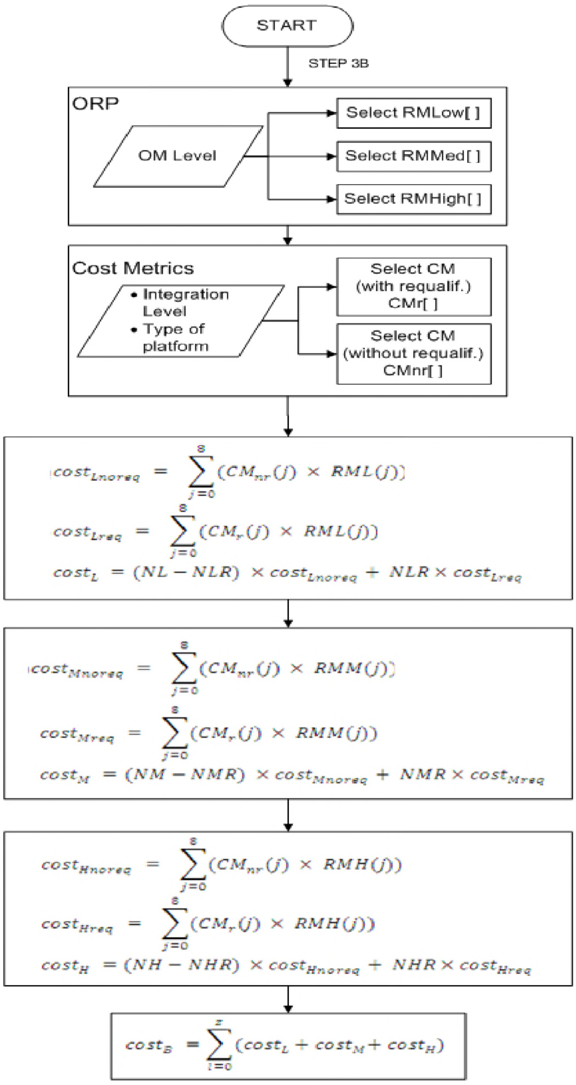
Francisco J. Romero Rojo <f.romerorojo@cranfield.ac.uk>

Page 8 of 9

PSS-Cost Project

Cranfield UNIVERSITY

Cost Estimating algorithm for STEP 3B



Francisco J. Romero Rojo <f.romerorojo@cranfield.ac.uk>

Page 9 of 9

APPENDIX A.9 Validation M-FORCE (Aerospace Domain) Questionnaire

PSS-Cost Project

M-FORCE (AIR) TOOL VALIDATION QUESTIONNAIRE

Cranfield UNIVERSITY

M-FORCE (AIR) TOOL VALIDATION QUESTIONNAIRE

GENERAL:

1. Name: ……………………………………………………………………………………….
2. Organisation: …………………………………………………………………………………….
3. Role: ....
4. Years of experience (on obsolescence)…………………….……………………………

- **OVERVIEW OF THE CASE STUDY:**

5. Description of the case study

……………………………………………………………………………………………………

……………………………………………………………………………………………………

……………………………………………………………………………………………………

6. Information available

……………………………………………………………………………………………………

……………………………………………………………………………………………………

- **QUALITATIVE:**

7. Is the logic (process/rationale) to build the cost estimate valid?

1	2	3	4	5	6	7	8	9	10
Totally Invalid	Valid, with major deficiencies				Valid, with minor deficiencies				Totally valid

If there are deficiencies please describe them: …………………………………………………..

……………………………………………………………………………………………………

8. Is the framework suitable for the bid stage?

1	2	3	4	5	6	7	8	9	10
Totally unsuitable	Suitable, with major deficiencies				Suitable, with minor deficiencies				Totally suitable

If it is not totally suitable please explain why: …………………………………………....……..

……………………………………………………………………………………………………

Francisco J. Romero Rojo <f.romerorojo@cranfield.ac.uk>

9. Is this cost estimating framework truly generalisable to different defence and aerospace platforms? Yes No

   Can it be easily calibrated? Yes No

10. Is the list of resolution techniques indicated in the framework complete? Yes No

If not, please indicate the missing resolution techniques:...

……………………………………………………………………………………………

11. How could the tool benefit a bidding team?...

……………………………………………………………………………………………

……………………………………………………………………………………………

   Can it be used at other stages of the CADMID cycle? Yes No

Please specify which:..........................………………………………………………………

12. Who should own the tool in the organisation?...

……………………………………………………………………………………………

13. What are the potential limitations and challenges in using the tool? ....

……………………………………………………………………………………………

……………………………………………………………………………………………

14. Assessment of the usability of the tool

   a. What are the strongest features?..

      ………………………………………………………………………………………..

   b. What are the weakest features?..

      ………………………………………………………………………………………..

   c. Is it intuitive?

1	2	3	4	5	6	7	8	9	10
Counter-intuitive	Low intuitive				Quite intuitive				Very intuitive

   d. Does the tool provide enough initial information? Yes No

15. Are the terminology and concepts used in this framework consistent? Yes No

16. Are the key cost drivers considered in this cost estimating framework? Yes No

17. Is the tool flexible enough to adapt to the different levels of information available?

   Yes No

18. Is the materials obsolescence management classification defined in the tool valid?

    Yes No

    If not, please explain:..

19. Is the materials complexity classification defined in the tool valid? Yes No

    If not, please explain:..

20. Is the materials criticality classification defined in the tool valid? Yes No

    If not, please explain:..

21. Are the assumptions made acceptable?

    a. The level of complexity, level of criticality and level of integration are not correlated.

       Yes No

       If not, please explain:..

       ....

    b. A calibration data point can be applied to derive the spectrum of cost metrics based on the "weight matrix". Yes No

       If not, please explain:..

       ....

    c. The Obsolescence Management Level does not have a significant impact on the NRE cost of resolving obsolescence issues for materials. Yes No

       If not, please explain:..

       ....

    d. The cost of materials obsolescence is independent from EEE components obsolescence. Yes No

       If not, please explain:..

       ....

    e. The cost of materials obsolescence is independent from software obsolescence.

       Yes No

       If not, please explain:..

       ....

PSS-Cost Project

M-FORCE (AIR) TOOL VALIDATION QUESTIONNAIRE

- **QUANTITATIVE:**

22. Evaluation of the output of the tool after populating it with information from the case study..
....
....

23. Is the cost estimating framework accurate enough for the purpose from which it has been developed? Yes No
Please explain: ....
....
....

24. Is the Montecarlo simulation applied suitable to incorporate uncertainty to the cost estimate? Yes No
Please explain: ....
....
....

25. Please explain the uncertainty in the output: ....
....
....

Francisco J. Romero Rojo <f.romerorojo@cranfield.ac.uk>

APPENDIX A.10 Validation M-FORCE (Ammunition Domain) Questionnaire

M-FORCE (AMMUNITION) TOOL VALIDATION QUESTIONNAIRE

GENERAL:

1. Name: ……………………………………………………………………………………….
2. Organisation: …………………………………………………………………………………….
3. Role: ....
4. Years of experience (on obsolescence)…………………….……………………………

- **OVERVIEW OF THE CASE STUDY:**

5. Description of the case study

…………………………………………………………………………………………………

…………………………………………………………………………………………………

…………………………………………………………………………………………………

6. Information available

…………………………………………………………………………………………………

…………………………………………………………………………………………………

- **QUALITATIVE:**

7. Is the logic (process/rationale) to build the cost estimate valid?

1	2	3	4	5	6	7	8	9	10
Totally Invalid	Valid, with major deficiencies				Valid, with minor deficiencies				Totally valid

If there are deficiencies please describe them: …………………………………………………....

…………………………………………………………………………………………………

8. Is the framework suitable for the bid stage?

1	2	3	4	5	6	7	8	9	10
Totally unsuitable	Suitable, with major deficiencies				Suitable, with minor deficiencies				Totally suitable

If it is not totally suitable please explain why: ………………………………………….…......

…………………………………………………………………………………………………

9. Is this cost estimating framework truly generalisable to different defence and aerospace platforms? Yes No

   Can it be easily calibrated? Yes No

10. Is the list of resolution techniques indicated in the framework complete? Yes No

If not, please indicate the missing resolution techniques:..

....

11. How could the tool benefit a bidding team?..

....

....

   Can it be used at other stages of the CADMID cycle? Yes No

Please specify which:...

12. Who should own the tool in the organisation?...

....

13. What are the potential limitations and challenges in using the tool? ....

....

....

14. Assessment of the usability of the tool

    a. What are the strongest features?..

       ....

    b. What are the weakest features?..

       ....

    c. Is it intuitive?

1	2	3	4	5	6	7	8	9	10
Counter-intuitive	Low intuitive				Quite intuitive				Very intuitive

    d. Does the tool provide enough initial information? Yes No

15. Are the terminology and concepts used in this framework consistent? Yes No

16. Are the key cost drivers considered in this cost estimating framework? Yes No

17. Is the tool flexible enough to adapt to the different levels of information available?

    Yes No

18. Is the materials obsolescence management classification defined in the tool valid?
    Yes No
    If not, please explain:……………………………………………………………………
19. Is the materials complexity classification defined in the tool valid? Yes No
    If not, please explain:……………………………………………………………………
20. Is the materials criticality classification defined in the tool valid? Yes No
    If not, please explain:……………………………………………………………………
21. Are the assumptions made acceptable?
    a. The level of complexity, level of criticality, level of integration and resolution approach are correlated with the type of material and platform. Yes No
       If not, please explain:……………………………………………………………………
       ……………………………………………………………………………………
    b. The database in STEP 4/5 represents the whole range of possible obsolescence issues, their characteristics, costs and probabilities. Yes No
       If not, please explain:……………………………………………………………………
       ……………………………………………………………………………………
    c. The Obsolescence Management Level does not have a significant impact on the NRE cost of resolving obsolescence issues for materials. Yes No
       If not, please explain:……………………………………………………………………
       ……………………………………………………………………………………
    d. The cost of materials obsolescence is independent from EEE components obsolescence. Yes No
       If not, please explain:……………………………………………………………………
       ……………………………………………………………………………………
    e. The cost of materials obsolescence is independent from software obsolescence.
       Yes No
       If not, please explain:……………………………………………………………………
       ……………………………………………………………………………………

- **QUANTITATIVE:**

22. Evaluation of the output of the tool after populating it with information from the case study..
....
....

23. Is the cost estimating framework accurate enough for the purpose from which it has been developed? Yes No
Please explain: ....
....
....

24. Is the Montecarlo simulation applied suitable to incorporate uncertainty to the cost estimate? Yes No
Please explain: ....
....
....

25. Please explain the uncertainty in the output: ....
....
....

THIS PAGE IS INTENTIONALLY LEFT BLANK

Appendix

B

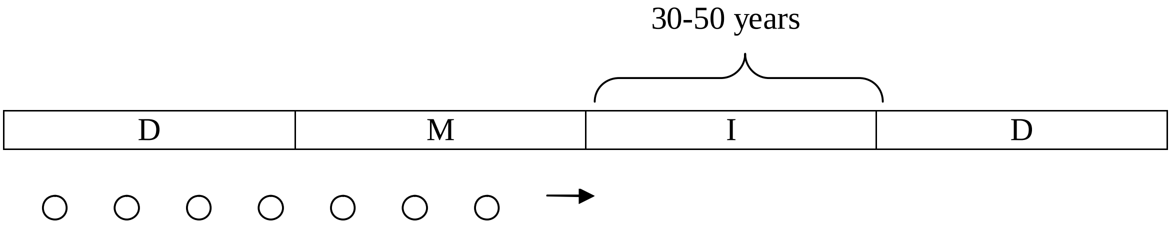
APPENDIX B: INTERVIEW TRANSCRIPTS AND MINDMAPS

APPENDIX B.1 Example of a Transcript from Interviews

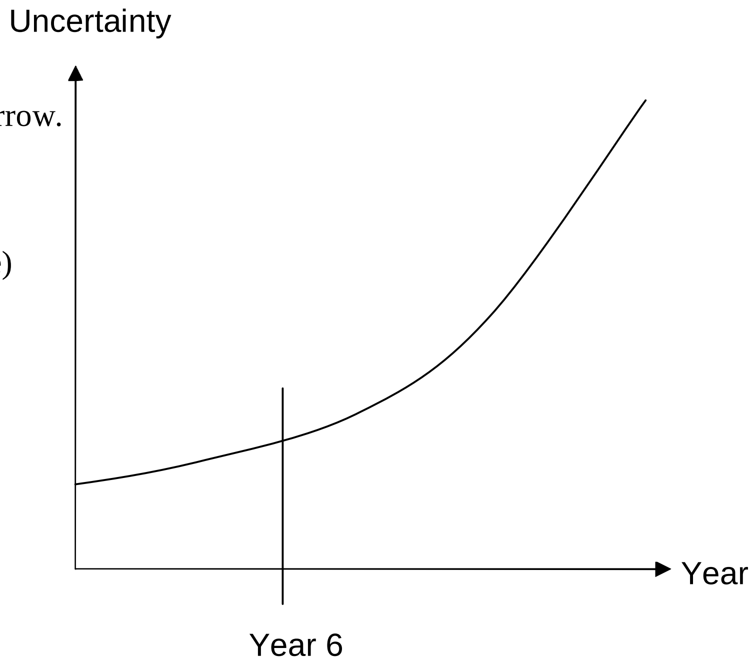
An example of the responses (sanitised to preserve confidentiality) from one of the interviews carried out during the introductory meetings is shown as follows. All interview transcripts and recordings are available for inspection if required.

1. Scope of the estimate

SE.1.1 What is the scope of the estimate in programme terms, e.g. for contracts what stages of the CADMID/CADMIT cycle are included?



The points above reflect the A-D and M is just the last part of the phase, which is represented by the arrow. I and D reflect this contract and associated uncertainty in relation to time, has been demonstrated in the latter figure. (on the CADMID cycle)



Estimating costs for the in-service and disposal stages are made in the design and manufacturing stages, though as can be seen in Figure 2 the level of uncertainty increases drastically after the sixth year. For this reason, the contract has set a review procedure every 5 years.

SE.1.2 What is the scope of the estimate in technical terms, e.g. coverage of interfaces, platform integration costs, evolutionary increments, in-service support?

60 different systems are integrated by the organisation. They are made up of 33 Government Furnished Assets (GFA) and 27 Procured Assets under contract.

SE.1.3 Are disposal costs considered within the life cycle cost considerations?

There usually is a counter balance between the benefit and the loss within the disposal stage. This is why this project neglects disposal costs.

2. Programme Baseline

SE.2.1 Is there an agreed master data and assumptions list (MDAL) e.g. that supports translation of programme requirements into a defendable cost estimate?

The MDAL is used to capture and store assumptions.

3. Cost Breakdown Structure

CBS.3.1 Describe the CBS that you employ in capability contract?

CBS is built for specific contracts. The CBS contains the product and the service elements in the CADMID cycle. CBS may be constructed from an external perspective, the customer the MoD, requires buckets of operations to be able to acquire required budgets. With this view, the customer delivers a CRBS to be followed by the organisation but the alignment of these with the organisation applications is difficult. There are different perspectives to CBS. These may vary in three different approaches: Organisational/departmental, required tasks to be covered and the structure of the product. The latter two approaches tend to be used in the engineering and maintenance domains.

- <u>Organizational</u> - CBS reflects the departmental understanding of the project i.e. management.
- <u>Process</u> - considering processes helps to list the necessary tasks in delivering the outcome to the customer. This makes it simpler to assign man-hours.
- <u>Product structure</u> - considering the product structure helps to understand the necessary parts to be able to build the solution that the customer demands. A CBS is represented in a mind map.

These different perspectives cause difficulties in aligning operations and understanding not only within the organisation but also with the customer. This is why in SAP, a standardized flow of CBS information are aimed to be achieved.

CBS.3.2 Does the CBS for capability contracts differ from the CBS' of the past?

Currently, design-manufacturing is considered separately from the in-service section of the life cycle. So, it is hard to say that applications have changed when moving into a capability contract application. There are different uncertainties within these two areas. For instance, in the product centric section the integration cost is highly uncertain.

CBS.3.4 If a CBS is in use, where has it drilled-down (e.g. for de-risking) has the corresponding detail been added to the MDAL to support the audit process?

Ambiguity surrounds the information that is acquired from the customer. Though, internally, all applications are stored in the MDAL to be able to support the audit process.

CBS.3.5 If a CBS is in use, is its scope and structure based on any particular standard (e.g. as mandated by the customer or to comply with legacy practices)?

The process begins from the beginning.

CBS.3.6 If a CBS is in use, at what LCM stage was it first created and through which LCM stages is it intended to maintain it (e.g. to support cost metrics)?

It was created in the assessment stage, mainly in the beginning, and it changes from one stage to the other.

4. Data Collection & Analysis

DCA.4.1 Where historical costs have been collected, what strategies have been used to analyze it (e.g. simple statistics, investigating anomalies, visualization?)

The organisation faces challenges in storing historic data and do not have a standard CBS structure. As a result, it is difficult to transfer information from one project to another. Software costs are stored though their significance is problematic due to the unstandardised nature of the stored data.

5. Method Selection

MS.5.1 What commercial or in-house tools are used to make estimates (e.g. parametric, simulation, optimisation, decision support, historical trends analysis)?

- Parametric analysis, (done at the concept stage as a top down application)
- Bottom up, (after two years into the project it became increasingly used)
- Spreadsheets, (NPV analysis)
- For spares analysis: OPUS is used as the customer uses this software to optimise

At the bidding stage, the use of commercial tools is limited due to the lack of visibility of algorithms (i.e. SEER and Price). COCOMO has mostly been used to validate and support cases when negotiating with the customer.

MS.5.2 What process assets (e.g. LCM, BMS) have you invoked in support of cost estimating, price build-up, managing uncertainty and risk, and phase reviews? (Risk Register?)

There are several reviews that take place. These involve management, risk, technical, engineering, design, commercial and cost reviews that lead to an overall review. LCM presents varying levels of detail to the reviewer.

MS.5.3 What rationale was used to select the estimating method(s) for the programme (e.g. by analogy, expert opinion, extrapolation, parametric, or bottom-up)?

In the early stages, in the design and assessment, parametric methods are used. As data grows, bottom up methods are used. The rational relates to the phase in the CADMID cycle.

MS.5.4 Are there shortcomings in the available estimating methods that need to be addressed outside of the immediate project (e.g. cluster or functional level)?

- Poor historic data
- Lack of common terminology among departments (semantics and ontology) (e.g. terms such as risk and uncertainty are interpreted differently)
- Building a common model (employees change the template that has been delivered)
- Holes or double counting due to the lack of coordination among departments.
- Visibility issues derived from different considerations in Excel.

The process begins by developing the CBS by using mind maps and Excel. Then, the estimate is done for each specific area. Finally, these are put together (issue of holes and double counting). Then, results are reviewed, by comparing expert opinion and parametric techniques. Finally, these are incorporated into the contract offered to the customer.

MS.5.5 Where do we focus within a contract? Which areas should we concentrate on?

- General concentration on every part. Bigger contracts (in terms of value) receive more interest as associated risks are more heavily examined. Though, high risk areas can not be identified beforehand.

- A cost estimating framework would be very useful, as it makes the process easier.

6. Whole life cycle cost estimation

WLCC.6.1 How does the WLC estimation process change when a WLC approach is taken?

Depends on whether it is a single sourcing or a competitive bid. In a whole life cycle approach, costs can be optimized at the early phases such as Design and Manufacture in order to make it easier to support the system.

WLCC.6.2 Which are the main cost drivers in capability contracts? (E.g. major 3)

- Supply chain – Most of the components are COTS however most of the cost is due to the bespoke components. (80% cost is in 20% of the items)
- Integration of systems – 60 systems need to be integrated so they can interact together. Also need to take into account mid-life integration and upgrades.
- Management Cost

WLCC.6.3 How do you compare estimates with the actual and how do you use this information to improve methods? (Do you use a CBS to calculate both estimates and actual e.g. EVM, CPI, SPI)

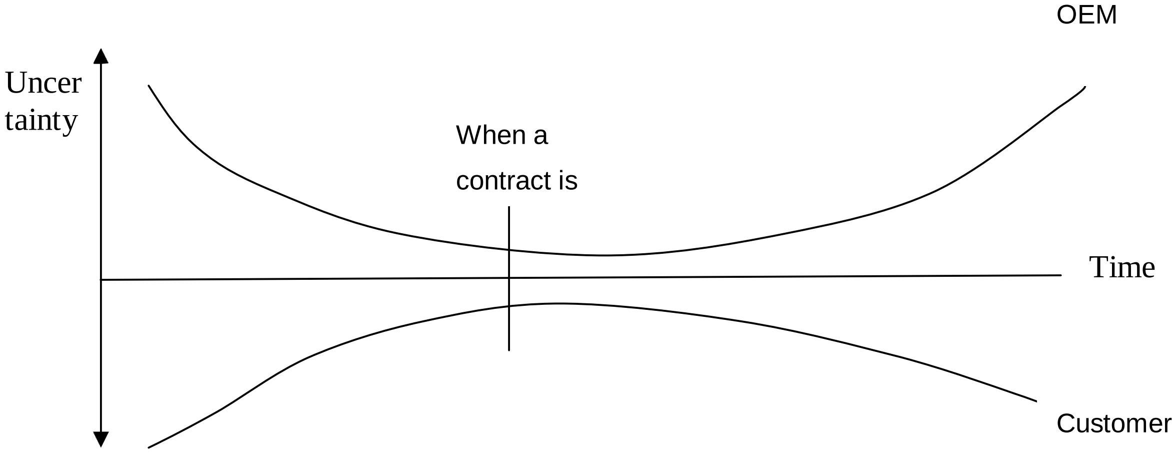
EVM is focussed on product without taking into account the service element. Also, EVM is not effective because supply chain costs are driven by random events. However, the cost of managing and integrating is easier to predict.

7. Capability Contract Process

CCP.7.1 How do you agree a price with the customer? (e.g. Competitive or single supplier)

In a competitive bid, customer decides based on best price.
In a single source situation, a Design To Cost approach is taken, where the target price is known and the supplier works to it. The supplier is more open to the customer and provides the customer with cost information.

CCP.7.2 Could you please describe the issues for each capability contract? (What are the challenges, expectations, cost drivers, uncertainties and risks?



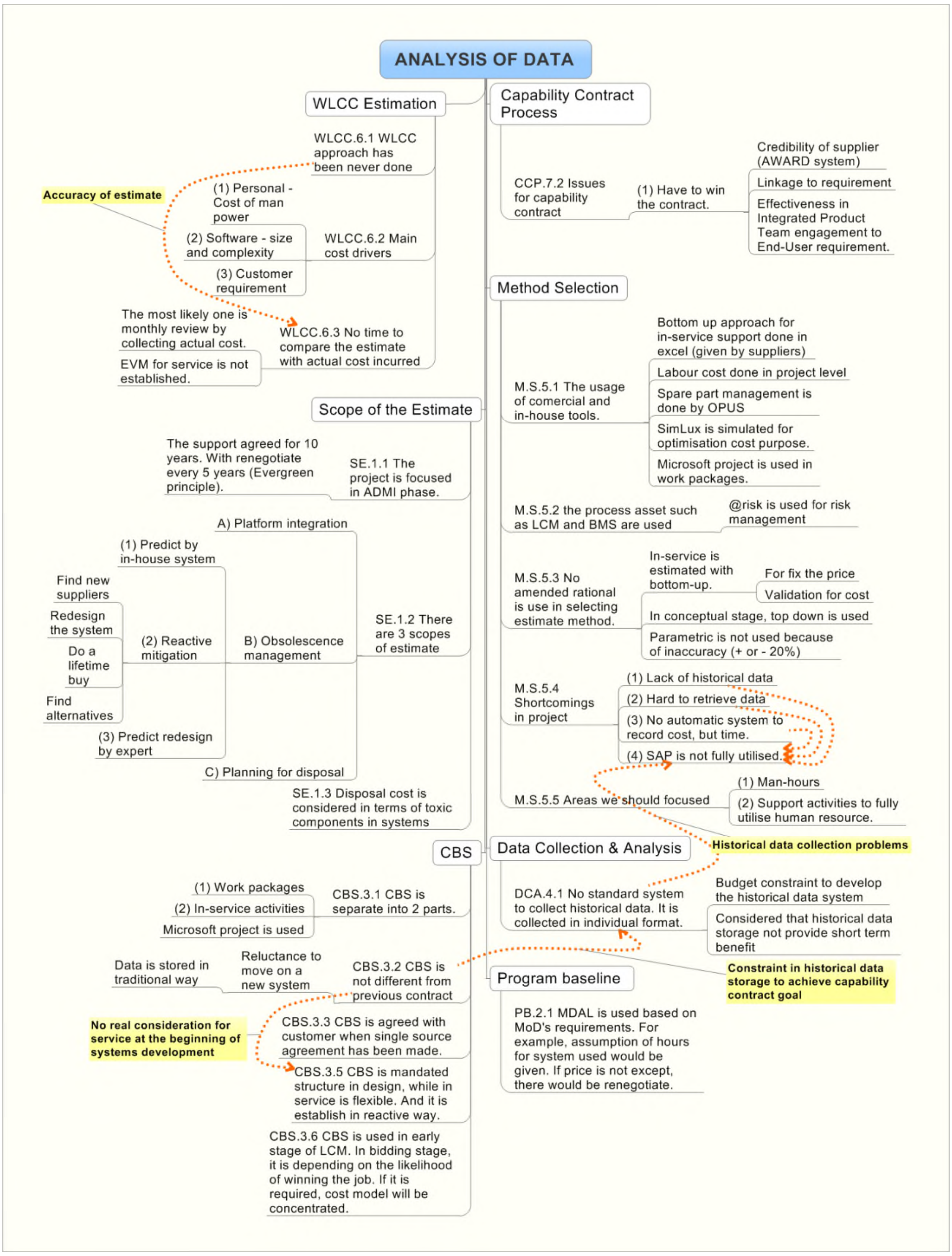
This graph shows the nature of both OEM and Customer as being risk averse. The objective of the customer is to pay the least amount possible, while Supplier wants to charge the best price, taking the costs, risks and uncertainties into account.

Summary of Results from the Interview:

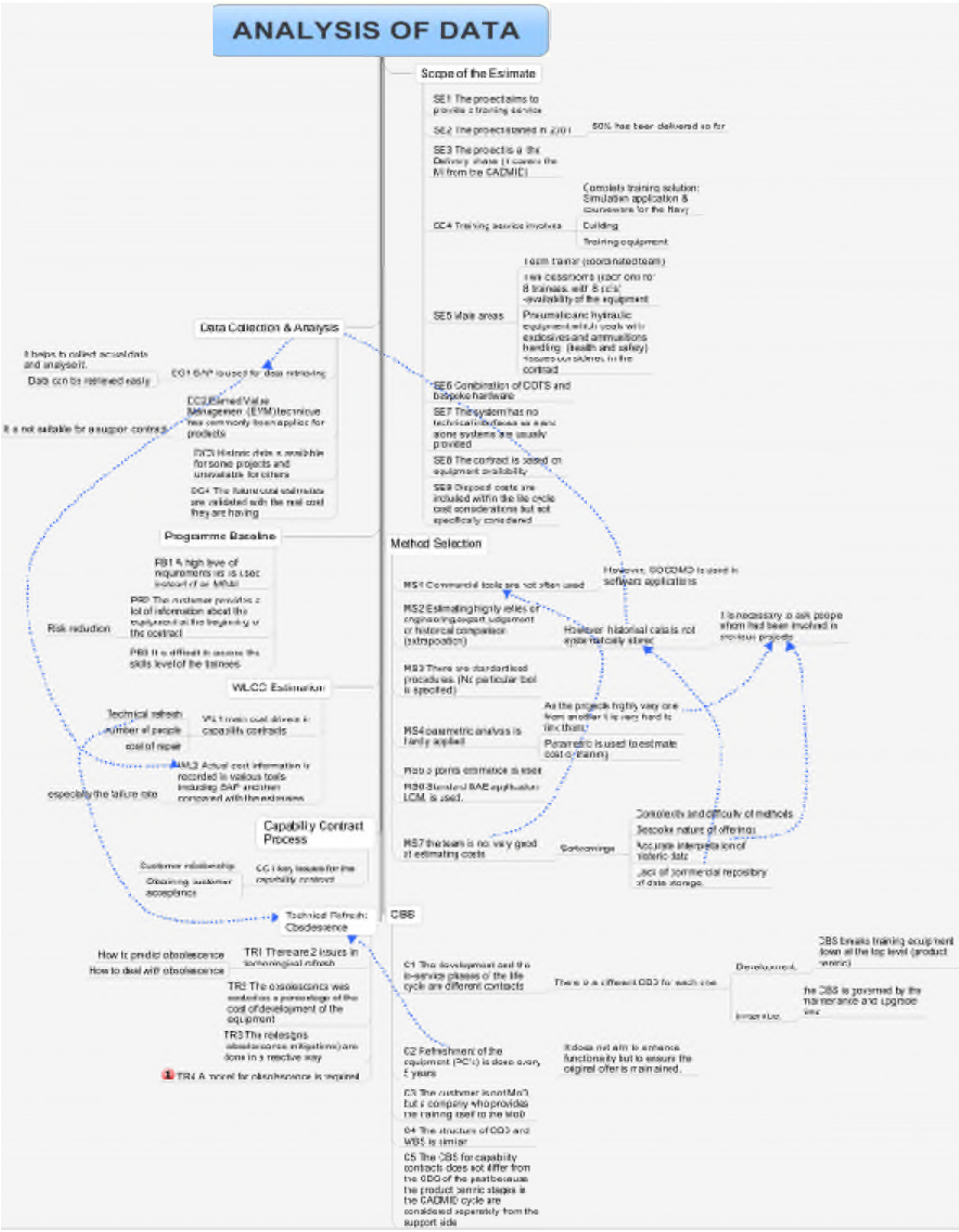
The following issues were identified:

- At the initial stage it is hard to prioritize the uncertainties
- Lack of cost estimating framework
- Poor management of historic data
- Lack of EVM application for services
- Lack of common terminology among departments (semantics and ontology) (e.g. terms such as risk and uncertainty are interpreted differently)
- Building a common model (employees change the template that has been delivered)
- Holes or double counting due to the lack of coordination among departments.
- Visibility issues derived from different considerations in Excel.
- Supply chain – Most of the components are COTS however most of the cost is due to the bespoke components. (80% cost is in 20% of the items)
- Integration of systems – 60 systems need to be integrated so they can interact together. Also need to take into account mid-life integration and upgrades.
- Management Cost
- Growth in service offerings means that new areas are of interest to the OEM. This has brought about new issues such as who does what? Additional risks?
- New metrics are necessary to assess performance
- Disposal costs are not considered currently. The counter balance assumption could be further investigated.
- CBS structures need updating to be able to cater for the integrated nature of products and services
- Ambiguity in information that comes from the customer

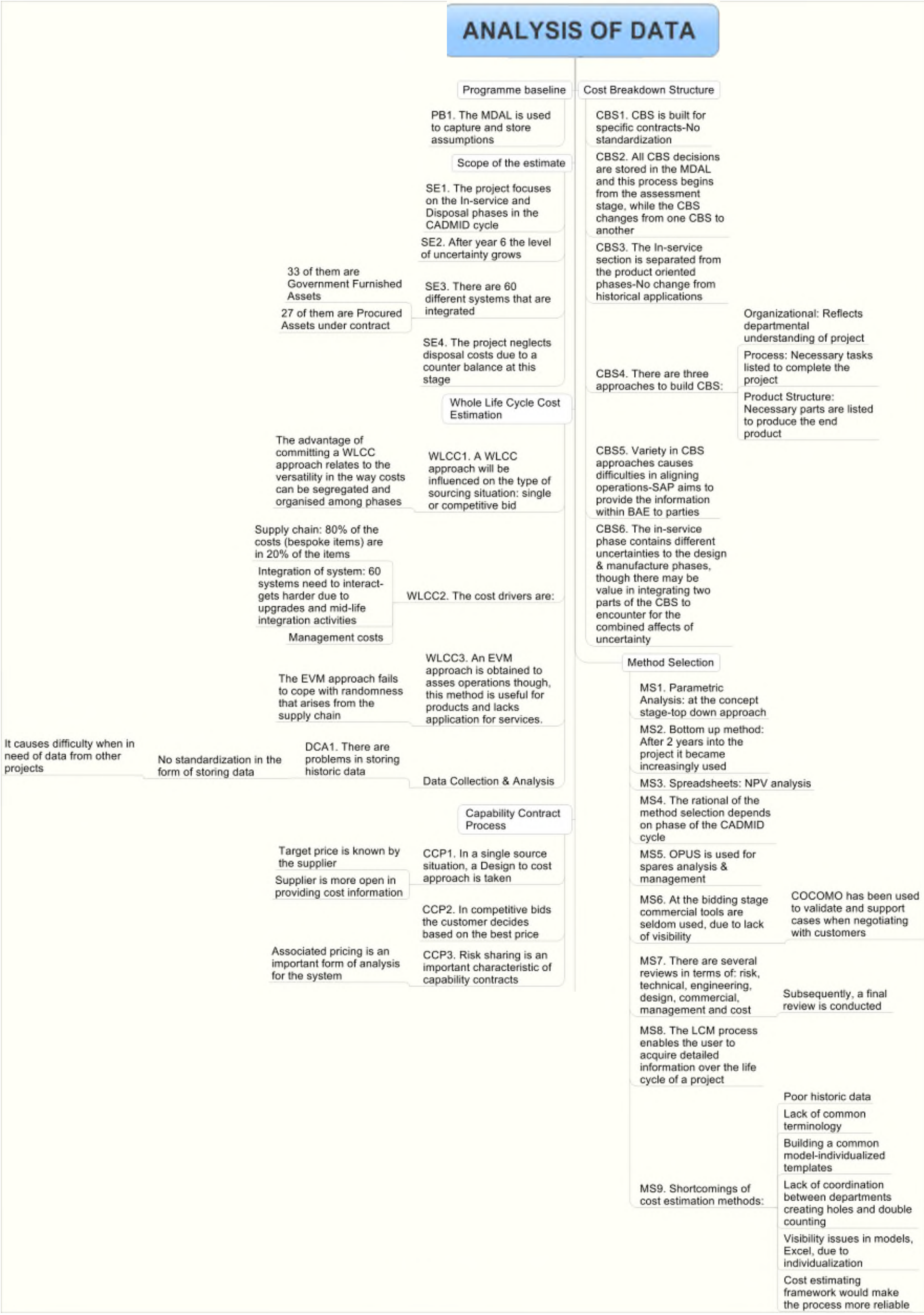
APPENDIX B.2 MindMaps



Mindmap resulting from the analysis of the information gathered during introductory meeting with Project A



Mindmap resulting from the analysis of the information gathered during introductory meeting with Project B



Mindmap resulting from the analysis of the information gathered during introductory meeting with Project C

Appendix

C

APPENDIX C: EEE-FORCE MAINTENANCE MANUAL

PSS Cost Project

Maintenance Manual for EEE-FORCE Tool

Abstract

This maintenance manual, produced by the PSS-Cost Project team at Cranfield University, provides an understanding about the algorithms behind the EEE-FORCE (Electronic, Electromechanical and Electrical Components – Framework for Obsolescence Robust Cost Estimation) tool that are used to turn the input information into a NRE cost estimation for EEE components obsolescence. This tool is intended to be applied at the bidding stage for support contracts, where obsolescence management has been transferred to the prime contractor. Additionally, it can be used for the cost estimation of obsolescence at the "pre-contract" stage, at which it is agreed to solve the existing obsolescence issues before starting the support contract. This tool has been validated to be used in the defence sector, but it can potentially be applied to long-term support contracts in other sectors such as nuclear and railway.

Researcher: Francisco Javier Romero Rojo

Supervisors: Prof. Rajkumar Roy, Dr. Essam Shehab

Project Manager: Dr. Kalyan Cheruvu

E-mail: {f.romerorojo, r.roy, e.shehab, k.cheruvu}@cranfield.ac.uk

Address: Building 50, Manufacturing Department, School of Applied Sciences, Cranfield University, Cranfield, Bedfordshire, MK43 0AL

Approved:

Professor Rajkumar Roy
Head of Manufacturing Department
Cranfield University

Identity: PSS-Cost-Obsolescence
Version: Final
Dated: 7th June 2010

Document History

Version	Date	Comments
Final	07/06/10	Initial release by Cranfield University

Glossary of Terms

BoM	Bill of Materials
EEE	Electronic, Electromechanical and Electrical
EEE-FORCE	Electronic, Electromechanical and Electrical Components – Framework for Obsolescence Robust Cost Estimation
LRU	Line Replaceable Unit
MoD	Ministry of Defence
MTBF	Mean Time Between Failures
NRE	Non-Recurring Engineering
OM	Obsolescence Management
OML	Obsolescence Management Level
OMP	Obsolescence Management Plan
ORM	Obsolescence Cost Metrics
ORP	Obsolescence Resolution Profiles
PBS	Product Breakdown Structure
VBA	Visual Basic for Applications

Contents

1. General Information

This maintenance manual, produced by the PSS-Cost Project team at Cranfield University, provides an understanding about the algorithms behind the EEE-FORCE (Electronic, Electromechanical and Electrical Components – Framework for Obsolescence Robust Cost Estimation) tool that are used to turn the input information into a NRE cost estimation for EEE components obsolescence. This tool is intended to be applied at the bidding stage for support contracts, where obsolescence management has been transferred to the prime contractor. Additionally, it can be used for the cost estimation of obsolescence at the "pre-contract" stage, at which it is agreed to solve the existing obsolescence issues before starting the support contract. This tool has been validated to be used in the defence sector, but it can potentially be applied to long-term support contracts in other sectors such as nuclear and railway.

1.1 System Requirements

This is a MS Excel-based tool. Therefore, MS Excel 2003 or a more recent version is required for the usage of this tool. In order to run the Montecarlo simulation, it is necessary to have previously installed an add-on for MS Excel called "Crystal Ball". Although this particular software has been applied for the development of this prototype tool, it can be replaced by any other Montecarlo-simulation software package if necessary. The algorithms used are coded in MS Excel using VBA.

1.2 Scope

The scope for the usage of this tool is the bidding stage for support contracts in the defence sector. This tool is intended to provide a systematic approach to estimate the cost of EEE components obsolescence at the bidding stage. It is flexible enough to adapt to any level of information available and provide a cost estimate accordingly. However, it is necessary to input in this tool all the relevant information available. This will increase the accuracy of the estimation.
This tool can also be applied for the cost estimation of obsolescence for pre-contract, that is to say, to solve the existing obsolescence issues before signing for a new support contract.

2. Cost Estimating Procedure

The overall picture of the cost estimating process is shown in Figure 1.

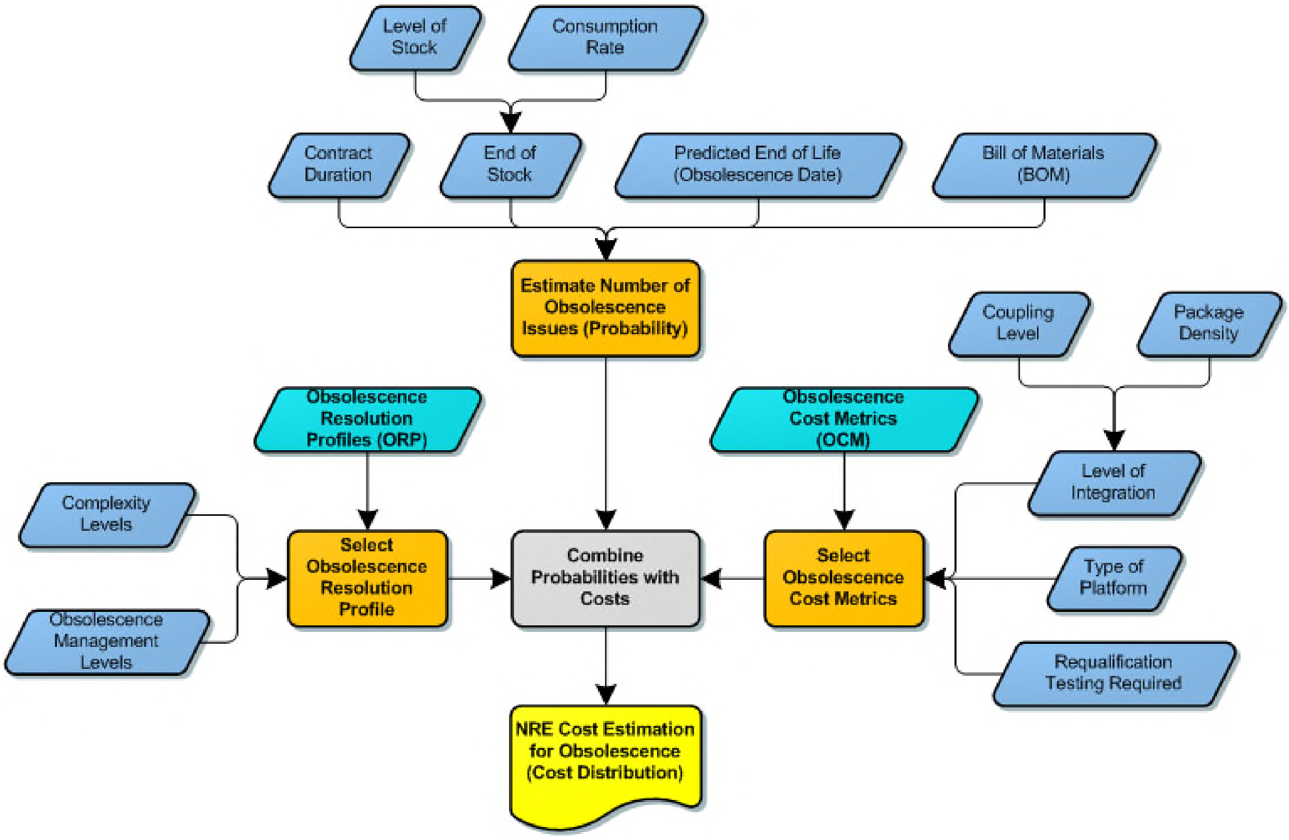


Figure 1 EEE-FORCE framework diagram

In Figure 1 it is shown that there are three main elements which are combined to estimate the cost of obsolescence:

- Number of obsolescence issues during the contracted period
- Obsolescence Resolution Profiles (ORP)
- Obsolescence Cost Metrics (ORM)

3. Key Algorithms Used in the EEE-FORCE Tool

3.1 Calculation of Level of Integration

3.1.1 Parameters

- Coupling Level
  - Case ("Low")
  - Case ("Medium")
  - Case ("High")
- Package Density
  - Case ("Small (standalone)")
  - Case ("Medium")
  - Case ("Large")
  - Case ("Very Large (fully integrated)")

3.1.2 Algorithm

LEVEL OF INTEGRATION		Package Density			
		Small (standalone)	Medium	Large	Very Large (fully integrated)
Coupling Level	Low	Small	Small	Medium	Medium
	Medium	Small	Medium	Large	Very Large
	High	Medium	Large	Very Large	Very Large

3.1.3 Code

```
Select Case (Coupling Level)
  Case ("Low")
    cl = 1
  Case ("Medium")
    cl = 2
  Case ("High")
    cl = 3
End Select

Select Case (Package Density)
  Case ("Small (standalone)")
    pd = 1
  Case ("Medium")
    pd = 2
  Case ("Large")
    pd = 3
  Case ("Very Large (fully integrated)")
    pd = 4
End Select
```

```
il = cl * pd

If il <= 2 Then
    Level of Integration = "Small (standalone)"
   ElseIf il < 5 Then
    Level of Integration = "Medium"
   ElseIf il = 6 Then
    Level of Integration = "Large"
   Else
    Level of Integration = "Very Large (fully integrated)"
End If
```

3.2 Calculation of Consumption Rate for Each Component

3.2.1 Parameters

- MTBF (years)
- Fleet size
- Number of same components per platform
- Probability of scrapping when trying to repair (% of Scrap)

3.2.2 Algorithm

$$Consumption\ Rate = \frac{Fleet\ size\ \times\ Nº\ of\ same\ comp.per\ platform\ \times\ \%\ of\ Scrap}{MTBF}$$

3.3 Calculation of Date to Run out of Stock

3.3.1 Parameters

- Stock Level Exclusive for this Project --- Stock
- Consumption Rate (items used per year) --- Consumption Rate
- Date when the stock level was reviewed --- Date Review

3.3.2 Algorithm

$$Date\ Run\ out\ of\ Stock =\ Date\ Review + \frac{365\ \times\ Stock}{Consumption\ Rate}$$

3.4 Calculation of Probability of Obsolescence Issues

3.4.1 Parameters

- Contract End Date
- Probability of Running Out of Stock during the Contracted Period
    - Case ("100% Yes")
    - Case ("High") --- 75%
    - Case ("Medium") --- 50%
    - Case ("Low") --- 25%
    - Case ("0% No")
- Probability of Becoming Obsolete during the Contracted Period
    - Case ("100% Yes")
    - Case ("High") --- 75%
    - Case ("Medium") --- 50%
    - Case ("Low") --- 25%
    - Case ("0% No")
- Predicted End of Life (Obsolescence Date)
- Date Run out of Stock

3.4.2 Algorithm

```
If Obsolescence Date and Date Run out of Stock are available then
        If (Obsolescence Date < Contract End Date) and (Date Run out of Stock < Contract End
        Date) then
        Probability of Obs. Issue = 100%
        Else
        Probability of Obs. Issue = 0%
End If

If Obsolescence Date is available and Date Run out of Stock is not available (because stock is
shared across different projects) then
        If (Obsolescence Date < Contract End Date) then
                Probability of Obs. Issue = Probability of Running Out of Stock during the Con-
                tracted Period
        Else
        Probability of Obs. Issue = 0%
        End If
End If

If Obsolescence Date is not available and Date Run out of Stock is available then
        If (Date Run out of Stock < Contract End Date) then
                Probability of Obs. Issue = Probability of Becoming Obsolete during the Contracted
                Period
        Else
        Probability of Obs. Issue = 0%
        End If
End If
```

If Obsolescence Date is not available and Date Run out of Stock is not available (because stock is shared across different projects) then

Probability of Obs. Issue = Probability of Becoming Obsolete during the Contracted Period × Probability of Running Out of Stock during the Contracted Period

End If

3.5 Calculation of Alternative Obsolescence Resolution Profiles

3.5.1 Parameters

- Obsolescence Resolution Profiles
    - Existing Stock (%)
    - LTB (%)
    - Cannibalisation (%)
    - Equivalent (%)
    - Alternative (%)
    - Authorised Aftermarket (%)
    - Emulation (%)
    - Minor Redesign (%)
    - Major Redesign (%)

3.5.2 Algorithm

If the contract is covering the last years of the in-service phase:

Remains constant	Existing Stock	Authorised Aftermarket		
Is reduced by half	Minor Redesign	Major Redesign	Emulation	FFF replacement
Increases proportionally	LTB	Cannibalisation		

$$A_1 = Alt.\,Existing\ Stock\ (\%) = Existing\ Stock\ (\%)$$

$$A_2 = Alt.\,Authorised\ Aftermarket\ (\%) = Authorised\ Aftermarket\ (\%)$$

$$A_3 = Alt.\,Equivalent\ (\%) = \frac{Equivalent\ (\%)}{2}$$

$$A_4 = Alt.Alternative\ (\%) = \frac{Alternative\ (\%)}{2}$$

$$A_5 = Alt.Emulation\ (\%) = \frac{Emulation\ (\%)}{2}$$

$$A_6 = Alt.Minor\ Redesign\ (\%) = \frac{Minor\ Redesign\ (\%)}{2}$$

$$A_7 = Alt.Major\ Redesign\ (\%) = \frac{Major\ Redesign\ (\%)}{2}$$

$$Alt.Cannibalisation\ (\%) = \frac{100\% - (A_1 + A_2 + A_3 + A_4 + A_5 + A_6 + A_7)}{Cannibalisation\ (\%) + LTB\ (\%)} \times Cannibalisation\ (\%)$$

$$Alt.LTB\ (\%) = \frac{100\% - (A_1 + A_2 + A_3 + A_4 + A_5 + A_6 + A_7)}{Cannibalisation\ (\%) + LTB\ (\%)} \times LTB\ (\%)$$

The same formulae apply for Low, Medium and High Complexity Obsolescence Resolution Profiles.

3.6 Cost Metrics Calculations

3.6.1 Parameters 1

- Cost Metrics without requalification --- Derived from several experts
  - Cost Metrics1= f_1(Resolution Approach, Level of Integration, Type of Platform)
- Cost Metrics with requalification --- Derived from several experts
  - Cost Metrics2= f_2(Resolution Approach, Level of Integration, Type of Platform)
- Level of Integration
  - Case ("Small (standalone)")
  - Case ("Medium")
  - Case ("Large")
  - Case ("Very Large (fully integrated)")

3.6.2 Algorithm 1: Development

$$BaseCost = CostMetrics1(\text{Level of Integration} = \text{Small})$$

$$Factor1 = \frac{CostMetrics1}{BaseCost}$$

$$Factor2 = \frac{CostMetrics2 - CostMetrics1}{BaseCost}$$

3.6.3 Parameters 2

- Base Cost
- Factor1 (F_1) --- Indicates the impact of the Integration Level when there is no requalification
- Factor2 (F_2) --- Indicates the impact of the Integration Level when there is requalification
- Factor3 (F_3) --- Indicates the impact of the Type of Platform
- Factor4 (F_4) --- Indicates whether requalification is required or not
- Clustering Factor

3.6.4 Algorithm 2: Usage

The NRE resolution cost is calculated using the following formulae:

$$Cost = BaseCost \times (F_1 + F_2 \times F_3 \times F_4)$$

For the following resolution approaches:

- o Existing Stock
- o LTB
- o Cannibalisation
- o Equivalent
- o Alternative
- o Authorised Aftermarket

$$Cost = BaseCost \times ClusteringFactor \times (F_1 + F_2 \times F_3 \times F_4)$$

For the following resolution approaches:

- o Emulation
- o Minor Redesign
- o Major Redesign

3.7 Application of Clustering Factor to Number of Obsolescence Issues

3.7.1 Parameters

- Level of Complexity
- Probability of Becoming Obsolete
- Number of Products that Contain this Component
- Number of Low Complexity components expected to become obsolete during the contracted period
- Obsolescence Management Level (OMLevel)
- Obsolescence Resolution Profiles for Emulation, Minor and Major Redesign
- Clustering Factor (represents the number of redesigns that would be applied to solve 100 obsolescence issues requiring a redesign)

3.7.2 Algorithm

Collection of information from Step 3A:

```
Do for all Components
   If IgnoreComponent = "no" Then
      Select Case (Level of Complexity)
       Case ("Low")
      issueLow = issueLow + (Probability of Becoming Obsolete) * (Number of Products that
      Contain this Component)
       Case ("Medium")
      issueMed = issueMed + (Probability of Becoming Obsolete) * (Number of Products that
      Contain this Component)
       Case ("High")
      issueHigh = issueHigh + (Probability of Becoming Obsolete) * (Number of Products that
      Contain this Component)
      End Select
   End If
```

Collection of information from Step 3B:

```
Do for all Components
      issueLow = issueLow + Number of Low Complexity components expected to become obso-
      lete during the contracted period
      issueMed = issueMed + Number of Medium Complexity components expected to become
      obsolete during the contracted period
      issueHigh = issueHigh + Number of High Complexity components expected to become ob-
      solete during the contracted period
```

Calculation

```
Dim RMLow(2) As Variant
Dim RMMed(2) As Variant
Dim RMHigh(2) As Variant

   If OMLevel = "Bespoke" Then
      For j = 0 To 2
         RMLow(j) = ORP.Cells(j + 27, 7).Value
         RMMed(j) = ORP.Cells(j + 27 + 12, 7).Value
         RMHigh(j) = ORP.Cells(j + 27 + 24, 7).Value
      Next j
   Else
      m = OMLevel
      For j = 0 To 2
         RMLow(j) = ORP.Cells(j + 27, m + 1).Value
         RMMed(j) = ORP.Cells(j + 27 + 12, m + 1).Value
         RMHigh(j) = ORP.Cells(j + 27 + 24, m + 1).Value
      Next j
   End If
```

MAX NUMBER OF:

'Emulation

$$MaxEmul = issueLow \times RMLow(0) + issueMed \times RMMed(0) + issueHigh \times RMHigh(0)$$

'Minor redesign

$$MaxMinRed = issueLow \times RMLow(1) + issueMed \times RMMed(1) + issueHigh \times RMHigh(1)$$

'Major redesign

$$MaxMajRed = issueLow \times RMLow(2) + issueMed \times RMMed(2) + issueHigh \times RMHigh(2)$$

MOST LIKELY NUMBER OF:

'Emulation

$$MostLikelyEmul = MaxEmul \times clustering\ factor$$

'Minor redesign

$$MostLikelyMinRed = MaxMinRed \times clustering\ factor$$

'Major redesign

$$MostLikelyMajRed = MaxMajRed \times clustering\ factor$$

3.8 Cost Calculation when Resolution Approach Decided

3.8.1 Parameters

- Integration Level
    - Case ("Small (standalone)")
    - Case ("Medium")
    - Case ("Large")
    - Case ("Very Large (fully integrated)")
- Resolution Approach Decided
- Probability of Obsolescence Issue
- Component Requires Qualification Test
- Cost Metrics = f(Integration Level, Resolution Approach, Qualification Test Required)

3.8.2 Algorithm

```
If Component Requires Qualification Test Then
   req = 1
else
   req = 0
End If

Select Case (Integration Level)
Case ("Small (standalone)")
  iln = 0
Case ("Medium")
```

```
    iln = 1
  Case ("Large")
    iln = 2
  Case ("Very Large (fully integrated)")
    iln = 3
  End Select
```

Select Case (Resolution Approach Decided)

Case ("Existing Stock")

$$cost = cost + \frac{CostMetrics * Probability\ of\ Obsolescence\ Issue}{q}$$

Case ("LTB")

$$cost = cost + \frac{CostMetrics * Probability\ of\ Obsolescence\ Issue}{q}$$

Case ("Cannibalisation")

$$cost = cost + \frac{CostMetrics * Probability\ of\ Obsolescence\ Issue}{q}$$

Case ("Equivalent")

$$cost = cost + \frac{CostMetrics * Probability\ of\ Obsolescence\ Issue}{q}$$

Case ("Alternative")

$$cost = cost + \frac{CostMetrics * Probability\ of\ Obsolescence\ Issue}{q}$$

Case ("Authorised Aftermarket")

$$cost = cost + \frac{CostMetrics * Probability\ of\ Obsolescence\ Issue}{q}$$

Case ("Emulation")

$$cost = cost + CostMetrics * Probability\ of\ Obsolescence\ Issue$$

Case ("Minor Redesign")

$$cost = cost + CostMetrics * Probability\ of\ Obsolescence\ Issue$$

Case ("Major Redesign")

$$cost = cost + CostMetrics * Probability\ of\ Obsolescence\ Issue$$

End Select

where,
n = number of different components in the system (listed in STEP 3A)
q = number of products that contain a component

3.9 Cost Calculation Using Obsolescence Resolution Profiles and Cost Metrics

3.9.1 Parameters

- Obsolescence Management Level (OMLevel)
- Level of Complexity
- Integration Level
  - o Case ("Small (standalone)")
  - o Case ("Medium")
  - o Case ("Large")
  - o Case ("Very Large (fully integrated)")
- Resolution Approach Decided
- Type of Platform
- Probability of Obsolescence Issue
- Component Requires Qualification Test
- Cost Metrics = f(Integration Level, Resolution Approach, Qualification Test Required)
- Probability of Becoming Obsolete
- Number of Products that Contain this Component
- Number of Low Complexity components expected to become obsolete during the contracted period (NL)
- Number of Medium Complexity components expected to become obsolete during the contracted period (NM)
- Number of High Complexity components expected to become obsolete during the contracted period (NH)
- Number of Medium Complexity components expected to become obsolete during the contracted period that require requalification (NLR)
- Number of High Complexity components expected to become obsolete during the contracted period that require requalification (NMR)
- Number of Low Complexity components expected to become obsolete during the contracted period that require requalification(NHR)
- Obsolescence Resolution Profiles

3.9.2 Algorithm

```
Select Case (Type of Platform)
        Case ("Space")
          pn = 1
        Case ("Air / Safety Critical")
          pn = 2
        Case ("Sea/Submersible")
          pn = 3
        Case ("Land-Mobile (military)")
          pn = 4
```

```
            Case ("Land-Fixed (consumer) Office - Industrial")
              pn = 5
   End Select
```

Do for all Components in STEP3A for which there is no Resolution Approach Decided

Obsolescence Resolution Profiles

```
Select Case (Level of Complexity)
     Case ("Low")
       comp = 0
     Case ("Medium")
       comp = 1
     Case ("High")
       comp = 2
   End Select

 Dim RM(8) As Variant

   If OMLevel = "Bespoke" Then
      For j = 0 To 8
         RM(j) = ORP.Cells(j + 21 + 12 * comp, 7).Value
      Next j
   Else
      k = OMLevel
      For j = 0 To 8
         RM(j) = ORP.Cells(j + 21 + 12 * comp, k + 1).Value
      Next j
   End If
```

Cost metrics

```
   If Component Requires Qualification Test Then
      req = 1
   Else
      req = 0
   End If

   Select Case (Integration Level)
   Case ("Small (standalone)")
     For j = 0 To 5
```

$$CM(j) = \frac{HOCM.Cells(12 * pn * req + j + 3, 8).Value}{q}$$

```
     Next j
     For j = 6 To 8
```

$$CM(j) = HOCM.Cells(12 * pn * req + j + 3, 8).Value$$

```
     Next j
   Case ("Medium")
     For j = 0 To 5
```

$$CM(j) = \frac{HOCM.Cells(12 * pn * req + j + 3, 9).Value}{q}$$

```
    Next j
    For j = 6 To 8
```

$$CM(j) = HOCM.Cells(12 * pn * req + j + 3, 9).Value$$

```
    Next j
  Case ("Large")
    For j = 0 To 5
```

$$CM(j) = \frac{HOCM.Cells(12 * pn * req + j + 3, 10).Value}{q}$$

```
    Next j
    For j = 6 To 8
```

$$CM(j) = HOCM.Cells(12 * pn * req + j + 3, 10).Value$$

```
    Next j
  Case ("Very Large (fully integrated)")
    For j = 0 To 5
```

$$CM(j) = \frac{HOCM.Cells(12 * pn * req + j + 3, 11).Value}{q}$$

```
    Next j
    For j = 6 To 8
```

$$CM(j) = HOCM.Cells(12 * pn * req + j + 3, 11).Value$$

```
    Next j
  End Select
```

$$cost_A = \sum_{i=0}^{n}(\sum_{p=1}^{q} Probability\ of\ Obsolescence\ Issue_i \times \sum_{j=0}^{8}(CM_i(j) \times RM_i(j)))$$

where,
n = number of different components in the system (listed in STEP 3A)
q = number of products that contain a component

Do for all Components in STEP3B

Obsolescence Resolution Profiles

```
  If OMLevel = "Bespoke" Then
     For j = 0 To 8
        RML(j) = ORP.Cells(j + 21, 7).Value
     Next j
  Else
     k = OMLevel
     For j = 0 To 8
        RML(j) = ORP.Cells(j + 21, k + 1).Value
     Next j
```

```
End If

 If OMLevel = "Bespoke" Then
   For j = 0 To 8
      RMM(j) = ORP.Cells(j + 33, 7).Value
   Next j
Else
   k = OMLevel
   For j = 0 To 8
      RMM(j) = ORP.Cells(j + 33, k + 1).Value
   Next j
End If

 If OMLevel = "Bespoke" Then
   For j = 0 To 8
      RMH(j) = ORP.Cells(j + 45, 7).Value
   Next j
Else
   k = OMLevel
   For j = 0 To 8
      RMH(j) = ORP.Cells(j + 45, k + 1).Value
   Next j
End If
```

Cost metrics

‘Cost metrics with requalification

```
Select Case (Integration Level)
Case ("Small (standalone)")
  For j = 0 To 8
     CMr(j) = HOCM.Cells(12 * pn + j + 3, 8).Value
  Next j
Case ("Medium")
  For j = 0 To 8
     CMr(j) = HOCM.Cells(12 * pn + j + 3, 9).Value
  Next j
Case ("Large")
  For j = 0 To 8
     CMr(j) = HOCM.Cells(12 * pn + j + 3, 10).Value
  Next j
Case ("Very Large (fully integrated)")
  For j = 0 To 8
     CMr(j) = HOCM.Cells(12 * pn + j + 3, 11).Value
  Next j
End Select
```

‘Cost metrics without requalification

```
Select Case (Integration Level)
```

```
Case ("Small (standalone)")
  For j = 0 To 8
     CMnr(j) = HOCM.Cells(j + 3, 8).Value
  Next j
Case ("Medium")
  For j = 0 To 8
     CMnr(j) = HOCM.Cells(j + 3, 9).Value
  Next j
Case ("Large")
  For j = 0 To 8
     CMnr(j) = HOCM.Cells(j + 3, 10).Value
  Next j
Case ("Very Large (fully integrated)")
  For j = 0 To 8
     CMnr(j) = HOCM.Cells(j + 3, 11).Value
  Next j
End Select
```

$$cost_{Lnoreq} = \sum_{j=0}^{8}(CM_{nr}(j) \times RML(j))$$

$$cost_{Lreq} = \sum_{j=0}^{8}(CM_{r}(j) \times RML(j))$$

$$cost_{L} = (NL - NLR) \times cost_{Lnoreq} + NLR \times cost_{Lreq}$$

$$cost_{Mnoreq} = \sum_{j=0}^{8}(CM_{nr}(j) \times RMM(j))$$

$$cost_{Mreq} = \sum_{j=0}^{8}(CM_{r}(j) \times RMM(j))$$

$$cost_{M} = (NM - NMR) \times cost_{Mnoreq} + NMR \times cost_{Mreq}$$

$$cost_{Hnoreq} = \sum_{j=0}^{8}(CM_{nr}(j) \times RMH(j))$$

$$cost_{Hreq} = \sum_{j=0}^{8}(CM_{r}(j) \times RMH(j))$$

$$cost_{H} = (NH - NHR) \times cost_{Hnoreq} + NHR \times cost_{Hreq}$$

$$cost_{B} = \sum_{l=0}^{z}(cost_{L} + cost_{M} + cost_{H})$$

where,

z = number of products (listed in STEP 3B)

$$cost_{Total} = cost + cost_{A} + cost_{B}$$

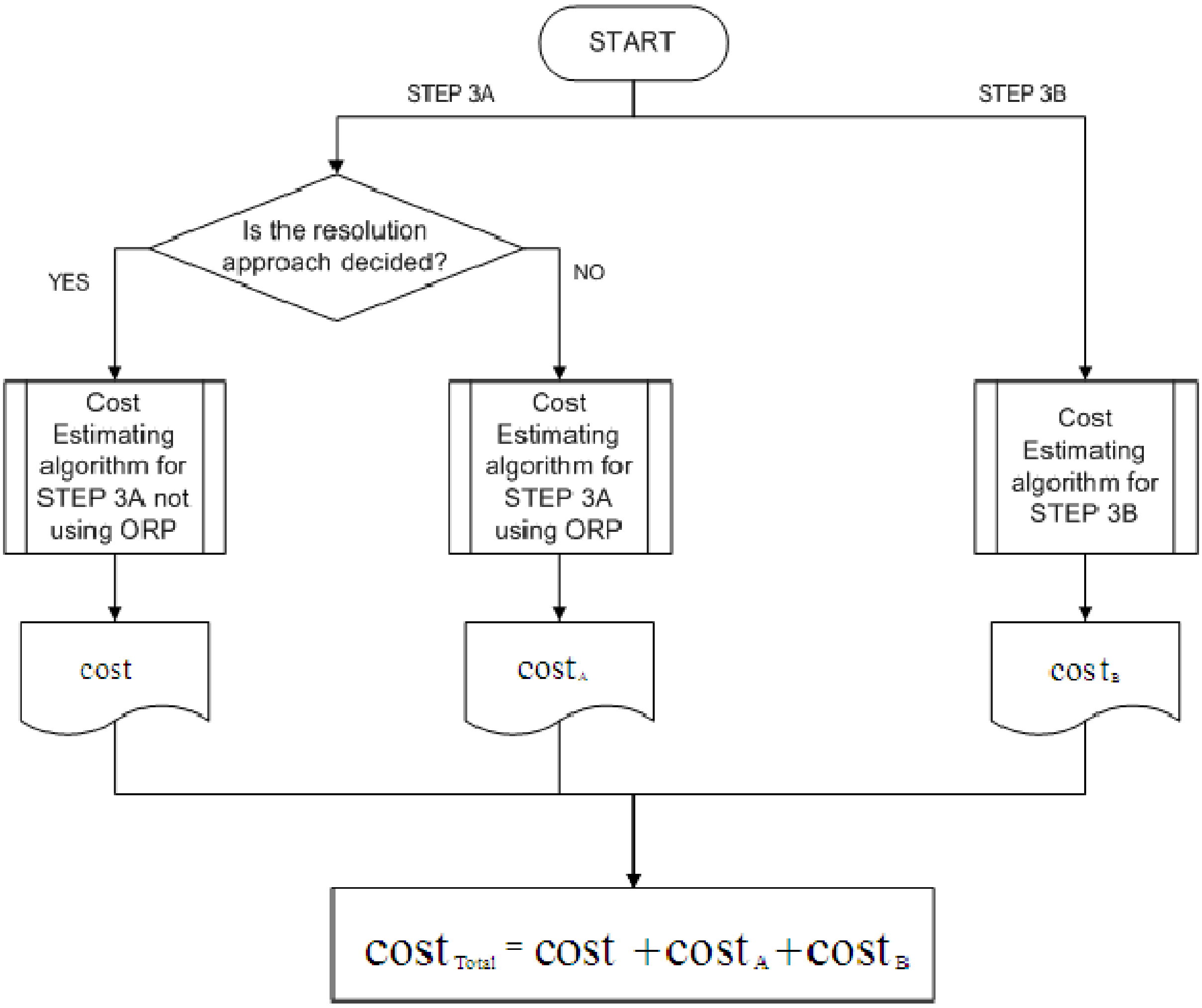
where,

cost = cost from components listed in STEP 3A with obs. resolution approach decided

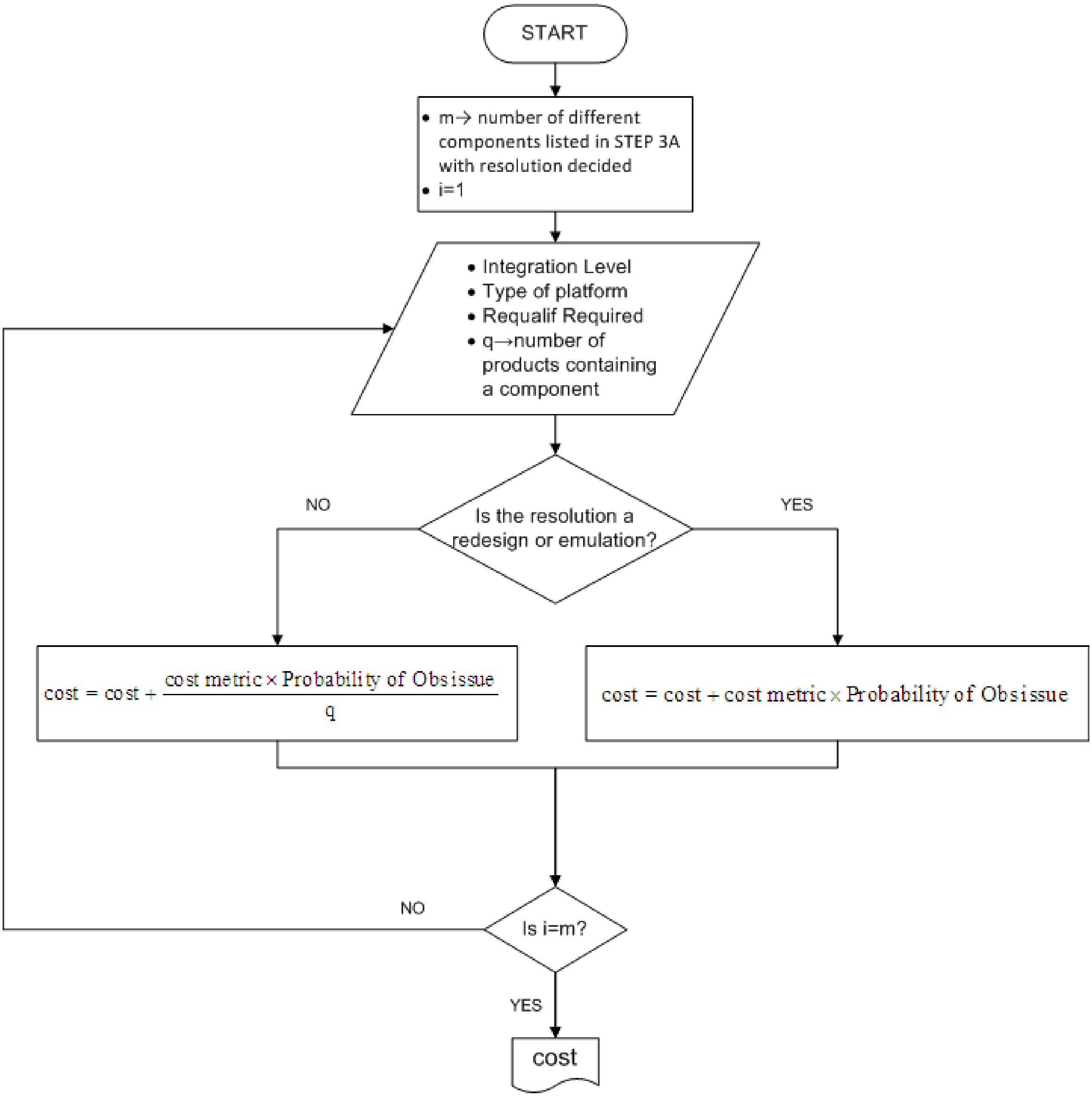
$cost_A$ = cost from components listed in STEP 3A without obs. resolution approach decided

$cost_B$ = cost from components listed in STEP 3B

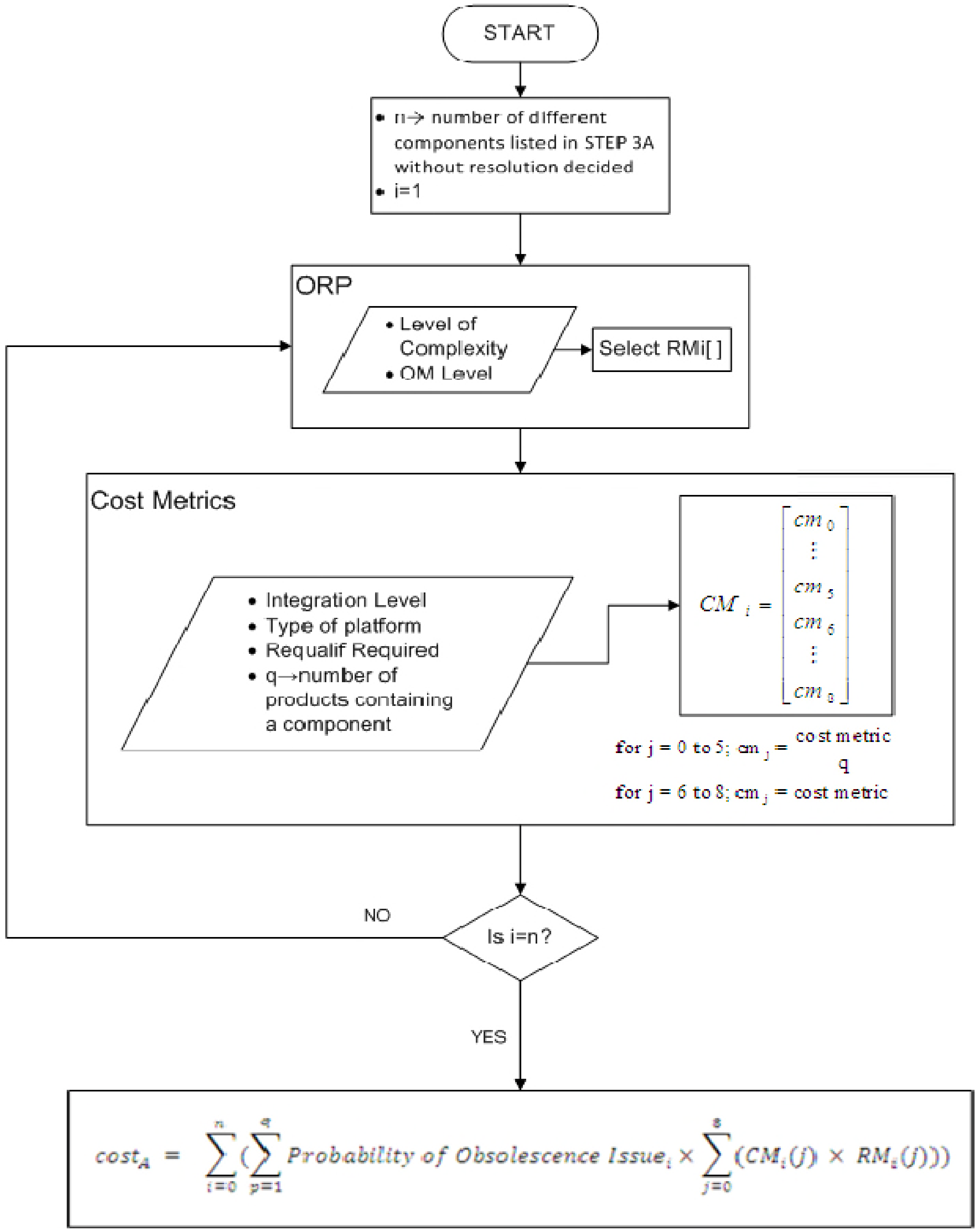
4. Flowcharts of the Cost Estimating Algorithms in the EEE-FORCE Tool



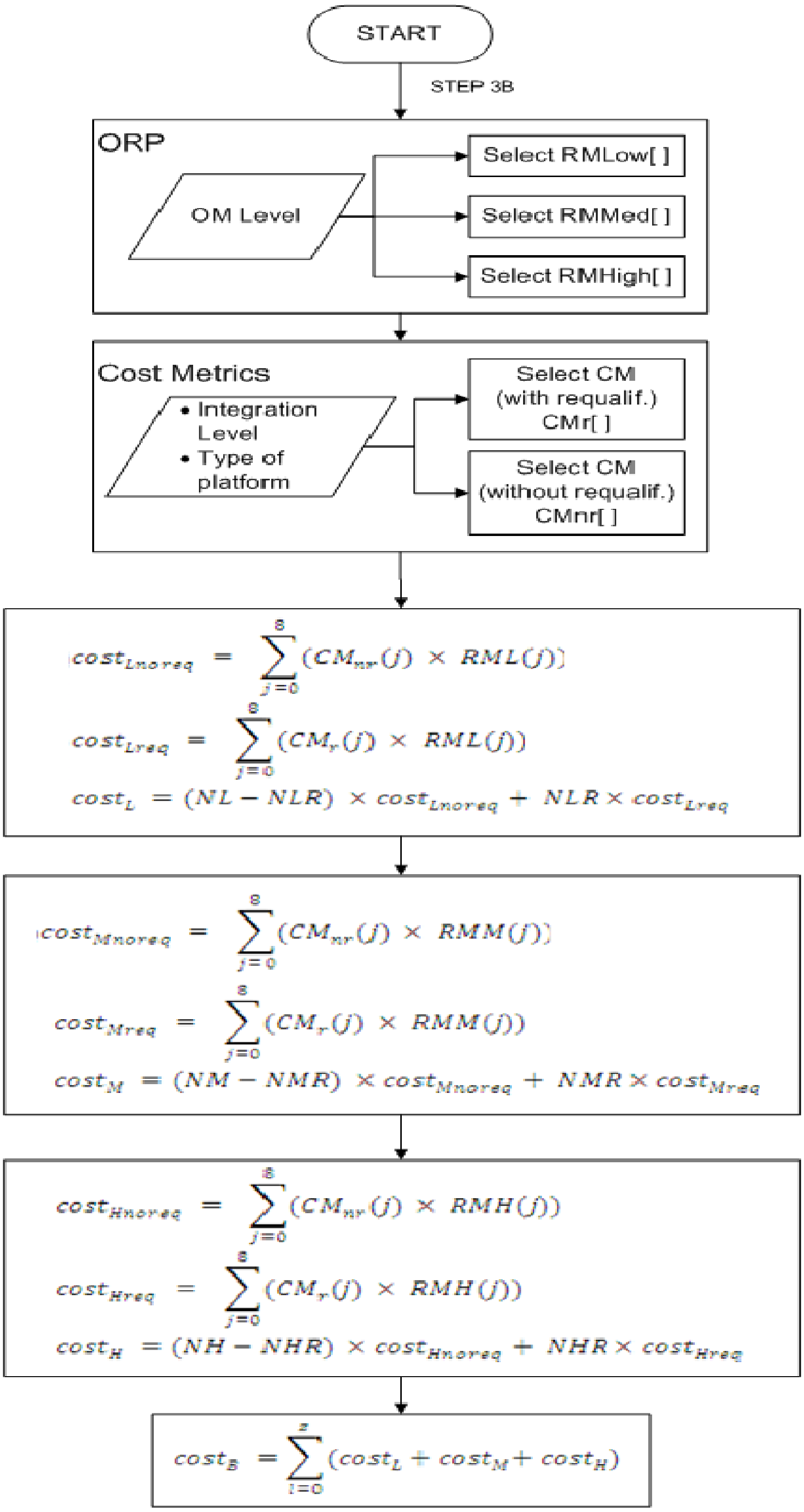
Cost Estimating Algorithm for STEP 3A When Resolution Approach is Decided



Cost Estimating Algorithm for STEP 3A
Using Obsolescence Resolution Profiles (ORP)



Cost Estimating algorithm for STEP 3B



5. Source Code of the EEE-FORCE Tool

5.1 Sub Procedure 1: Calculate Level of Integration

```
Sub IntLev()

' IntLev Macro

Set Sys = Worksheets("System-Platform-Products")

i = 0

Do Until IsEmpty(Sys.Cells(i + 44, 4))

pd = 0
cl = 0
il = 0

    Select Case (Sys.Cells(i + 44, 5).Value)
      Case ("Low")
        cl = 1
      Case ("Medium")
        cl = 2
      Case ("High")
        cl = 3
    End Select

    Select Case (Sys.Cells(i + 44, 6).Value)
      Case ("Small (standalone)")
        pd = 1
      Case ("Medium")
        pd = 2
```

```
    Case ("Large")
      pd = 3
    Case ("Very Large (fully integrated)")
      pd = 4
  End Select

il = cl * pd

If il = 0 Then
   GoTo 10
  ElseIf il <= 2 Then
   Sys.Cells(i + 44, 9).Value = "Small (standalone)"
  ElseIf il < 5 Then
   Sys.Cells(i + 44, 9).Value = "Medium"
  ElseIf il = 6 Then
   Sys.Cells(i + 44, 9).Value = "Large"
  Else
   Sys.Cells(i + 44, 9).Value = "Very Large (fully integrated)"
End If

10: i = i + 1

Loop

End Sub
```

5.2 Sub Procedure 2: Estimate Date to Run out of Stock

```
Sub RunOutStock()

' RunOutStock Macro

Set BoM = Worksheets("Components-BoM")
Set NoBoM = Worksheets("Components-No BoM")
```

```
Set Sys = Worksheets("System-Platform-Products")
Set OCM = Worksheets("Obsolescence Cost Metrics")
Set OCE = Worksheets("Obsolescence Cost Estimation")
Set HOCM = Worksheets("Hidden OCM")
Set User = Worksheets("User")

i = 0

If IsEmpty(BoM.Cells(15, 6)) Then
   j = 0
   Do Until IsEmpty(User.Cells(11 + j, 5))
      BoM.Cells(15, 6).Value = User.Cells(11 + j, 5).Value
      j = j + 1
   Loop
End If

Do Until IsEmpty(BoM.Cells(i + 17, 4))

If (BoM.Cells(i + 17, 4).Value = "No") Then
      If IsEmpty(BoM.Cells(i + 17, 7)) Then
         BoM.Cells(i + 17, 7).Value = BoM.Cells(i + 17, 12).Value * BoM.Cells(i + 17, 11).Value *
BoM.Cells(i + 17, 10).Value / BoM.Cells(i + 17, 9).Value
         BoM.Cells(i + 17, 13).Value = BoM.Cells(15, 6).Value + 365 * BoM.Cells(i + 17, 6).Value /
BoM.Cells(i + 17, 7).Value
      Else
         BoM.Cells(i + 17, 13).Value = BoM.Cells(15, 6).Value + 365 * BoM.Cells(i + 17, 6).Value /
BoM.Cells(i + 17, 7).Value
      End If
End If

i = i + 1

Loop

End Sub
```

5.3 Sub Procedure 3: Calculate Number of Obsolescence Issues Expected During the Contracted Period

```
Sub CalcObsIssues()

Set BoM = Worksheets("Components-BoM")
Set NoBoM = Worksheets("Components-No BoM")
Set Sys = Worksheets("System-Platform-Products")
Set OCM = Worksheets("Obsolescence Cost Metrics")
Set OCE = Worksheets("Obsolescence Cost Estimation")
Set HOCM = Worksheets("Hidden OCM")

Call RunOutStock

i = 0

Do Until IsEmpty(BoM.Cells(i + 17, 2))

    Select Case (BoM.Cells(i + 17, 5).Value)
      Case ("100% Yes")
        RofS = 1
      Case ("High")
        RofS = 0.75
      Case ("Medium")
        RofS = 0.5
      Case ("Low")
        RofS = 0.25
      Case ("0% No")
        RofS = 0
    End Select
```

```
    Select Case (BoM.Cells(i + 17, 16).Value)
     Case ("100% Yes")
      OD = 1
     Case ("High")
      OD = 0.75
     Case ("Medium")
      OD = 0.5
     Case ("Low")
      OD = 0.25
     Case ("0% No")
      OD = 0
    End Select

'A-1
If BoM.Cells(i + 17, 4) = "Yes" And IsEmpty(BoM.Cells(i + 17, 14)) Then
  Select Case (RofS * OD)
    Case (1)
      BoM.Cells(i + 17, 20).Value = "YES"
      BoM.Cells(i + 17, 21).Value = 1
    Case (0)
      BoM.Cells(i + 17, 20).Value = "NO"
      BoM.Cells(i + 17, 21).Value = 0
    Case Else
      BoM.Cells(i + 17, 20).Value = "MAYBE"
      BoM.Cells(i + 17, 21).Value = RofS * OD
  End Select
End If

'A-2
If BoM.Cells(i + 17, 4) = "Yes" And IsEmpty(BoM.Cells(i + 17, 14)) = False Then
  If (Sys.Cells(35, 2).Value > BoM.Cells(i + 17, 14).Value) Then
    BoM.Cells(i + 17, 21).Value = RofS
    Select Case (RofS)
      Case (1)
        BoM.Cells(i + 17, 20).Value = "YES"
```

```
            Case (0)
                BoM.Cells(i + 17, 20).Value = "NO"
            Case Else
                BoM.Cells(i + 17, 20).Value = "MAYBE"
        End Select
    Else
        BoM.Cells(i + 17, 21).Value = 0
        BoM.Cells(i + 17, 20).Value = "NO"
    End If
End If

'B-1
If BoM.Cells(i + 17, 4) = "No" And IsEmpty(BoM.Cells(i + 17, 14)) Then
    If (Sys.Cells(35, 2).Value > BoM.Cells(i + 17, 13).Value) Then
        BoM.Cells(i + 17, 21).Value = OD
        Select Case (OD)
            Case (1)
                BoM.Cells(i + 17, 20).Value = "YES"
            Case (0)
                BoM.Cells(i + 17, 20).Value = "NO"
            Case Else
                BoM.Cells(i + 17, 20).Value = "MAYBE"
        End Select
    Else
        BoM.Cells(i + 17, 21).Value = 0
        BoM.Cells(i + 17, 20).Value = "NO"
    End If
End If

'B-2
If BoM.Cells(i + 17, 4) = "No" And IsEmpty(BoM.Cells(i + 17, 14)) = False Then
        If (Sys.Cells(35, 2).Value > BoM.Cells(i + 17, 13).Value) And (Sys.Cells(35, 2).Value >
BoM.Cells(i + 17, 14).Value) Then
            BoM.Cells(i + 17, 21).Value = 1
            BoM.Cells(i + 17, 20).Value = "YES"
```

```
        Else
            BoM.Cells(i + 17, 21).Value = 0
            BoM.Cells(i + 17, 20).Value = "NO"
        End If
End If
i = i + 1
Loop
End Sub
```

5.4 Sub Procedure 4: Precontract

```
Sub precontract()

Set BoM = Worksheets("Components-BoM")
Set NoBoM = Worksheets("Components-No BoM")
Set Sys = Worksheets("System-Platform-Products")
Set OCM = Worksheets("Obsolescence Cost Metrics")
Set OCE = Worksheets("Obsolescence Cost Estimation")
Set HOCM = Worksheets("Hidden OCM")
Set User = Worksheets("User")

i = 0

Answer = MsgBox("ATTENTION: YOU ARE ABOUT TO ENTER IN PRECONTRACT MODE. Do
you want to continue?", vbYesNo)

If Answer = vbNo Then Exit Sub

Do Until IsEmpty(BoM.Cells(i + 17, 2))

    BoM.Cells(i + 17, 6).Value = 0
    BoM.Cells(i + 17, 14).Value = 0
    BoM.Cells(i + 17, 7).Value = 1
```

```
  BoM.Cells(i + 17, 4).Value = "No"

i = i + 1

Loop

Sys.Cells(32, 3).Value = 1

Call CalcObsIssues

End Sub
```

5.5 Sub Procedure 5: Calculate Obsolescence Cost

```
Public Sub calc()

'1)

Set BoM = Worksheets("Components-BoM")
Set NoBoM = Worksheets("Components-No BoM")
Set Sys = Worksheets("System-Platform-Products")
Set OCM = Worksheets("Obsolescence Cost Metrics")
Set OCE = Worksheets("Obsolescence Cost Estimation")
Set HOCM = Worksheets("Hidden OCM")

Call CalcObsIssues


'Use Obs Resolution Profiles or Alt. Obs Resolution Profiles?

Select Case (Worksheets("Obs Resolution Profiles").Cells(12, 1).Value)
  Case (0)
    MsgBox "The information required in Step 4 is incomplete. Please revisit it and try again."
    GoTo 20
```

```
  Case (1)
    Set ORP = Worksheets("Alt. Obs Resolution Profiles")
  Case (2)
    Set ORP = Worksheets("Obs Resolution Profiles")
End Select

' Calculate clustering factor that will be applied to the cost metrics

  issueLow = 0
  issueMed = 0
  issueHigh = 0

  'Step3A

  k = 0
  Do Until IsEmpty(BoM.Cells(k + 17, 2))
    If BoM.Cells(k + 17, 19).Value = "no" Then
      Select Case (BoM.Cells(k + 17, 18).Value)
        Case ("Low")
          issueLow = issueLow + BoM.Cells(k + 17, 21).Value * (BoM.Cells(k + 17, 3).Value)
        Case ("Medium")
          issueMed = issueMed + BoM.Cells(k + 17, 21).Value * (BoM.Cells(k + 17, 3).Value)
        Case ("High")
          issueHigh = issueHigh + BoM.Cells(k + 17, 21).Value * (BoM.Cells(k + 17, 3).Value)
      End Select
    End If
  k = k + 1

  Loop

  'Step3B

  k = 0
  Do Until IsEmpty(BoM.Cells(k * 6 + 17, 1))
    issueLow = issueLow + NoBoM.Cells(k * 6 + 20, 3).Value
```

```
        issueMed = issueMed + NoBoM.Cells(k * 6 + 19, 3).Value
        issueHigh = issueHigh + NoBoM.Cells(k * 6 + 18, 3).Value

    k = k + 1
    Loop

'calculation

Dim RMLow(2) As Variant
Dim RMMed(2) As Variant
Dim RMHigh(2) As Variant

    If Sys.Cells(32, 3).Value = "Bespoke" Then
        For j = 0 To 2
            RMLow(j) = ORP.Cells(j + 27, 7).Value
            RMMed(j) = ORP.Cells(j + 27 + 12, 7).Value
            RMHigh(j) = ORP.Cells(j + 27 + 24, 7).Value
        Next j
    Else
        m = Sys.Cells(32, 3).Value
        For j = 0 To 2
            RMLow(j) = ORP.Cells(j + 27, m + 1).Value
            RMMed(j) = ORP.Cells(j + 27 + 12, m + 1).Value
            RMHigh(j) = ORP.Cells(j + 27 + 24, m + 1).Value
        Next j
    End If

'MAX NUMBER OF:

'Emulation
MaxEmul = issueLow * (RMLow(0) + RMLow(1) + RMLow(2))
'Minor redesign
MaxMinRed = issueMed * (RMLow(0) + RMLow(1) + RMLow(2))
'Major redesign
MaxMajRed = issueHigh * (RMLow(0) + RMLow(1) + RMLow(2))
```

```
'AVERAGE NUMBER OF:

'Emulation
MeanEmul = issueLow * (RMLow(0) + RMLow(1) + RMLow(2)) * OCE.Cells(15, 3).Value
'Minor redesign
MeanMinRed = issueMed * (RMLow(0) + RMLow(1) + RMLow(2)) * OCE.Cells(15, 3).Value
'Major redesign
MeanMajRed = issueHigh * (RMLow(0) + RMLow(1) + RMLow(2)) * OCE.Cells(15, 3).Value

'clustering factor

If MeanEmul = 0 Then
  EmulFactor = 0
  Else
  EmulFactor = MaxEmul / MeanEmul
End If

If MeanMinRed = 0 Then
  MinRedFactor = 0
  Else
  MinRedFactor = MaxMinRed / MeanMinRed
End If

If MeanMajRed = 0 Then
  MajRedFactor = 0
  Else
  MajRedFactor = MaxMajRed / MeanMajRed
End If

'report

OCE.Cells(16, 12).Value = issueLow
OCE.Cells(17, 12).Value = issueMed
OCE.Cells(18, 12).Value = issueHigh
```

```
OCE.Cells(17, 3).Value = MaxEmul
OCE.Cells(18, 3).Value = MaxMinRed
OCE.Cells(19, 3).Value = MaxMajRed

OCE.Cells(17, 4).Value = MeanEmul
OCE.Cells(18, 4).Value = MeanMinRed
OCE.Cells(19, 4).Value = MeanMajRed


' make sure the integration level has been calculated

Call IntLev

'S3A

i = 1

'Type of Platform?

Select Case (Sys.Cells(16, 2).Value)
   Case ("Space systems")
     pn = 1
   Case ("Air systems / Safety Critical")
     pn = 2
   Case ("Surface sea-based systems / Submersible sea-based systems")
     pn = 3
   Case ("Mobile land-based systems (military)")
     pn = 4
   Case ("Land-Fixed systems / Office-Industrial (consumer)")
     pn = 5
   End Select

Do Until IsEmpty(BoM.Cells(i + 16, 2))
```

```
' Dismissed component or Probability of obs. issue = 0 ?
If BoM.Cells(i + 16, 19).Value = "yes" Or BoM.Cells(i + 16, 20).Value = "NO" Then
  GoTo 10
End If


  Select Case (BoM.Cells(i + 16, 18).Value)
    Case ("Low")
      comp = 0
    Case ("Medium")
      comp = 1
    Case ("High")
      comp = 2
  End Select

  q = BoM.Cells(i + 16, 3).Value

For p = 1 To q

  lru = BoM.Cells(i + 16, 22 + p).Value
  il = Sys.Cells(43 + lru, 9).Value

'Type of Environment

      If IsEmpty(Sys.Cells(43 + lru, 7)) Then
        pn = pn
      Else
        Select Case (Sys.Cells(43 + lru, 7).Value)
          Case ("Space")
            pn = 1
          Case ("Air / Safety Critical")
            pn = 2
          Case ("Sea/Submersible")
            pn = 3
          Case ("Land-Mobile (military)")
```

```
            pn = 4
          Case ("Land-Fixed (consumer) Office - Industrial")
            pn = 5
          End Select
     End If

'resolution approach decided?

If IsEmpty(BoM.Cells(i + 16, 22).Value) = False Then
   req = 0
   If BoM.Cells(i + 16, 17).Value = "yes" Then
      req = 1
   End If

   Select Case (il)
   Case ("Small (standalone)")
     iln = 0
   Case ("Medium")
     iln = 1
   Case ("Large")
     iln = 2
   Case ("Very Large (fully integrated)")
     iln = 3
   End Select

   Select Case (BoM.Cells(i + 16, 22).Value)
      Case ("Existing Stock")
        cost = cost + HOCM.Cells(12 * pn * req + 3, 8 + iln).Value * BoM.Cells(i + 16, 21).Value / q
      Case ("LTB")
        cost = cost + HOCM.Cells(12 * pn * req + 4, 8 + iln).Value * BoM.Cells(i + 16, 21).Value / q
      Case ("Cannibalisation")
        cost = cost + HOCM.Cells(12 * pn * req + 5, 8 + iln).Value * BoM.Cells(i + 16, 21).Value / q
      Case ("Equivalent")
        cost = cost + HOCM.Cells(12 * pn * req + 6, 8 + iln).Value * BoM.Cells(i + 16, 21).Value / q
      Case ("Alternative")
```

```
        cost = cost + HOCM.Cells(12 * pn * req + 7, 8 + iln).Value * BoM.Cells(i + 16, 21).Value / q
      Case ("Authorised Aftermarket")
        cost = cost + HOCM.Cells(12 * pn * req + 8, 8 + iln).Value * BoM.Cells(i + 16, 21).Value / q
      Case ("Emulation")
        cost = cost + HOCM.Cells(12 * pn * req + 9, 8 + iln).Value * BoM.Cells(i + 16, 21).Value
      Case ("Minor Redesign")
        cost = cost + HOCM.Cells(12 * pn * req + 10, 8 + iln).Value * BoM.Cells(i + 16, 21).Value
      Case ("Major Redesign")
        cost = cost + HOCM.Cells(12 * pn * req + 11, 8 + iln).Value * BoM.Cells(i + 16, 21).Value
      End Select
GoTo 10

End If

'4)Obs Resolution Profile
 Dim RM(8) As Variant

   If Sys.Cells(32, 3).Value = "Bespoke" Then
      For j = 0 To 8
         RM(j) = ORP.Cells(j + 21 + 12 * comp, 7).Value
      Next j
   Else
      k = Sys.Cells(32, 3).Value
      For j = 0 To 8
         RM(j) = ORP.Cells(j + 21 + 12 * comp, k + 1).Value
      Next j
   End If

 '5)Cost metric
 Dim CM(8) As Variant

   If BoM.Cells(i + 16, 17).Value = "yes" Then
      req = 1
   Else
      req = 0
```

```
  End If

  Select Case (il)
  Case ("Small (standalone)")
    For j = 0 To 5
      CM(j) = HOCM.Cells(12 * pn * req + j + 3, 8).Value / q
    Next j
    For j = 6 To 8
      CM(j) = HOCM.Cells(12 * pn * req + j + 3, 8).Value
    Next j
  Case ("Medium")
    For j = 0 To 5
      CM(j) = HOCM.Cells(12 * pn * req + j + 3, 9).Value / q
    Next j
    For j = 6 To 8
      CM(j) = HOCM.Cells(12 * pn * req + j + 3, 9).Value
    Next j
  Case ("Large")
    For j = 0 To 5
      CM(j) = HOCM.Cells(12 * pn * req + j + 3, 10).Value / q
    Next j
    For j = 6 To 8
      CM(j) = HOCM.Cells(12 * pn * req + j + 3, 10).Value
    Next j
  Case ("Very Large (fully integrated)")
    For j = 0 To 5
      CM(j) = HOCM.Cells(12 * pn * req + j + 3, 11).Value / q
    Next j
    For j = 6 To 8
      CM(j) = HOCM.Cells(12 * pn * req + j + 3, 11).Value
    Next j
  End Select

costcomp = 0
For j = 0 To 8
```

```
   costcomp = costcomp + (CM(j) * RM(j))
 Next j

 cost = cost + costcomp * BoM.Cells(i + 16, 21).Value

Next p

10: i = i + 1

Loop

'S3B

i = 0
Do Until IsEmpty(NoBoM.Cells(6 * i + 17, 1))

   lru = NoBoM.Cells(6 * i + 17, 1).Value
   il = Sys.Cells(43 + lru, 9).Value

 '4)Obs Resolution Profiles

   Dim RML(8) As Variant
   Dim RMM(8) As Variant
   Dim RMH(8) As Variant

   If Sys.Cells(32, 3).Value = "Bespoke" Then
      For j = 0 To 8
         RML(j) = ORP.Cells(j + 21, 7).Value
      Next j
   Else
      k = Sys.Cells(32, 3).Value
      For j = 0 To 8
         RML(j) = ORP.Cells(j + 21, k + 1).Value
      Next j
   End If
```

```
 If Sys.Cells(32, 3).Value = "Bespoke" Then
   For j = 0 To 8
      RMM(j) = ORP.Cells(j + 33, 7).Value
   Next j
 Else
   k = Sys.Cells(32, 3).Value
   For j = 0 To 8
      RMM(j) = ORP.Cells(j + 33, k + 1).Value
   Next j
 End If

 If Sys.Cells(32, 3).Value = "Bespoke" Then
   For j = 0 To 8
      RMH(j) = ORP.Cells(j + 45, 7).Value
   Next j
 Else
   k = Sys.Cells(32, 3).Value
   For j = 0 To 8
      RMH(j) = ORP.Cells(j + 45, k + 1).Value
   Next j
 End If

'5)Cost metrics

 Dim CMnr(8) As Variant
 Dim CMr(8) As Variant

 Select Case (il)
 Case ("Small (standalone)")
   For j = 0 To 8
      CMr(j) = HOCM.Cells(12 * pn + j + 3, 8).Value
   Next j
 Case ("Medium")
   For j = 0 To 8
```

```
        CMr(j) = HOCM.Cells(12 * pn + j + 3, 9).Value
    Next j
  Case ("Large")
    For j = 0 To 8
        CMr(j) = HOCM.Cells(12 * pn + j + 3, 10).Value
    Next j
  Case ("Very Large (fully integrated)")
    For j = 0 To 8
        CMr(j) = HOCM.Cells(12 * pn + j + 3, 11).Value
    Next j
  End Select

  Select Case (il)
  Case ("Small (standalone)")
    For j = 0 To 8
        CMnr(j) = HOCM.Cells(j + 3, 8).Value
    Next j
  Case ("Medium")
    For j = 0 To 8
        CMnr(j) = HOCM.Cells(j + 3, 9).Value
    Next j
  Case ("Large")
    For j = 0 To 8
        CMnr(j) = HOCM.Cells(j + 3, 10).Value
    Next j
  Case ("Very Large (fully integrated)")
    For j = 0 To 8
        CMnr(j) = HOCM.Cells(j + 3, 11).Value
    Next j
  End Select

costLnoreq = 0
For j = 0 To 8
  costLnoreq = costLnoreq + (CMnr(j) * RML(j))
Next j
```

```
 costLreq = 0
 For j = 0 To 8
   costLreq = costLreq + (CMr(j) * RML(j))
 Next j

costL = (NoBoM.Cells(6 * i + 20, 3).Value - NoBoM.Cells(6 * i + 20, 4).Value) * costLnoreq + NoBoM.Cells(6 * i + 20, 4).Value * costLreq

 costMnoreq = 0
 For j = 0 To 8
   costMnoreq = costMnoreq + (CMnr(j) * RMM(j))
 Next j

 costMreq = 0
 For j = 0 To 8
   costMreq = costMreq + (CMr(j) * RMM(j))
 Next j

costM = (NoBoM.Cells(6 * i + 19, 3).Value - NoBoM.Cells(6 * i + 19, 4).Value) * costMnoreq + NoBoM.Cells(6 * i + 19, 4).Value * costMreq

 costHnoreq = 0
 For j = 0 To 8
   costHnoreq = costHnoreq + (CMnr(j) * RMH(j))
 Next j

 costHreq = 0
 For j = 0 To 8
   costHreq = costHreq + (CMr(j) * RMH(j))
 Next j

costH = (NoBoM.Cells(6 * i + 18, 3).Value - NoBoM.Cells(6 * i + 18, 4).Value) * costHnoreq + NoBoM.Cells(6 * i + 18, 4).Value * costHreq
```

```
costLRU = costL + costM + costH

cost = cost + costLRU

i = i + 1
Loop

'Total obsolescence cost

OCE.Cells(25, 7).Value = cost
CBAfterRecalc = cost

20:
End Sub
```

Disclaimer:

The content of this manual is based on the features and content of the EEE-FORCE tool developed as a deliverable of the PSS-Cost project.

Appendix

D

APPENDIX D: M-FORCE MAINTENANCE MANUAL

PSS Cost Project

Maintenance Manual for M-FORCE Tool

Abstract

This maintenance manual, produced by the PSS-Cost Project team at Cranfield University, provides an understanding about the algorithms behind the M-FORCE (Materials – Framework for Obsolescence Robust Cost Estimation) tool that are used to turn the input information into a NRE cost estimation for materials obsolescence. This tool is intended to be applied at the bidding stage for support contracts, where obsolescence management has been transferred to the prime contractor. This tool has been validated to be used in the defence sector for ammunition and for air platforms, but it can potentially be applied to long-term support contracts in other platforms such as land and sea.

Researcher: Francisco Javier Romero Rojo

Supervisors: Prof. Rajkumar Roy, Dr. Essam Shehab

Project Manager: Dr. Kalyan Cheruvu

E-mail: {f.romerorojo, r.roy, e.shehab, k.cheruvu}@cranfield.ac.uk

Address: Building 50, Manufacturing Department, School of Applied Sciences, Cranfield University, Cranfield, Bedfordshire, MK43 0AL

Approved:

Professor Rajkumar Roy
Head of Manufacturing Department
Cranfield University

Identity: PSS-Cost-Obsolescence
Version: Final
Dated: 7th June 2010

Document History

Version	Date	Comments
Final	07/06/10	Initial release by Cranfield University

Glossary of Terms

BoM	Bill of Materials
EEE	Electronic, Electromechanical and Electrical
EEE-FORCE	Electronic, Electromechanical and Electrical Components – Framework for Obsolescence Robust Cost Estimation
LRU	Line Replaceable Unit
MoD	Ministry of Defence
MTBF	Mean Time Between Failures
NRE	Non-Recurring Engineering
OM	Obsolescence Management
OML	Obsolescence Management Level
OMP	Obsolescence Management Plan
ORM	Obsolescence Cost Metrics
ORP	Obsolescence Resolution Profiles
PBS	Product Breakdown Structure
VBA	Visual Basic for Applications

Contents

1. General Information

This maintenance manual, produced by the PSS-Cost Project team at Cranfield University, provides an understanding about the algorithms behind the M-FORCE (Materials – Framework for Obsolescence Robust Cost Estimation) tool that are used to turn the input information into a NRE cost estimation for materials obsolescence. This tool is intended to be applied at the bidding stage for support contracts, where obsolescence management has been transferred to the prime contractor. This tool has been validated to be used in the defence sector for ammunition and for air platforms, but it can potentially be applied to long-term support contracts in other platforms such as land and sea.

1.1 System Requirements

This is a MS Excel-based tool. Therefore, MS Excel 2003 or a more recent version is required for the usage of this tool. In order to run the Montecarlo simulation, it is necessary to have previously installed an add-on for MS Excel called “Crystal Ball”. Although this particular software has been applied for the development of this prototype tool, it can be replaced by any other Montecarlo-simulation software package if necessary. The algorithms used are coded in MS Excel using VBA.

1.2 Scope

The scope for the usage of this tool is the bidding stage for support contracts in the defence sector for air platforms and ammunition. This tool is intended to provide a systematic approach to estimate the cost of materials obsolescence at the bidding stage. It is flexible enough to adapt to any level of information available and provide a cost estimate accordingly. However, it is necessary to input in this tool all the relevant information available. This will increase the accuracy of the estimation.

2. Key Algorithms Used in the M-FORCE Tool

2.1 Calculation of Obsolescence Cost for Air Platform if the List of Components/Materials is Available

2.1.1 Parameters

- Obsolescence Management Level Deployed (This parameter is actually not used in the calculations as it does not have an impact on the cost estimate)
- Contract Duration
- Level of Complexity
  - Case ("High")
  - Case ("Medium")
  - Case ("Low")
- Level of Criticality
  - Case ("High")
  - Case ("Medium")
  - Case ("Low")
- Level of Integration
  - Case ("High")
  - Case ("Medium")
  - Case ("Low")
- Probability of becoming obsolete during the contracted period
  - Case ("High")
  - Case ("Medium")
  - Case ("Low")
- Obsolescence Resolution Profiles (RM)
- Calibration Reference (for the Cost Metrics)

2.1.2 Algorithm

Do for all the materials/components

```
  Select Case (Level of Complexity)
    Case ("Low")
      comp = 0
    Case ("Medium")
```

```
    comp = 9
  Case ("High")
    comp = 18
End Select

Select Case (Level of Criticality)
  Case ("Low")
    crit = 0
  Case ("Medium")
    crit = 3
  Case ("High")
    crit = 6
End Select

Select Case (Level of Integration)
  Case ("Low")
    inte = 1
  Case ("Medium")
    inte = 2
  Case ("High")
    inte = 3
End Select

Select Case (Probability of becoming obsolete during the contracted period)
  Case ("Low")
    lc = 25
  Case ("Medium")
    lc = 12.5
  Case ("High")
    lc = 5
End Select

'Low Probability = 25years life-cycle
'Medium Probability = 12.5years life-cycle
'High Probability = 5years life-cycle
```

If $\frac{ContractDuration}{lc} \geq 1$ Then $Certainty = 1$

Else

$$Certainty = \frac{ContractDuration}{lc}$$

End If

Dim RM(3) As Variant

```
For j = 0 To 3
   RM(j) = STEP4-air.Cells(j + 21, 2 + (comp / 9)).Value
Next j
```

‘ This algorithm selects the right ORP from STEP4 that will be applied for the calculation based on the Level of Complexity of the material.

Dim CM(3) As Variant

ord = comp + crit + inte

```
For j = 0 To 3
   CM(j) = STEP5-air.Cells(60 + j, 2 + ord).Value
Next j
```

‘ This algorithm selects the right Cost Metric from the Obsolescence Cost Matrix in STEP5 that will be applied for the calculation based on the Level of Complexity, Level of Criticality and Level of Integration of the material.

$$costcomp = costcomp + \sum_{j=0}^{3}[CM(j) \times RM(j)]$$

$$cost = cost + costcomp \times certainty$$

Repeat this process for all the materials.

2.2 Calculation of Obsolescence Cost for Air Platform if the List of Components/Materials is not Available

2.2.1 Parameters

- Obsolescence Management Level Deployed (This parameter is actually not used in the calculations as it does not have an impact on the cost estimate)
- Contract Duration
- Number of Components/Materials in the system for each:
  - Level of Complexity (a)
    - Case ("Low") = 1
    - Case ("Medium") = 2
    - Case ("High") = 3
  - Level of Criticality (b)
    - Case ("Low") = 1
    - Case ("Medium") = 2
    - Case ("High") = 3
  - Level of Integration (c)
    - Case ("Low") = 1
    - Case ("Medium") = 2
    - Case ("High") = 3
- Percentage of those components/materials expected to become obsolete during the contracted period
- Obsolescence Resolution Profiles
  - Low Complexity (RML)
  - Medium Complexity (RMM)
  - High Complexity (RMH)
- Calibration Reference (for the Cost Metrics)

2.2.2 Algorithm

Do for all the materials/components

```
Dim RML(3) As Variant
Dim RMM(3) As Variant
Dim RMH(3) As Variant
```

‘ This algorithm selects the right Obsolescence Resolution Profile for each level of complexity in STEP4.

```
For j = 0 To 3
   RML(j) = STEP4-air.Cells(j + 21, 2).Value
Next j

For j = 0 To 3
   RMM(j) = STEP4-air.Cells(j + 21, 3).Value
Next j

For j = 0 To 3
   RMH(j) = STEP4-air.Cells(j + 21, 4).Value
Next j
```

‘ This algorithm selects the right Cost Metric from the Obsolescence Cost Matrix in STEP5 that will be applied for the calculation based on the Level of Complexity (a), Level of Criticality (b) and Level of Integration (c) of the material.

```
‘ (a=1) (b=1)
For c = 1 To 3
     For j = 0 To 3
        CM(j) = STEP5-air.Cells(60 + j, 2 + c).Value
     Next j

costcomp = 0
```

$$costcomp = costcomp + \sum_{j=0}^{3}[CM(j) \times RML(j)]$$

$$cost = cost + costcomp \times A \times B$$

Where,

A= Number of Components/Materials in the system for which a=1 and b=1

B= Percentage of Components/Materials for which a=1 and b=1 that become obsolete

Next c

```
‘ (a=1) (b=2)
For c = 1 To 3

    For j = 0 To 3
      CM(j) = S5air.Cells(60 + j, 5 + c).Value
    Next j

costcomp = 0
```

$$costcomp = costcomp + \sum_{j=0}^{3}[CM(j) \times RML(j)]$$

$$cost = cost + costcomp \times A \times B$$

Where,

A= Number of Components/Materials in the system for which a=1 and b=2

B= Percentage of Components/Materials for which a=1 and b=2 that become obsolete

```
Next c

 ‘ (a=1) (b=3)
For c = 1 To 3

    For j = 0 To 3
      CM(j) = S5air.Cells(60 + j, 8 + c).Value
    Next j

costcomp = 0
```

$$costcomp = costcomp + \sum_{j=0}^{3}[CM(j) \times RML(j)]$$

$$cost = cost + costcomp \times A \times B$$

Where,

A= Number of Components/Materials in the system for which a=1 and b=3

B= Percentage of Components/Materials for which a=1 and b=3 that become obsolete

Next c

‘ (a=2) (b=1)

For c = 1 To 3

```
    For j = 0 To 3
        CM(j) = S5air.Cells(60 + j, 11 + c).Value
    Next j
```

costcomp = 0

$$costcomp\ =\ costcomp + \sum_{j=0}^{3}[CM(j) \times RMM(j)]$$

$$cost\ = cost\ +\ costcomp \times A \times B$$

Where,

A= Number of Components/Materials in the system for which a=2 and b=1

B= Percentage of Components/Materials for which a=2 and b=1 that become obsolete

Next c

‘ (a=2) (b=2)

For c = 1 To 3

```
    For j = 0 To 3
        CM(j) = S5air.Cells(60 + j, 14 + c).Value
    Next j
```

costcomp = 0

$$costcomp = costcomp + \sum_{j=0}^{3}[CM(j) \times RMM(j)]$$

$$cost = cost + costcomp \times A \times B$$

Where,

A= Number of Components/Materials in the system for which a=2 and b=2

B= Percentage of Components/Materials for which a=2 and b=2 that become obsolete

```
Next c

 ' (a=2) (b=3)
For c = 1 To 3

    For j = 0 To 3
      CM(j) = S5air.Cells(60 + j, 17 + c).Value
    Next j

  costcomp = 0
```

$$costcomp = costcomp + \sum_{j=0}^{3}[CM(j) \times RMM(j)]$$

$$cost = cost + costcomp \times A \times B$$

Where,

A= Number of Components/Materials in the system for which a=2 and b=3

B= Percentage of Components/Materials for which a=2 and b=3 that become obsolete

```
Next c

 ' (a=3) (b=1)
For c = 1 To 3

    For j = 0 To 3
```

```
        CM(j) = S5air.Cells(60 + j, 20 + c).Value
    Next j

      costcomp = 0
```

$$costcomp = costcomp + \sum_{j=0}^{3} [CM(j) \times RMH(j)]$$

$$cost = cost + costcomp \times A \times B$$

Where,

A= Number of Components/Materials in the system for which a=3 and b=1

B= Percentage of Components/Materials for which a=3 and b=1 that become obsolete

```
Next c

 ' (a=3) (b=2)
For c = 1 To 3

    For j = 0 To 3
        CM(j) = S5air.Cells(60 + j, 23 + i).Value
    Next j

  costcomp = 0
```

$$costcomp = costcomp + \sum_{j=0}^{3} [CM(j) \times RMH(j)]$$

$$cost = cost + costcomp \times A \times B$$

Where,

A= Number of Components/Materials in the system for which a=3 and b=2

B= Percentage of Components/Materials for which a=3 and b=2 that become obsolete

```
Next c
```

```
  ‘ (a=3) (b=3)
For c = 1 To 3

    For j = 0 To 3
       CM(j) = S5air.Cells(60 + j, 26 + i).Value
    Next j

   costcomp = 0
```

$$costcomp = costcomp + \sum_{j=0}^{3}[CM(j) \times RMH(j)]$$

$$cost = cost + costcomp \times A \times B$$

Where,

A= Number of Components/Materials in the system for which a=3 and b=3

B= Percentage of Components/Materials for which a=3 and b=3 that become obsolete

```
Next c
```

2.3 Calculation of Obsolescence Cost for Ammunition

2.3.1 Parameters

- Type of Platform
  - Large Calibre Ammunition (Artillery, Tank, Mortar)
  - Medium Calibre Ammunition (20-40mm)
  - Small Calibre Ammunition (5.5-7.62mm)
- Obsolescence Management Level Deployed (This parameter is actually not used in the calculations as it does not have an impact on the cost estimate)
- Contract Duration
- Life Cycle of Materials
  - Long LifeCycle (Metallic, Non Metallic parts, Energetic Components)
  - Medium LifeCycle (Energetic Materials)
  - Short LifeCycle (Other)
- Regularity of Manufacture
  - regular manufacture (within 1 year)
  - irregular manufacture (every 2 years)
  - very irregular manufacture (3 years or more)
- Type of Material
  - Metallic (Shell bodies; Containers) -- met
  - Energetic Materials (Propellants; Explosives) -- enm
  - Non Metallic parts (Cotton bags; Plastics) -- nmet
  - Other (Adhesives; Paints; Lacquers; Chemicals) -- oth
  - Energetic Components (Fuzes; Primers; Detonators) -- enc
- Cost Metrics and Probability Database

2.3.2 Algorithm

```
Set S2ammo = Worksheets("System-Platform ammo")
Set S3Aammo = Worksheets("Components-BoM-ammunition")
Set S3Bammo = Worksheets("Components-No BoM ammo")
Set S45ammo = Worksheets("Database-ammunition")
Set ResultAmmo = Worksheets("Cost Estimation ammo")

Select Case (S2ammo.Cells(14, 2).Value)
  Case ("Large Calibre Ammunition (Artillery, Tank, Mortar)")
    Plat = 1
    first = Application.Match("Large Calibre Ammunition", S45ammo.Range("B4:B103"), 0)
    last = Application.Match("Large Calibre Ammunition", S45ammo.Range("B4:B103"), 1)
```

```
  Case ("Medium Calibre Ammunition (20-40mm)")
    Plat = 2
    first = Application.Match("Medium Calibre Ammunition", S45ammo.Range("B4:B103"), 0)
    last = Application.Match("Medium Calibre Ammunition", S45ammo.Range("B4:B103"), 1)
  Case ("Small Calibre Ammunition (5.5-7.62mm)")
    Plat = 3
    first = Application.Match("Small Calibre Ammunition", S45ammo.Range("B4:B103"), 0)
    last = Application.Match("Small Calibre Ammunition", S45ammo.Range("B4:B103"), 1)
End Select

If list of materials/components is available then

i = 1
met = 0
nmet = 0
enc = 0
enm = 0
oth = 0
'Initialise all the counters of types of materials.

Do for all the materials listed in STEP3A (for i=1 to last material)

    Select Case (Type of Material)
      Case ("Metallic (Shell bodies; Containers)")
        met = met + 1
      Case ("Non Metallic parts (Cotton bags; Plastics)")
        nmet = nmet + 1
      Case ("Energetic Components (Fuzes; Primers; Detonators)")
        enc = enc + 1
      Case ("Energetic Materials (Propellants; Explosives)")
        enm = enm + 1
      Case ("Other (Adhesives; Paints; Lacquers; Chemicals)")
        oth = oth + 1
    End Select
```

i = i + 1
Loop

else
‘If list of materials/components is not available then

met = STEP3B-ammo.Cells(14, 2).Value
nmet = STEP3B-ammo.Cells(15, 2).Value
enc = STEP3B-ammo.Cells(16, 2).Value
enm = STEP3B-ammo.Cells(17, 2).Value
oth = STEP3B-ammo.Cells(18, 2).Value

EndIf

' Long LifeCycle = Low probability obsolescence (Metallic, Non Metallic parts, Energetic Components)
lcLow = Long LifeCycle

If $\frac{ContractDuration}{lcLow} \geq 1$ Then $CertaintyL = 1$

Else
$$CertaintyL = \frac{ContractDuration}{lcLow}$$
End If

' Medium LifeCycle = Medium probability obsolescence (Energetic Materials)
lcMed = Medium LifeCycle

If $\frac{ContractDuration}{lcMed} \geq 1$ Then $CertaintyM = 1$

Else
$$CertaintyM = \frac{ContractDuration}{lcMed}$$

End If

' Short LifeCycle = High probability obsolescence (Other)
lcHigh = Short LifeCycle

If $\frac{ContractDuration}{lcHigh} \geq 1$ Then $CertaintyH = 1$

Else

$$CertaintyH = \frac{ContractDuration}{lcHigh}$$

End If

For i = first To last
mat = Application.VLookup(i, S45ammo.Range("A1:I103"), 3, False)

Select Case (mat)
Case ("Metallic (Shell bodies; Containers)")
Cmet = Cmet + Application.VLookup(i, S45ammo.Range("A1:I103"), 8, False) * Application.WorksheetFunction.VLookup(i, S45ammo.Range("A1:I103"), 9, False)
Case ("Non Metallic parts (Cotton bags; Plastics)")
Cnmet = Cnmet + Application.VLookup(i, S45ammo.Range("A1:I103"), 8, False) * Application.WorksheetFunction.VLookup(i, S45ammo.Range("A1:I103"), 9, False)
Case ("Energetic Components (Fuzes; Primers; Detonators)")
Cenc = Cenc + Application.VLookup(i, S45ammo.Range("A1:I103"), 8, False) * Application.WorksheetFunction.VLookup(i, S45ammo.Range("A1:I103"), 9, False)
Case ("Energetic Materials (Propellants; Explosives)")
Cenm = Cenm + Application.VLookup(i, S45ammo.Range("A1:I103"), 8, False) * Application.WorksheetFunction.VLookup(i, S45ammo.Range("A1:I103"), 9, False)
Case ("Other (Adhesives; Paints; Lacquers; Chemicals)")
Coth = Coth + Application.VLookup(i, S45ammo.Range("A1:I103"), 8, False) * Application.WorksheetFunction.VLookup(i, S45ammo.Range("A1:I103"), 9, False)

```
  End Select

Next i
```

$$cost1 = Cmet \times met \times certaintyL + Cnmet \times nmet \times certaintyL + Cenc \times enc \times certaintyL + Cenm \times enm \times certaintyM + Coth \times oth \times certaintyH$$

```
  Select Case (Regularity of Manufacture)
    Case ("regular manufacture (within 1 year)")
      regman = 0.2
    Case ("irregular manufacture (every 2 years)")
      regman = 1
    Case ("very irregular manufacture (3 years or more)")
      regman = 2
  End Select

cost = cost1 * regman
```

3. Source Code of the EEE-FORCE Tool

3.1 Sub Procedure 1: Calculate Obsolescence Cost for Air Platform

```
Public Sub calcObs()

'1)

Set S2air = Worksheets("System-Platform air")
Set S3Aair = Worksheets("Components-BoM-air")
Set S3Bair = Worksheets("Components-No BoM air")
Set S4air = Worksheets("Obs Resolution Profiles")
Set S5air = Worksheets("Air Matrix")
Set ResultAir = Worksheets("Cost Estimation air")

cost = 0

'S2

OMair = S2air.Cells(17, 3).Value
ContractDuration = S2air.Cells(22, 2).Value

If (S2air.Cells(12, 1).Value = 1) Then
   GoTo 10
ElseIf (S2air.Cells(12, 1).Value = 2) Then
   GoTo 20
Else
   MsgBox "Please input the data required in Step 3"
   GoTo 30
End If

'S3A
10:
```

```
i = 1
Do Until IsEmpty(S3Aair.Cells(i + 16, 2))

    Select Case (S3Aair.Cells(i + 16, 3).Value)
      Case ("Low")
        comp = 0
      Case ("Medium")
        comp = 9
      Case ("High")
        comp = 18
    End Select

    Select Case (S3Aair.Cells(i + 16, 4).Value)
      Case ("Low")
        crit = 0
      Case ("Medium")
        crit = 3
      Case ("High")
        crit = 6
    End Select

    Select Case (S3Aair.Cells(i + 16, 5).Value)
      Case ("Low")
        inte = 1
      Case ("Medium")
        inte = 2
      Case ("High")
        inte = 3
    End Select

    Select Case (S3Aair.Cells(i + 16, 6).Value)
      Case ("Low")
        lc = 25
      Case ("Medium")
```

```
      lc = 12.5
    Case ("High")
      lc = 5
  End Select

'Low prob = 25years life-cycle
'Medium prob = 12.5years life-cycle
'High prob = 5years life-cycle

If (ContractDuration / lc) >= 1 Then
  certainty = 1
Else
  certainty = (ContractDuration / lc)
End If

'4)Obs Resolution Profiles
 Dim RM(3) As Variant

        For j = 0 To 3
            RM(j) = S4air.Cells(j + 21, 2 + (comp / 9)).Value
        Next j

'5)Cost metrics
 Dim CM(3) As Variant

 ord = comp + crit + inte

       For j = 0 To 3
           CM(j) = S5air.Cells(60 + j, 2 + ord).Value
       Next j

 costcomp = 0
 For j = 0 To 3
   costcomp = costcomp + (CM(j) * RM(j))
 Next j
```

```
 cost = cost + costcomp * certainty

i = i + 1
   Loop

GoTo 30

'S3B
20:

 '4)Obs Resolution Profiles

   Dim RML(3) As Variant
   Dim RMM(3) As Variant
   Dim RMH(3) As Variant

      For j = 0 To 3
         RML(j) = S4air.Cells(j + 21, 2).Value
      Next j

      For j = 0 To 3
         RMM(j) = S4air.Cells(j + 21, 3).Value
      Next j

      For j = 0 To 3
         RMH(j) = S4air.Cells(j + 21, 4).Value
      Next j

  '5)Cost metrics

   For i = 1 To 3
     For j = 0 To 3
        CM(j) = S5air.Cells(60 + j, 2 + i).Value
     Next j
```

```
  costcomp = 0
     For j = 0 To 3
     costcomp = costcomp + (CM(j) * RML(j))
     Next j

  cost = cost + costcomp * S3Bair.Cells(17 + i, 3).Value * S3Bair.Cells(17 + i, 4).Value

 Next i

 For i = 4 To 6
   For j = 0 To 3
      CM(j) = S5air.Cells(60 + j, 2 + i).Value
   Next j

  costcomp = 0
     For j = 0 To 3
     costcomp = costcomp + (CM(j) * RML(j))
     Next j

  cost = cost + costcomp * S3Bair.Cells(25 + i, 3).Value * S3Bair.Cells(25 + i, 4).Value

 Next i

For i = 7 To 9
   For j = 0 To 3
      CM(j) = S5air.Cells(60 + j, 2 + i).Value
   Next j

  costcomp = 0
     For j = 0 To 3
     costcomp = costcomp + (CM(j) * RML(j))
     Next j

  cost = cost + costcomp * S3Bair.Cells(33 + i, 3).Value * S3Bair.Cells(33 + i, 4).Value
```

```
 Next i

For i = 10 To 12
    For j = 0 To 3
        CM(j) = S5air.Cells(60 + j, 2 + i).Value
    Next j

  costcomp = 0
      For j = 0 To 3
      costcomp = costcomp + (CM(j) * RMM(j))
      Next j

  cost = cost + costcomp * S3Bair.Cells(11 + i, 3).Value * S3Bair.Cells(11 + i, 4).Value

 Next i

For i = 13 To 15
    For j = 0 To 3
        CM(j) = S5air.Cells(60 + j, 2 + i).Value
    Next j

  costcomp = 0
      For j = 0 To 3
      costcomp = costcomp + (CM(j) * RMM(j))
      Next j

  cost = cost + costcomp * S3Bair.Cells(19 + i, 3).Value * S3Bair.Cells(19 + i, 4).Value

 Next i

For i = 16 To 18
    For j = 0 To 3
        CM(j) = S5air.Cells(60 + j, 2 + i).Value
    Next j
```

```
  costcomp = 0
    For j = 0 To 3
    costcomp = costcomp + (CM(j) * RMM(j))
    Next j

  cost = cost + costcomp * S3Bair.Cells(27 + i, 3).Value * S3Bair.Cells(27 + i, 4).Value

 Next i

For i = 19 To 21
   For j = 0 To 3
      CM(j) = S5air.Cells(60 + j, 2 + i).Value
   Next j

  costcomp = 0
    For j = 0 To 3
    costcomp = costcomp + (CM(j) * RMH(j))
    Next j

  cost = cost + costcomp * S3Bair.Cells(5 + i, 3).Value * S3Bair.Cells(5 + i, 4).Value

 Next i



For i = 22 To 24
   For j = 0 To 3
      CM(j) = S5air.Cells(60 + j, 2 + i).Value
   Next j

  costcomp = 0
    For j = 0 To 3
    costcomp = costcomp + (CM(j) * RMH(j))
    Next j
```

```
    cost = cost + costcomp * S3Bair.Cells(13 + i, 3).Value * S3Bair.Cells(13 + i, 4).Value

   Next i

  For i = 25 To 27
     For j = 0 To 3
        CM(j) = S5air.Cells(60 + j, 2 + i).Value
     Next j

    costcomp = 0
       For j = 0 To 3
       costcomp = costcomp + (CM(j) * RMH(j))
       Next j

    cost = cost + costcomp * S3Bair.Cells(21 + i, 3).Value * S3Bair.Cells(21 + i, 4).Value

   Next i

'Total obsolescence cost
30:

ResultAir.Cells(17, 7).Value = cost
CBAfterRecalc = cost

End Sub
```

3.2 Sub Procedure 2: Calculate Obsolescence Cost for Ammunition

```
Sub calcAmmo()

' calc Macro

'1)
Set S2ammo = Worksheets("System-Platform ammo")
Set S3Aammo = Worksheets("Components-BoM-ammunition")
Set S3Bammo = Worksheets("Components-No BoM ammo")
Set S45ammo = Worksheets("Database-ammunition")
Set ResultAmmo = Worksheets("Cost Estimation ammo")

cost = 0

'S2
OMammo = S2ammo.Cells(22, 3).Value
ContractDuration = S2ammo.Cells(27, 2).Value

Select Case (S2ammo.Cells(14, 2).Value)
  Case ("Large Calibre Ammunition (Artillery, Tank, Mortar)")
    Plat = 1
    first = Application.Match("Large Calibre Ammunition", S45ammo.Range("B4:B103"), 0)
    last = Application.Match("Large Calibre Ammunition", S45ammo.Range("B4:B103"), 1)
  Case ("Medium Calibre Ammunition (20-40mm)")
    Plat = 2
    first = Application.Match("Medium Calibre Ammunition", S45ammo.Range("B4:B103"), 0)
    last = Application.Match("Medium Calibre Ammunition", S45ammo.Range("B4:B103"), 1)
  Case ("Small Calibre Ammunition (5.5-7.62mm)")
    Plat = 3
    first = Application.Match("Small Calibre Ammunition", S45ammo.Range("B4:B103"), 0)
    last = Application.Match("Small Calibre Ammunition", S45ammo.Range("B4:B103"), 1)
End Select
```

```
If (S2ammo.Cells(12, 1).Value = 1) Then
   GoTo 10
ElseIf (S2ammo.Cells(12, 1).Value = 2) Then
   GoTo 20
Else
   MsgBox "Please input the data required in Step 3"
   GoTo 30
End If

'S3A
10:
i = 1
met = 0
nmet = 0
enc = 0
enm = 0
oth = 0

Do Until IsEmpty(S3Aammo.Cells(i + 16, 2))

   Select Case (S3Aammo.Cells(i + 16, 3).Value)
     Case ("Metallic (Shell bodies; Containers)")
       met = met + 1
     Case ("Non Metallic parts (Cotton bags; Plastics)")
       nmet = nmet + 1
     Case ("Energetic Components (Fuzes; Primers; Detonators)")
       enc = enc + 1
     Case ("Energetic Materials (Propellants; Explosives)")
       enm = enm + 1
     Case ("Other (Adhesives; Paints; Lacquers; Chemicals)")
       oth = oth + 1
   End Select

i = i + 1
```

```
Loop

GoTo 25

'S3B
20:
   met = S3Bammo.Cells(14, 2).Value
   nmet = S3Bammo.Cells(15, 2).Value
   enc = S3Bammo.Cells(16, 2).Value
   enm = S3Bammo.Cells(17, 2).Value
   oth = S3Bammo.Cells(18, 2).Value



25:
If IsEmpty(S2ammo.Cells(30, 6)) Or IsEmpty(S2ammo.Cells(31, 6)) Or IsEmpty(S2ammo.Cells(32,
6)) Then
   GoTo 30
End If

'Low prob (Metallic, Non Metallic parts, Energetic Components) = 25years life-cycle
lcLow = S2ammo.Cells(30, 6).Value

If (ContractDuration / lcLow) >= 1 Then
   certaintyL = 1
Else
   certaintyL = (ContractDuration / lcLow)
End If

'Medium prob (Energetic Materials)= 12.5years life-cycle
lcMed = S2ammo.Cells(31, 6).Value

If (ContractDuration / lcMed) >= 1 Then
   certaintyM = 1
Else
   certaintyM = (ContractDuration / lcMed)
```

```
End If

'High prob (Other)= 5years life-cycle
lcHigh = S2ammo.Cells(32, 6).Value

If (ContractDuration / lcHigh) >= 1 Then
   certaintyH = 1
Else
   certaintyH = (ContractDuration / lcHigh)
End If

For i = first To last
mat = Application.VLookup(i, S45ammo.Range("A1:I103"), 3, False)

   Select Case (mat)
     Case ("Metallic (Shell bodies; Containers)")
       Cmet = Cmet + Application.VLookup(i, S45ammo.Range("A1:I103"), 8, False) * Applica-
tion.WorksheetFunction.VLookup(i, S45ammo.Range("A1:I103"), 9, False)
     Case ("Non Metallic parts (Cotton bags; Plastics)")
       Cnmet = Cnmet + Application.VLookup(i, S45ammo.Range("A1:I103"), 8, False) * Applica-
tion.WorksheetFunction.VLookup(i, S45ammo.Range("A1:I103"), 9, False)
     Case ("Energetic Components (Fuzes; Primers; Detonators)")
       Cenc = Cenc + Application.VLookup(i, S45ammo.Range("A1:I103"), 8, False) * Applica-
tion.WorksheetFunction.VLookup(i, S45ammo.Range("A1:I103"), 9, False)
     Case ("Energetic Materials (Propellants; Explosives)")
       Cenm = Cenm + Application.VLookup(i, S45ammo.Range("A1:I103"), 8, False) * Applica-
tion.WorksheetFunction.VLookup(i, S45ammo.Range("A1:I103"), 9, False)
     Case ("Other (Adhesives; Paints; Lacquers; Chemicals)")
       Coth = Coth + Application.VLookup(i, S45ammo.Range("A1:I103"), 8, False) * Applica-
tion.WorksheetFunction.VLookup(i, S45ammo.Range("A1:I103"), 9, False)
   End Select

Next i
```

```
 cost1 = Cmet * met * certaintyL + Cnmet * nmet * certaintyL + Cenc * enc * certaintyL + Cenm *
enm * certaintyM + Coth * oth * certaintyH

    Select Case (S2ammo.Cells(34, 3).Value)
      Case ("regular manufacture (within 1 year)")
        regman = 0.2
      Case ("irregular manufacture (every 2 years)")
        regman = 1
      Case ("very irregular manufacture (3 years or more)")
        regman = 2
    End Select

cost = cost1 * regman

'Total obsolescence cost

30:
ResultAmmo.Cells(17, 7).Value = cost
CBAfterRecalc = cost

End Sub
```

Disclaimer:

The content of this manual is based on the features and content of the M-FORCE tool developed as a deliverable of the PSS-Cost project.