

CRANFIELD UNIVERSITY

JOHN AHMET ERKOYUNCU

COST UNCERTAINTY MANAGEMENT AND MODELLING FOR  
INDUSTRIAL PRODUCT-SERVICE SYSTEMS

SCHOOL OF APPLIED SCIENCES

PhD

Academic Year: 2010 - 2011

Supervisor: Prof. Rajkumar Roy & Dr. Essam Shehab  
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## **ABSTRACT**

Globally manufacturing based industries are typically transforming operations to enhance the delivery of services throughout equipment use. Within the defence industry, Contracting for Availability (CfA) has emerged as an approach that is increasingly dominating the interaction between the customer and the manufacturers. This application serves as an example for an Industrial Product-Service System, and sets the context to this research. Predicting the delivery of services, particularly at the bidding stage, creates enhanced complexity and unpredictability in costs due to uncertainties.

Driven by this contextual challenge the aim of this research is to develop a framework for cost uncertainty management and modelling at the bidding stage of CfA in the defence industry. The thesis presents the existing literature associated to uncertainty in cost estimation, whilst the current practice is demonstrated based on interaction with seven organisations involved in the defence industry. A software prototype, Uncertainty Tool for Assessment and Simulation of Cost (U-TASC), has been developed to implement an integrated cost uncertainty management and modelling framework. The cost uncertainty management framework offers a systematic procedure at the bidding stage to guide subject matter experts to focus the attention on influential uncertainties, while also proposing suitable mitigation strategies. In contrast, the cost uncertainty modelling framework involves a step by step procedure to make use of subjective opinion collated from subject matter experts to reflect the influence of uncertainty in cost estimates.

The thesis also presents an agent based model that takes into account the influence of dynamic uncertainty (e.g. failure rate) on cost estimates over time. This is applied within a service supply network, where the interaction between the stakeholders represents a typical CfA with incentives and risk sharing scenarios.

The frameworks embedded in U-TASC are validated and verified through three case studies including, a naval radar, aircraft carrier, and naval electronic system. The outcomes indicate that reliable and useful results are generated and the tool is highly applicable. On the other hand, the framework for the agent based model is validated through expert opinion and a pilot case study in the naval domain.

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## LIST OF ACRONYMS

AACE	Association for the Advancement of Cost Engineering
ABM	Agent Based Modelling
AHP	Analytic Hierarchy Process
ATTAC	The Availability Transformation: Tornado Aircraft Contract
BER	Beyond Economical Repair
CADMID	Concept, Assessment, Demonstration, Manufacturing, In-Service, Disposal
CAPTOE	Commercial, Affordability, Performance, Training, Operation, Engineering
CBS	Cost Breakdown Structure
CfA	Contracting for Availability
CER	Cost Estimating Relationship
COTS	Commercial off the Shelf
DES	Discrete Event Simulation
DoD	Department of Defence
EACE	European Aerospace Cost Engineers (working group)
EPSRC	Engineering & Physical Sciences Research Council
EVM	Earned Value Management
GAO	USA Government Accountability Office
GFX	Government Furnished Asset
IPS <sup>2</sup>	Industrial Product-Service Systems
IPT	Integrated Project Team
ITT	Invitation to Tender
KPI	Key Performance Indicators
LCC	Life Cycle Cost
LRU	Line Replaceable Unit
MDAL	Master Data and Assumptions List
MOD	Ministry of Defence (UK)
MTBF	Mean Time Between Failure

MTTR	Mean Time to Repair
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organisation
NFF	No Fault Found
NN	Neural Networks
NRE	Non-recurring Engineering
NUSAP	Numeral, Unit, Spread, Assessment, Pedigree
OEM	Original Equipment Manufacturer
PBS	Product Breakdown Structure
PFI	Private Finance Initiative
PLC	Product Life Cycle
PSS	Product-Service Systems
PV	Present Value
RAF	Royal Air Force
RFQ	Request for Quotation
SCAF	Society of Costs Analyses and Forecasting
SCEA	The Society of Cost Estimating & Analysis
SD	Systems Dynamic
SWOT	Strength, Weakness, Opportunity, Threat
TEPIDOIL	Training, Equipment, Personnel, Information, Doctrine, Concept, Organisation, Infrastructure, Logistics
TPPI	Target Price Performance Incentive
U-TASC	Uncertainty Tool for Assessment and Simulation of Cost
WBS	Work Breakdown Structure
WLCC	Whole Life Cycle Cost

# 1 INTRODUCTION

The business model in the manufacturing industry is mostly experiencing a shift from selling products to delivering services. In the defence industry in the United Kingdom this has generally been achieved by Contracting for Availability (CfA). Various alternative terms have also been used for CfA including Performance Based Logistics. These involve a commercial process which seek to sustain an equipment/system/part at an agreed level of readiness, over a period of time (e.g. equipment operational life, 30 to 40 years), by building a partnering arrangement. The likes of Type 45 and Harrier provided by BAE Systems and Power by the Hour, or Total Care provided by Rolls Royce have commonly been cited as examples. The Availability Transformation: Tornado Aircraft Contract (ATTAC) program provided by BAE Systems offers an example of CfA. The contract with the MoD focuses on improving the availability of the Tornado fleet for frontline operations, while considerably reducing the cost of fleet maintenance (BAE Systems, 2010a). This partnership between industry and the customer enables an affordable solution as for instance costs are reduced particularly due to lesser failures, while saving the United Kingdom Ministry of Defence (UK MoD) some £500 million over an initial ten years (BAE Systems, 2008). This has promoted industry to grow its readiness and sustainment capabilities in partnership with the customer.

In this chapter the key concepts related to this research including uncertainty, cost estimation, bidding, CfA, Product-Service System (PSS), Industrial Product-Service System (IPS<sup>2</sup>), service, cost uncertainty modelling and cost uncertainty management are introduced. The chapter also presents the research scope of the parent project called 'PSS-Cost', the research context and the thesis layout.

## 1.1 Industrial Product-Service Systems

Integrating products and services have recently been suggested to be a strategy that offers enhanced profits and environmental sustainability over the long term for manufacturing based companies, which have traditionally focused on solely selling

products (Meier et al., 2010; Oliva and Kallenberg, 2003; Vargo and Lusch, 2008). The approach has been referred to as a PSS, where the goal is to deliver value to the customer through enhanced sharing of responsibilities over the long run (Roy and Cheruvu, 2009; Baines et al., 2007). IPS<sup>2</sup> is a sub-category of PSS, where the focus is on business to business interactions involving a product core with high monetary value (Meier et al., 2010). Across manufacturing based industries, while the contribution of services to revenues has typically been growing, the traditional distinction between manufacturers and service providers is increasingly becoming fuzzy.

The concept of IPS<sup>2</sup> offers a large opportunity to transform the traditional approach of selling equipment and independently providing services. Manufacturers can benefit from their traditional strength of product development, while adapting into the new business world that values individualistic benefits (Oliva and Kallenberg, 2003; Wise and Baumgartner, 1999). There are three business models in PSS including product, use and result oriented, whereby the transformation from a traditional business model varies across each one of these (Cook et al., 2006; Tukker, 2004). The product oriented model operates on the pay on order principle. Payment in the use oriented model concentrates on the delivered availability level (e.g. CfA), whilst promoting enhanced interaction across the supply chain as typically a large proportion of parts or support is brought in by the solution provider (Kim et al., 2006). In the result oriented model the payment is based on delivered capability. Across IPS<sup>2</sup> business models, the level of responsibility varies across the supply network (Aurich et al., 2006; Azarenko et al., 2009). The focus within this thesis is on the use-oriented model, whilst the experienced uncertainties can vary across the business models (Sakao et al., 2009).

In the defence industry in the UK, a standard definition of the life cycle has been established since 1999 with the Concept, Assessment, Demonstration, Manufacture, In-service, Disposal cycle (CADMID) (Smart Acquisition, 2007a). An illustration of the CADMID cycle is provided in Figure 1.1. Furthermore, the key stakeholders across the supply network include the customer, solution provider/ Original Equipment Manufacturer and the supplier. It is recognised that co-creation of value is triggering further collaboration between the customer and the solution provider (Prahalad and

Ramaswamy, 2004). This, refers to the collaborated nature of processes across the supply network to achieve value delivery.

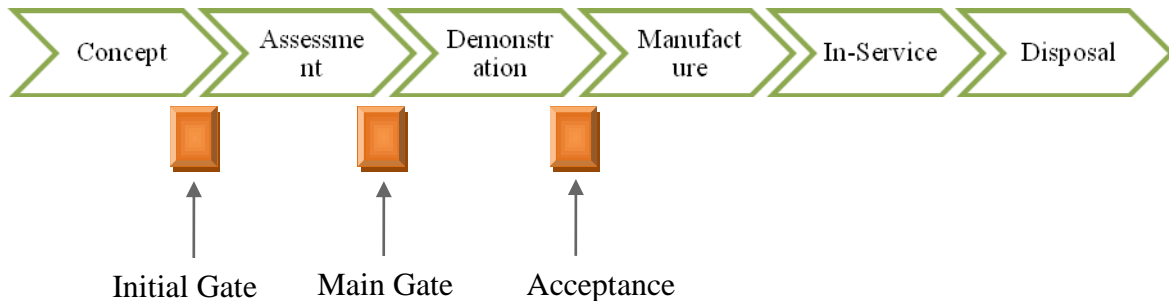


Figure 1.1 CADMID cycle

### 1.1.1 Emerging challenges with Contracting for Availability

CfA type agreements challenge the industry to consider not just the sale of equipment, but also its utilisation, which necessitates a life cycle view of the equipment. In CfA the shift in the business model is associated to the shift in the level of the service content, where service tends to be considered as processes and is experienced, created or participated in, while its production and consumption are simultaneous (Lovelock, 1983). The challenges that arise with the service orientation can be classified in to four areas including (Shehab and Roy, 2006):

- Firstly, the *supply chain challenge* is mainly associated to maintaining the desired level of performance to meet the service requirements, whilst considering the supply chain (Ward and Graves, 2005; Kim et al., 2006)
- Secondly, the *socio-ecological challenge* considers the implications of adopting CfA from two dimensions (Aurich et al., 2006): society (e.g. knowledge intensive jobs) and ecology (e.g. environmental load)
- Thirdly, the *business challenge* arises under CfA arrangements as the mean time to repair (MTTR) or other performance criterion is made the essence of the contract (Erkoyuncu et al., 2009b). At the time of bidding, the supplier typically offers a fixed price to the customer whilst assuming responsibility for estimating the cumulative number of transactions needed to sustain the MTTR. The

affordability of the customer, profitability of the solution provider and sustainability of the supplier are major challenges that are experienced in CfA

- Finally, the *technical challenge*, involves cost estimation and designing the IPS<sup>2</sup> solution. The design of an IPS<sup>2</sup> needs to take into account interrelations between physical products and non-physical services, proactively, in order to meet the life cycle expectations of the customer (Westkamper et al., 2001). In contrast, the cost challenge is due to the increased complexity and unpredictability, deriving from uncertainties in the provision of services (Datta and Roy, 2009).

Each of these challenges has a different influence over the IPS<sup>2</sup> delivery, while this research focuses on the influence of uncertainty in cost estimation in CfA. Uncertainty is the main source of the cost challenge as it undermines the ability to forecast.

### **1.1.2 Uncertainty and cost estimation in Contracting for Availability**

The aim of cost estimation is to forecast the future expenditures whether it be for development, production, service, or disposal of equipment (Arena et al., 2006). The predicted results represent the opinion concerning the possible or likely outcome and are not necessarily the actual outcome, due to the degree of uncertainty that influences the cost estimation. With the adoption of CfA the importance of understanding the influence of uncertainty has grown due to the long term nature of the contracts that distribute high financial responsibilities along the supply network. The bidding stage is a particularly important process as the commitments are established with limited information available and prevailing uncertainty. Uncertainty describes the variability inherent in an estimate, due to the range of expected outcomes. On the other hand, risk is considered to be a sub-category of uncertainty. There are two major drivers of uncertainties in CfA (Erkoyuncu et al., 2009a). Firstly, additional uncertainties derive from transferred responsibilities (e.g. equipment usage rate, failure rates, repair turnaround time, beyond economical repair, no fault found rate, obsolescence rate and labour efficiency). Secondly, CfA demands a left shift in the point-in-time at which some uncertainties that arise from predicting the 30-40 year duration of a CfA are addressed.

The sales value of each transaction with respect to costs incurred, which may be negotiated case-by-case, determines the supplier's profitability. Furthermore, at the bidding stage the solution provider must accept the uncertainty associated to the number of transactions (e.g. spares delivery) necessary, whilst the scenario of cost increase may hinder profitability. Such estimates need to anticipate a range of contributory technical, commercial, financial, and behavioural risks and uncertainties that are exacerbated because of the need to look-ahead over the long term. Thus, the accuracy of the cost estimates has a huge influence on the delivery of CfA due to the profitability to industry and affordability for the customer. The following section presents the research context.

## **1.2 Research Context**

The in-service phase of the CADMID cycle sets the context of this research whereby the focus is on the influence of uncertainty on cost at the bidding stage of CfA in the defence industry. In essence, when the solution provider takes decisions such as whether to bid for a contract or accept one when offered, they need to do so based on an understanding of uncertainty in cost for the duration of service delivery. This necessitates better prediction of uncertainty for CfA than has been typical of traditional contracts in the past because the contract timescales are much longer, and ownership of uncertainty has been transferred from customer to the solution provider - typically on a fixed-cost basis. Furthermore, considering that at the bidding stage driven by cost estimates major agreements with large financial burden are agreed, there is a need to apply rigorous steps to take account of the influence of uncertainty on cost. The following section presents the problem statement and motivation for the research.

## **1.3 Problem Statement and Motivation**

The CfA context offers a larger set of uncertainties that industry needs to manage, due to the enhanced scope and complexity of the service solution targeted. Some of the areas to consider include assessing the performance and the requirements of the service delivery, and enhanced dependence on external sources. Driven by these aspects the delivery of service is less understood at the early stages compared to the traditional

model, due to the increase in the experienced uncertainties. The shift in the uncertainties has a number of implications, which this study has focused on. From literature review it has been recognised that there is a divide between the service, CfA and IPS<sup>2</sup> domains and cost estimation in particular from the perspective of understanding the role of uncertainty in CfA. An important motivation of this research relates to its ambition to combine these two areas, which have not traditionally come together. Furthermore, from an industrial perspective there is not a standard approach to consider uncertainty in cost estimation, while integration of uncertainty to cost follows a highly subjective procedure. This is associated with the lack of experience/data in estimating, for instance, the rate of equipment reliability, obsolescence, assessing emergent work, lead time, quality of response, and labour availability in service delivery. Efficient consideration of uncertainty in cost is essential in order that CfA can be successfully delivered in the future. The evidence from both literature review and industrial interaction is that uncertainty is driven by both the lack of information and poor timeliness in its availability and requires adequate approaches that supports with decision making. Thus, the aim for this research is:

To develop a framework for cost uncertainty management and modelling at the bidding stage of Contracting for Availability in the defence industry

Expected growth in CfA further enhances the importance of better handling uncertainty in the in-service phase for cost estimation. The research presented in this thesis aims to support in agreeing reliable contracts based enhanced confidence in cost estimates and targets to support project managers, cost estimators, uncertainty modellers, and uncertainty management experts. The research contributes to knowledge in four major areas:

- Understanding the shifts (e.g. emergent and transformed) in uncertainties in CfA
- Systematic framework to manage cost uncertainties within the CfA context
- Systematic framework to model cost uncertainty within the CfA context using Monte Carlo Simulation



- Driven by the relatively more dynamic nature of uncertainties in CfA, application of a novel approach through agent based modelling to visualise the cost implications along the supply network with incentives and risk sharing

The following section presents the parent project of the research, which is called ‘PSS-Cost’ (Whole Life Cost Modelling for Product-Service Systems) in order to further illustrate the context of the research.

## **1.4 Parent Project of the Research: “PSS-Cost”**

The main industrial collaborators of the research have been BAE Systems, GE Aviation, Lockheed Martin, Ministry of Defence (MoD) and Rolls Royce. Additional partners of the project were Galorath, Cognition, the Association of Project Management Professionals and the Society of British Aerospace Companies. The research is part of the work conducted by the ‘PSS-Cost’ project, which was carried out between October 2007 and October 2010. The research has been funded by the Engineering & Physical Sciences Research Council (EPSRC) and it has been supervised by Prof. Rajkumar Roy and Dr. Essam Shehab. The industrial interaction was led by the project manager Dr. Kalyan Cheruvu, who also worked on specifying the contractual guidelines for CfA agreements. Fellow researchers of the ‘PSS-Cost’ project were Francisco Romero Rojo and Oyetola Bankole, whom focused on the obsolescence and affordability research domains, respectively. The project also gained a satellite project in design rework cost estimation, which was participated by Panumas Arundachawat. The initial interaction with industrial collaborators was carried out in alliance with fellow colleagues, whilst the author conducted the analysis for uncertainty separately.

### **1.4.1 ‘PSS-Cost’ project aim**

The ‘PSS-Cost’ project aims to improve understanding and knowledge in predicting costs for CfA at the bidding stage within the defence industry. The project also aims to integrate the cost estimating framework with an approach to assess the customers’

affordability level. The presented research in this thesis is carried out solely by the author and represents his contribution to the uncertainty domain of the project.

### **1.4.2 Research approach**

The research process was classified in to four phases as explained in Chapter 3. The first phase focused on “Understanding context”, where the researcher conducted a detailed literature review and defined the research approach. As a result of this phase the author gathered an understanding of the existing literature and identified the research gaps. In the second phase, “Developing research protocol”, industrial interaction took place by means of semi-structured interviews and a case study approach was applied. As a result of this phase, the researcher acquired an understanding of the research context and a means to offer solutions was defined to some of the existing challenges in considering uncertainty in cost. In the third phase, “Framework and tool development” was conducted, which involved a case study, workshops, semi-structured interviews, and initial validation. As a result of this phase the researcher developed an integrated framework, embedded in an MS Excel Software prototype tool, to manage and model the influence of uncertainty on cost. Within this phase the researcher also developed an agent based model in AnyLogic 6.5, which focuses on visualising the dynamic nature of cost across the supply network. The final phase of the research process concentrated on the validation of the framework, which involved three case studies and the agent based model was validated using expert opinion and a pilot case study. As a result of this phase adjustments and improvements to the framework and the agent based model were made. The following section presents the industrial collaborators of the research.

## **1.5 Industrial Collaborators**

### ***BAE Systems***

BAE Systems is the second largest global defence, security and aerospace company based on 2009 revenues with approximately 107,000 employees worldwide. Their range of products and services accounts for air, land and naval forces, as well as advanced electronics, security, information technology solutions and customer support services.

The company focuses on seven key markets including Australia, India, Saudi Arabia, South Africa, Sweden, UK and the US, through four operating groups Electronics, Intelligence and Support, Land and Armaments, Programmes and Support, International. BAE Systems have developed products and services in the following areas (BAE Systems website, 2010b):

- Land, Air and Sea
- Systems Integration and Electronics
- Through-life support
- Engineering and Manufacturing
- Technology and Innovation
- Homeland security
- Information Technology
- Intelligence security and Resilience

The company has embarked on a number of CfA projects, where the researcher has had the opportunity to understand the applications in the air and land domains. Currently, some of the key CfA projects that BAE Systems is involved in are ATTAC, Type 45 destroyer, the Type 26 combat ship program and the CVF Queen Elisabeth class future aircraft carriers. Over the years the company has gradually enhanced its focus on CfA, whilst availability is offered in many forms, including: transactional, component, material, operational, fleet and force availability. The Programmes and Support operating group leads the delivery of CfA, and primarily focuses on air, naval and security activities. The author interacted with the Insyte branch of BAE Systems. The main objective of this division is in delivering world class Mission systems and Information management to naval, joint, air and land sectors.

### ***Rolls-Royce***

The focus of Rolls-Royce Plc is to globally provide power systems for use on land, at sea and in the air. The company has classified its operations in to five domains including civil and defence aerospace, marine, nuclear, energy and services. More recently the contribution of services to total revenue has exceeded the 50% mark, and over the past ten years has grown 10%. Among the sources of revenue the TotalCare

support package managed to contribute around 57% of the civil aerospace fleet, including more than 8000 engines and auxiliary power units are covered by in-service monitoring, global repair services have been created, and the capability of global operation centres was expanded, including satellite sites with two major customers. There are a range of services that Rolls-Royce provides including field services, the sale of spare parts, equipment overhaul services, parts' repair, data management, equipment leasing, and inventory management services (Rolls Royce, 2010). Furthermore, *TotalCare*® provides a single source solution guaranteeing "peace of mind" for the life span of the engine, commencing at the time the engine is delivered to the customer until it goes out of service aligned with an agreed cost per flying hour. The service delivery procedure has drastically been transformed, while aiming to reach the hours of engine use (Ng et al., 2009a, Ng et al., 2009b). The company focuses on attaining reliability, maintainability, supportability and processes. The revenue generated from services, along with the percentage contribution of services to total group revenue is presented in Table 1.1.

Table 1.1 Service revenue and percentages, 2004-2008 (Source: R-R website, 2010)

Key performance indicators	2008	2007	2006	2005	2004
Underlying services revenue £m	4,755	4,265	3,901	3,457	3,251
Underlying services as percentage of Group revenue	52	55	53	54	55

### ***Ministry of Defence***

The Ministry of Defence (MoD) is the defence customer in the United Kingdom government department responsible for implementation of government defence policy and is the headquarters of the British Armed Forces. The organisation employs over 80,000 civilian staff, and the annual budget for 2009/2010 was £35.165 billion. The organisation classifies its interests into air, naval and land domains. Relatively recently the organisation has led the transition into the CfA context by promoting initiatives such

the “Defence Industrial Strategy” and during the mid-1990s the “Smart Acquisition” policies (Smart Acquisition, 2007b). In common the focus is on costs and capabilities of equipment throughout its life, not just the purchase price.

### ***Lockheed Martin***

Lockheed Martin UK is part of the Lockheed Martin Corporation, which is a leader in systems integration working on major programs spanning the aerospace, defence, civil and commercial sectors. In the UK, Lockheed Martin has annual sales in the range of £400-600 million working with more than 75 business partners. Lockheed Martin Corporation employs about 130,000 people worldwide and focuses on research, design, development, manufacture and integration of advanced technology systems, products and services. Lockheed Martin's operating units are organized into broad business areas, including (Lockheed Martin, 2010):

- Aeronautics, with approximately \$12.2 billion in 2009 sales, includes tactical aircraft, airlift, and aeronautical research and development lines of business.
- Electronic Systems, with approximately \$12.2 billion in 2009 sales, includes missiles and fire control, naval systems, platform integration, simulation and training and energy programs lines of business.
- Information Systems & Global Solutions, with approximately \$12.1 billion in 2009 sales, includes federal services, government and commercial IT solutions.
- Space Systems, with approximately \$8.6 billion in 2009 sales, includes space launch, commercial satellites, government satellites, and strategic missiles lines.

The researcher interacted with the Ampthill, Bedford site known as Insys. The focus of the activities at this site centers on full vehicle integration and shelter design work as well as final vehicle assembly and testing. Compared to the other organizations, it was acknowledged that the company had a more design centric focus rather than service.

### ***GE Aviation***

GE Aviation, an operating unit of General Electric, is a world-leading provider of jet engines, components and integrated systems for commercial and military aircraft (GE Aviation, 2010). GE Aviation has a global service network to support these offerings.

The interaction took place with the Cheltenham site, which was formerly owned by Smiths Industries and was taken over by the US giant in May 2007 in a £3.5 billion deal. The site currently employs around 1000 people. The operations that Smiths was involved in continued where the business holds key positions in the supply chains of all major military and civil aircraft and engine manufacturers and is a world-leader in digital, electrical power, mechanical systems, engine components and Systems Customer Services. The company has been involved in a number of CfA, such as the Hercules Integrated Operation Support Program for C-130J/K aircraft operated by the Royal Air Force (RAF). In the contract the company is responsible for managing the availability of all GE Aviation hardware for the RAF.

### ***Additional organisations***

Apart from the pre-defined organisations, the author additionally had, to a lesser degree, interaction with additional organisations including MBDA, C.I.C Consulting and QinetiQ. MBDA specialises in missiles and missile systems and has recently advanced in provision of support oriented product provision. C.I.C Consulting focuses on delivering consultancy services for design of products within the aerospace and defence industries, where the company specialises in cost estimation. QinetiQ operates across the defence, aerospace and security markets by providing technical advice in a range of engineering related areas including cost estimation. In the following section the thesis structure is presented in order to familiarise the reader with the contents of this study.

## **1.6 Thesis Layout**

The remainder of this thesis comprise nine chapters as shown in Figure 1.2. In Chapter 2, the author presents a critical analysis of the literature within the context of this study. Broadly, the literature review aimed to draw a bridge between the service and cost uncertainty related areas. The identified research gaps from the literature review are also presented. The chapter feeds into defining the research objectives for satisfying the overall aim of the study. In Chapter 3, the research aim and the objectives are presented. Subsequently, available approaches and strategies are critically assessed in light of the requirements of the research. Consequently, the overview of the research methodology

is presented, whereby the nature of the research objectives and the available support (e.g. industrial interaction) to the researcher helped to direct the research.

In Chapter 4, based on industrial interaction (including semi-structured interviews, workshops and case studies) with seven organisations in the defence industry in the UK the current practice to manage and model cost uncertainty is presented. This also covers detailed description of the industrial interaction. In Chapter 5, based on the current practice, initially an overview of the integrated framework for cost uncertainty management and modelling is presented. This has been classified into four phases, as discussed between Chapter 5 and 8. Chapter 5 focuses on defining the types of uncertainties that are associated to CfA at the bidding stage. Additionally, the chapter also explains the emergent and transformed types of uncertainties in relation to CfA. Validation results for the considered uncertainties are also presented.

In Chapter 6, the Cost Uncertainty Management framework is presented. As a result of the numerous industrial interactions, the author proposes a novel approach to identify, prioritise and control uncertainties, based on following the step by step procedure presented. In Chapter 7, the third phase of the framework, Cost Uncertainty Modelling, is presented. As a result of the numerous interactions with industry, the author proposes a novel approach to turn single point estimates into three point estimates, which are subsequently used in Monte Carlo simulation. In Chapter 8, the fourth phase of the framework, Agent Based Simulation for Cost Uncertainty modelling, which has been developed by using a software package called AnyLogic 6.5. The chapter presents an example application of this simulation approach to represent the dynamic uncertainty across the supply network within the CfA context.

In Chapter 9, verification and validation results for the first three phases are presented. The validation involves three case studies across the naval domain in the defence industry. In Chapter 10, the research findings are discussed with a view of the generalisability and applicability of the study. Also the key research contributions are presented, and overall conclusions are made in light of fulfilling the research objectives.

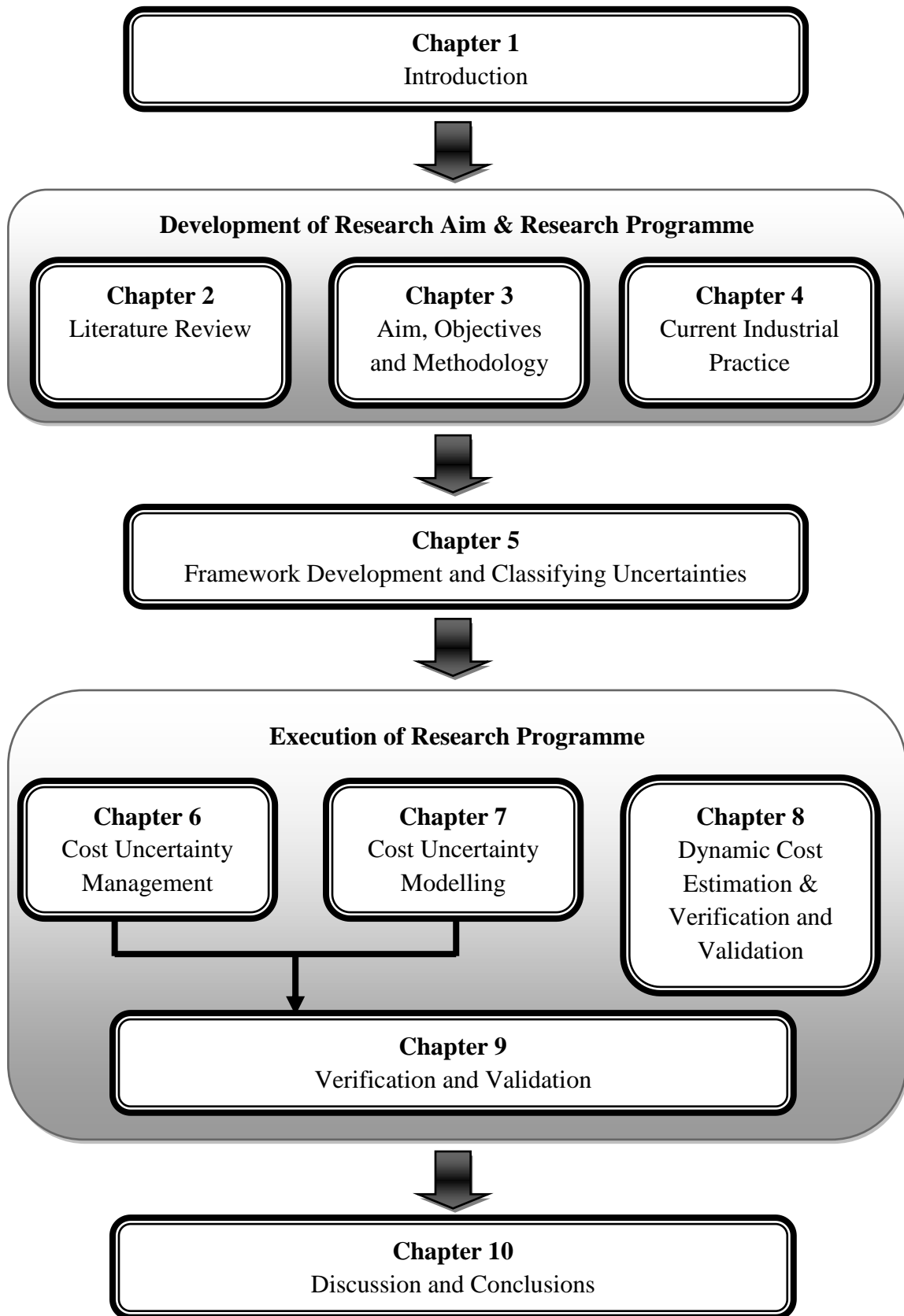


Figure 1.2 Thesis Structure



## 2 LITERATURE REVIEW

The global transition towards service orientation is posing challenges in cost estimation for manufacturers driven by the uncertainties that arise at the bidding stage of Contracting for Availability (CfA). Service uncertainty is driven by the quality of information flow and knowledge across a given service network, however it commonly suffers from the unavailability of useful data to assist cost predictions. The author identified a research gap concerning cost uncertainty for an Industrial Product-Service System (IPS<sup>2</sup>). To fill this gap, the literature review presented in this chapter combines research in IPS<sup>2</sup> and cost uncertainty in terms of its management and modelling. In Section 2.1 the relevant research in IPS<sup>2</sup> is presented, where the focus also encompasses the research in “Service”. Section 2.2 presents the understanding in uncertainty by providing definitions of the term and making comparisons with the concept of “risk”. Section 2.3 presents the service uncertainties by classifying the uncertainty based on supply and demand sources. In Section 2.4 an overview of the approaches for cost uncertainty analysis is provided. Section 2.5 concentrates on the process of integrating uncertainty to costs by covering the cost uncertainty modelling approaches. The literature in cost uncertainty management is presented in Section 2.6. Subsequently, in Section 2.7 the research gap analysis is presented.

The dominant interests within this research included service delivery systems, uncertainty, uncertainty management, cost estimation, uncertainty modelling, service and product supply chain, and PSS. Databases such as Engineering Village, Scopus, Science Direct, ProQuest, Emerald, Google Scholar, and EBSCO enabled the search for peer reviewed articles. The author selected these sources due to their high reliability and the comprehensiveness of the relevant information for the context of this research. Some of the main journals contributing to this research included Harvard Business Review (for service oriented research) and AIAA (for uncertainty in cost estimation). Along with those, Production and Operations Management, International Journal of Production Economics and Management Science were the other major contributors.

Figure 2.1 illustrates the linkages between the concepts that have been covered in this chapter. A lack of review papers that combines service delivery uncertainties and cost estimation has been identified. For this reason two groups of key words were used to cross-search papers in databases related to in-service phase uncertainties for IPS<sup>2</sup> and appropriate uncertainty modelling in cost estimation. The first group includes IPS<sup>2</sup>, service, service engineering, service delivery, marketing, product and service supply chain management, and operations management literatures. The second set of keywords contain (whole life cycle) cost estimation, uncertainty modelling including methods such as fuzzy logic, evidence theory, regression analysis, and artificial intelligence.

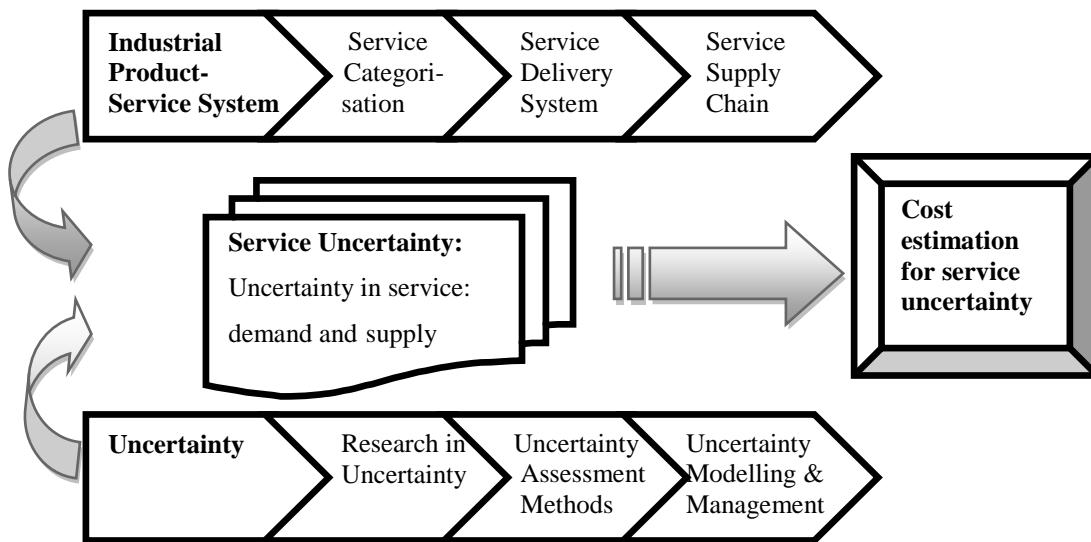


Figure 2.1 Linkage between concepts in the literature review (Erkoyuncu et al., 2010a)

## 2.1 Industrial Product-Service Systems

Recently much research has been conducted in the concept of servitization, which aims to explain the move from offering products to service solutions (Vandermerwe and Rada, 1988). The integration of products and services constitutes an important component of servitization. This has been studied under the Product-Service System (PSS) research domain, which a definition was provided by Baines et al., (2007) as “A PSS is an integrated product and service offering that delivers value in use”. In comparison to the traditional form of adding value, which was driven by the production process, today additional competitive advantage derives from value provided through

service use/function (Tukker and Tischner, 2006; Mont, 2002b). Within the PSS research domain, initial interest centred on the potential improvements in sustainability, which encapsulates economic, environmental and social aspects (Roy, 2000). Changing the product-service mix facilitates an increase in eco-efficiency, which helps to transform the present 'transactional economy' to a goal-orientated 'functional economy' (Stahel, 1997; Cooper and Evans, 2000). The aligned nature of product and service offers better communication between the consumer and the supplier (Alonso-Rasgado and Thompson, 2007; Martinez et al., 2010). This results in improved sustainability, where wastage of materials and energy is reduced (Goedkoop et al, 1999; Manzini et al., 2001). However, to conclude that PSS is solely about sustainability is just a myth, the ultimate goal of such systems is to provide the final need, demand or function to be fulfilled (Tukker and Tischner, 2006).

It is important to acknowledge the integrated nature of product, service and system in implementing PSS models (Durugbo et al., 2010). A product refers to the physical artefact that offers functional capacity to the customer. Whilst many definitions of service have been provided in literature there has not yet been an agreement over the use of a common description. Kotler (1982) defines service as any activity or benefit that one party can offer to another that is essentially intangible and does not result in the ownership of anything. A system refers to the interacting processes that enable the functioning of the equipment at the capacity that the customer requires (Mont, 2002a).

IPS<sup>2</sup>, also referred to as technical-PSS, is a specific case of PSS, which focuses on provision of services for a product core that has a high net value and involves transactions in a B2B context (Aurich et al., 2006). IPS<sup>2</sup> delivery has progressively increased in scale and complexity. Examples range from the humble photo-copier through to major infrastructure projects (e.g. Private Finance Initiative -PFI- hospitals) and large defence projects (e.g. complete sea, air or land platforms) (Alonso-Rasgado et al., 2004). IPS<sup>2</sup> offerings have generated interest in the defence industry typically through CfA because of (1) pressure in national defence budgets in most countries including the UK, (2) the UK defence customer's ambition to transfer financial uncertainty from itself to industry, and (3) UK industry's ambition to grow its share of

the diminishing defence budget in terms increased span across both the lifecycle (e.g. CADMID<sup>1</sup>) and defence lines of development (e.g. TEPIDOIL<sup>2</sup>).

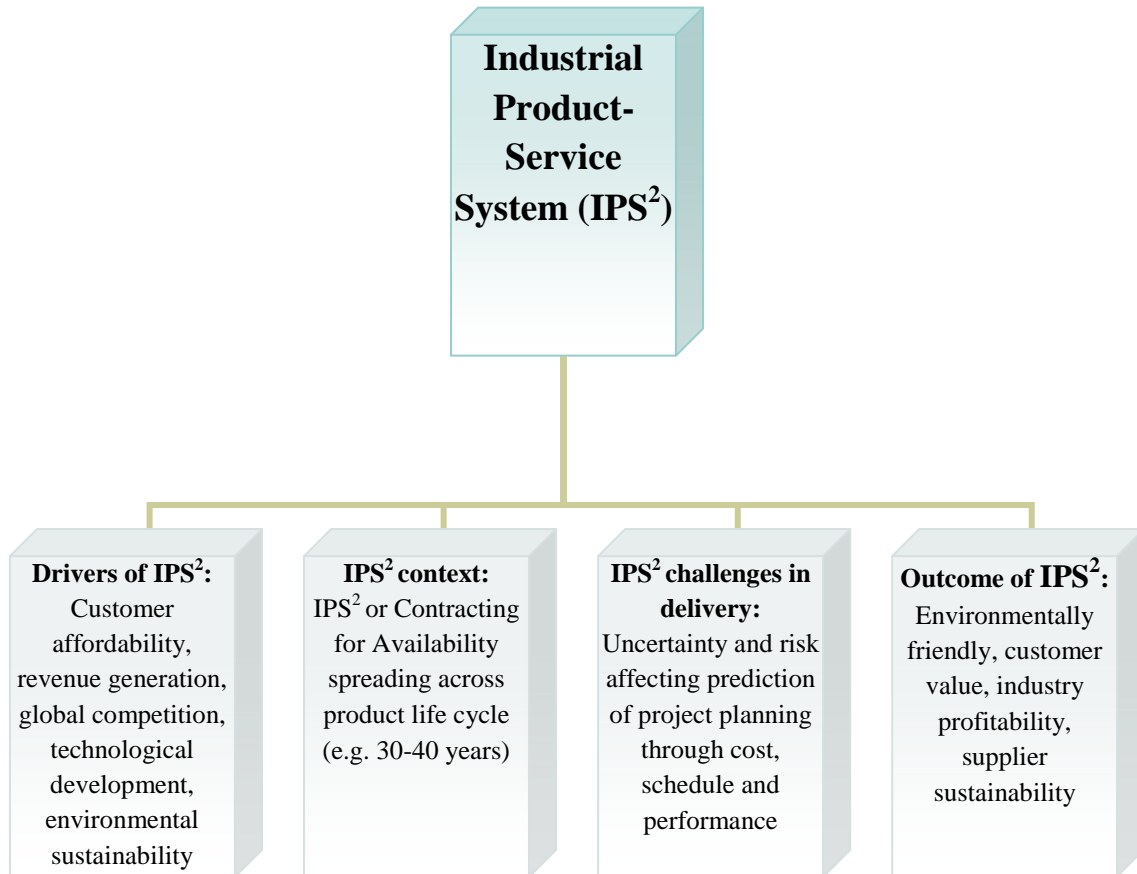


Figure 2.2 Defining the context

As represented in Figure 2.2, the main drivers of adopting an IPS<sup>2</sup> business model relates to increased customer affordability, revenue generation opportunity, capability to handle global competition, technological development and environmental sustainability. Within this research IPS<sup>2</sup> and Contracting for Availability (CfA) have been used interchangeably. Recent studies have identified several organisational challenges related to providing CfA. Some concern arises from cultural change, which necessitates a service dominant approach to business transactions (Ng and Yip 2009). The customer is concerned with the perceived loss of control over the service requirements of

<sup>1</sup> The Concept, Assessment, Demonstration, Manufacture, In-service, Disposal cycle has been used by the United Kingdom Ministry of Defence (MOD) since 1999, when it was devised as part of the Smart Procurement initiative, since replaced by Smart Acquisition, to deliver equipment capability within agreed performance, cost and time parameters.

<sup>2</sup> The United Kingdom's defence lines of development are training, equipment, personnel, information, doctrine and concepts, organisation, infrastructure and logistics

equipments. The blur concerning the boundaries of working together between industry and customer has also emerged as a concern. From a supplier's perspective achieving sufficient understanding of the delivery of service has become a significant challenge with the transfer of responsibilities from the customer to the solution provider. The financial implications of a contract necessitate adequate consideration of cost, which may be prone to uncertainty.

The shift to CfA promotes the use of performance criteria (e.g. key performance indicators) over the Product Life Cycle (PLC), which may last up to 40 years. Equipment availability, reliability and maintainability are some of the main areas of interest within these contracts. As a result, relationship between the customer and industry has been growing while co-creation of value has become a major theme across the industry (Ng and Yip, 2009). CfA has become widely considered as win-win solutions for both the customer and industry. Some of the major reasons behind this include opportunities for cost reduction, incentivising flexibility in IPS<sup>2</sup> delivery, extending PLC through higher reliability, payment based on unit of service rather than resources, optimisation of use, postponing disposal costs, incentivisation of component re-use, and fixed income achieved over longer duration (Morelli, 2002). These positive outcomes have been achieved through the enhancement of the role of service in the delivery of customer needs (Mathieu, 2001a). The significance of service arises due to its ability to ensure or to enhance the product performance expected by the customer throughout the whole PLC (Takata et al., 2004). Services such as health checks, spares and repairs services, defect response, on-call service, performance assessment, process management and training have become widely offered across the defence industry. Such services as part of an IPS<sup>2</sup> have enabled to tailor delivery to the individual customer needs (Aurich et al., 2009; Mathieu, 2001b).

A number of definitions of service have been proposed. It is difficult to determine a balance between too narrow or broad definitions. From a narrow perspective definitions tend to consider organisational memberships in the service sector, whilst broader definitions provide explanations of what constitutes a service (Metters and Maruchek, 2007). Furthermore, it is apparent that there is a conflict between definitions that are

based on industry or service delivery processes (Sasser et al., 1978; Johnston and Clark, 2001; Heineke and Davis, 2007). Services 'consist solely of acts or process(es), and exist in time only' (Shostack, 1982). However, the provision of a service is made in connection with the sale of a product, which involves 'tangible objects that exist in both time and space' (Shostack, 1982). Services can not be possessed, they can only be experienced, created or participated in (Cooper and Evans, 2000). Within a manufacturing context, service has also been referred to as customer support, product support, after-sales service and technical support (Goffin and New, 2001).

The author did not identify a connection between the "service" literature and the "cost estimation" literature. However, existing research that lays out the experienced challenges and adopted service processes supported the uncertainty associated considerations within this thesis. Along these lines it was realised that there are difficulties in categorising services and associated uncertainties due to the customised delivery of services (e.g. Cook et al., 1999). This was further recognised in literature with the breadth of research that covers various approaches to service delivery and in forming or structuring service supply chains (e.g. Cook et al., 2001; Baltacioglu et al., 2007; Clark and Armistead, 1991; Saccani et al., 2007; Meier and Volker, 2008). For instance, Youngdahl and Loomba (2000) presents the key aspects associated to globalisation by considering the service driven supply chains.

## **2.2 Understanding Uncertainty**

Interest in uncertainty has drastically grown over the past century (Bernstein, 1998). Growing understanding of its influence over decisions, designs, and behaviour has been critical. Researchers have been attracted with the terms' fuzziness, randomness, the doubtful nature it creates and the lack of confidence it causes (Bernstein, 1998; Walker et al., 2003; Refsgaard et al., 2007). Research in the area has mostly, centred on developing methodologies to reduce the impact of this phenomenon (Thunnissen, 2004a; Oberkampf et al., 2001). Along these lines, the approach has mostly involved, developing definitions and classifications of the term (Thunnissen, 2005). Furthermore, many definitions of uncertainty have been made in view of the scientific discipline'

purpose (Refsgaard et al., 2007). Interestingly research in the area has more so focused on finding applicable methods, i.e. industry oriented classifications of the term, as theoretical approaches have not been attractive. Furthermore, many researchers have developed strategies to manage/mitigate the influence of uncertainty. The challenge in managing uncertainty is particularly driven by the non-static nature of uncertainty. In Walker et al., (2003) uncertainty was defined as “any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system”. Hastings and McManus (2004) define uncertainty as “things that are not known, or known only imprecisely”, where it encompasses aspects including “liability to chance or accident,” “doubtfulness or vagueness,” “want of assurance or confidence; hesitation, irresolution,” and “something not definitely known or knowable”. The working definition for this thesis for uncertainty and risk is as follows:

**Uncertainty definition:**

Uncertainty is the stochastic behaviour of any physical phenomenon that causes the indefiniteness of outcomes meaning the expected and actual outcomes are never the same. The variation could have a negative, positive or no impact on the overall performance of a project involving physical systems. The stochastic nature of the project performance is caused by the variability in the environment, human error and/or human ambiguity (e.g. lack of knowledge).

**Risk definition:**

Risk is a special case of uncertainty where the outcomes of a specific event or a number of events have a negative effect on the overall performance of a project.

### **2.2.1 Research in uncertainty and risk**

Initial interest in uncertainty came from the Greeks, during the 4<sup>th</sup> century. Interest surrounded the identification of possibilities and limits of the human knowledge (Bernstein, 1998). This is known to be epistemic uncertainty. Its influence can be reduced through increased understanding, or increased (relevant) data. However,

traditionally, uncertainty has been associated with games and gambling (Thunnissen, 2005). With this case, it is considered that neither information nor knowledge can contribute to reduce uncertainty in the random nature. This refers to the lack of understanding of events in the surrounding environment, where irrespective to the available data events remain unpredictable (Jaafari, 2001). This has been considered to be aleatory uncertainty (Oberkampf et al., 1999). Figure 2.3 illustrates the main differences between aleatory and epistemic uncertainties. There is also a common area between the two, which derives from information that is hard to reach.

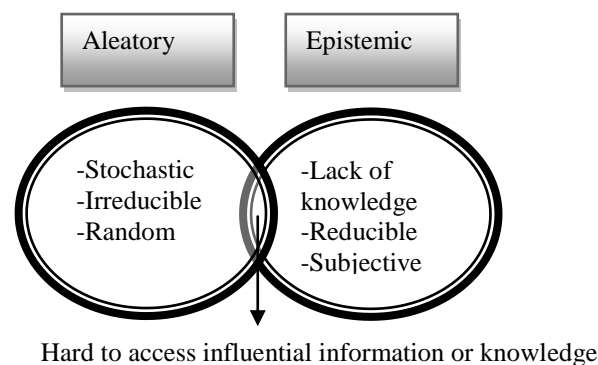


Figure 2.3 Natures of uncertainty

During the last century, the concepts of risk and uncertainty have manifested themselves in various academic and practitioner domains. Much has been made of Frank H. Knight's distinction between "risk" and "uncertainty" and his work on decision-making under uncertainty (Knight, 1921). Accordingly, he defined risk to be a simplistic form of uncertainty and related these to situations where experts were capable of assigning probabilities to outcomes. On the other hand, he related uncertainty to situations that mathematical considerations were incapable to assign probabilities to outcomes. The terms risk and uncertainty have often been used interchangeably; however there is an important distinction between the two where the concept risk deals with measurable probabilities while the concept uncertainty does not. Some researchers have used this point to claim that one can make predictions with his/her own will, arguing that all situations can be assigned probabilities (Tversky and Kahneman, 1974). Uncertainty arises from the non-static and non-linear interactions that occur in any case. On the other hand, risk focuses on a given event while it is possible to measure it through consequences (negative outcome) and likelihood (qualitative description of probability).



To understand risk, it is useful first to understand the nature of uncertainty, which refers to the state of being uncertain, doubtful, and hesitant. Neither loss, nor chance is necessarily associated with certainty (Emblemsvag, 2003). It is adequate to consider uncertainty as a special kind of ignorance (Smithson, 1989). The most common definitions concerning uncertainty to be found in the literature refer to the:

- State uncertainty - Inability to assign probabilities to the likelihood of future events (e.g. Ashill & Jobber, 1999, 2001; Duncan, 1972; Milliken, 1987)
- Effect uncertainty - Lack of information about cause-effect relationships (e.g. Ashill & Jobber, 1999, 2001; Duncan, 1972; Milliken, 1987)
- Response uncertainty - Inability to predict accurately what the outcomes of a decision might be (e.g. Ashill & Jobber, 1999, 2001; Downey et al., 1975; Duncan, 1972; Milliken, 1987)

Interestingly, many systems can not function without uncertainty (e.g. stock market, democracy). Furthermore, a reduction in uncertainty to zero may cause the risk to increase, but if the uncertainty is balanced, the risk may be acceptable. The reason for this relationship relates to uncertainty being the source of risk. Risks arise when we make decisions because we expose ourselves to uncertainty in which the risks lie (Emblemsvag, 2003).

In more recent literature (Hillson and Simon, 2007), risk is characterised as encompassing both threats and opportunities. Hillson and Simon argues that “Risk is an umbrella term, with two varieties: “opportunity” which is a risk with positive effects; “threat” which is a risk with negative effects”. Given the notion that risk has positive and negative effects on the project outcome it is often proposed to discriminate between risks as exposure to loss and opportunities as exposure to gains. In this document, the term risk is used to embrace uncertainties with downside impact. Whilst there are many definitions that have been provided for the terms uncertainty and risk, there is no definition that has commonly been used.

### **2.2.2 Uncertainty typology**

A common theme in uncertainty research has been to develop uncertainty typologies to create decision support tools (Refsgaard et al., 2007; DeLaurentis and Mavris, 2000). Though, there is no single approach that has commonly been accepted. A highly regarded approach was proposed in Walker et al. (2003). The paper, within the context of policy analysis, offers a systematic treatment of uncertainty. The tool classifies the literature into three dimensions: location (e.g. application in models), level (e.g. driven by knowledge continuum) and nature of uncertainty (e.g. aleatory and epistemic).

### **2.3 Service Uncertainty**

Sources of uncertainty can be categorised into customer demand and supply related activities (Armistead and Clark, 1992). The match between supply and demand influences the quality of the provided service and the productivity rate for resources (Johnston and Clark, 2001). Though, this hypothetical balance does not tend to occur (Wilding, 1998). Along these lines, product uptime drives service performance, which is driven by the duration to transform failed equipment into an operational state and equipment reliability. Alternatively, the primary source of customer perception derives from the product availability level, which involves the fraction of time that a product is available for use (Cohen et al., 2006b). Mismatches between demand and capacity or available resources cause uncertainty, though predicting the variation within this relationship is the governing challenge that needs to be addressed in service delivery (Sasser, 1976). Along with that it is also important to recognise the way in which uncertainties evolve over the life cycle of a product, which is represented in Figure 2.4.

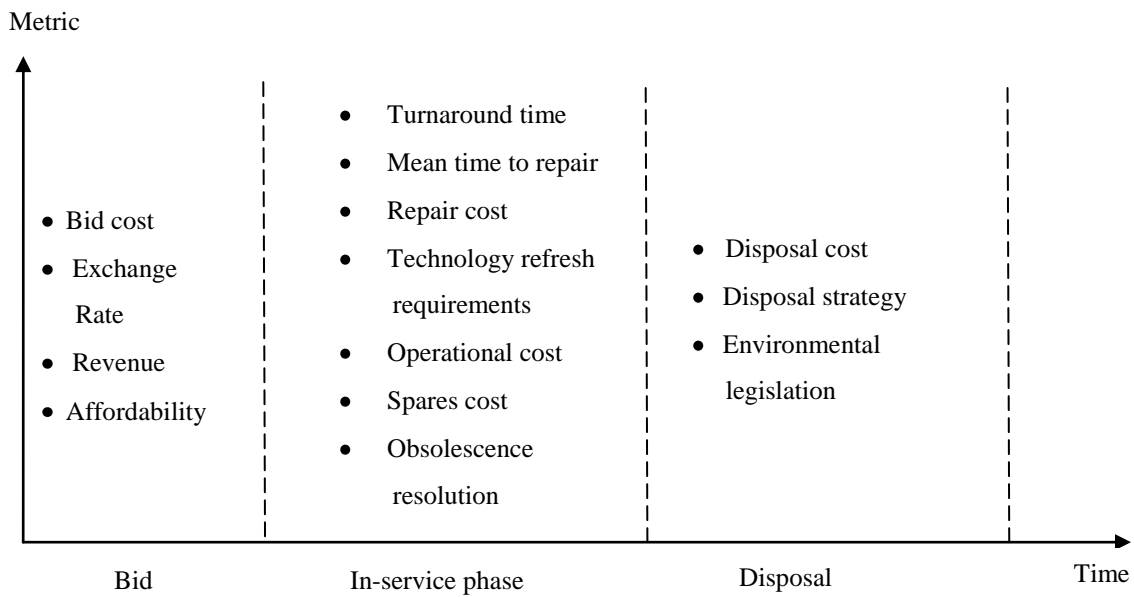


Figure 2.4 Sample evolution of uncertainty from service bid to disposal

For an  $IPS^2$  (e.g. CfA) demand is a function of mean time between failure and mean time to repair. Mean time between failure derives from considerations within the design phase. Furthermore, the design activities need to address equipment reliability, availability, maintainability and supportability for the in-service phase (Cohen and Whang, 1997). The process of achieving and sustaining performance metrics (i.e. key performance indicators) tend to be the major sources of uncertainty for the OEM and necessitate careful management in order to sustain service level agreements. On the other hand, for mean time to repair there are three levels of uncertainties that need consideration. Firstly, the appropriate processes need to be assigned to detect failures whether in a planned or unplanned manner. The second aspect relates to outcomes, where the rectification approach that is necessary plays an important role in the overall equipment availability. Thirdly, the cost of mean time to repair will have an important role in making decisions; however throughout the life cycle of equipment this constitutes an important source of uncertainty, which is illustrated in Figure 2.5.

One cause of demand-supply mismatch can be considered to be disturbances, where the supply chain literature has put much emphasis. These involve unwanted events that reduce the performance of a supply network. Sources of disturbances may be faulty

processes, uncertainties within an organisation, from interaction between different partners or a higher industry or environment level that derives uncertainty in demand (Datta, 2007). For instance, in maintenance a common area of interest has been on the influence of human errors causing disturbances (Dhillon and Liu, 2006). Resilience, which studies approaches to handle disturbances, has also received much interest.

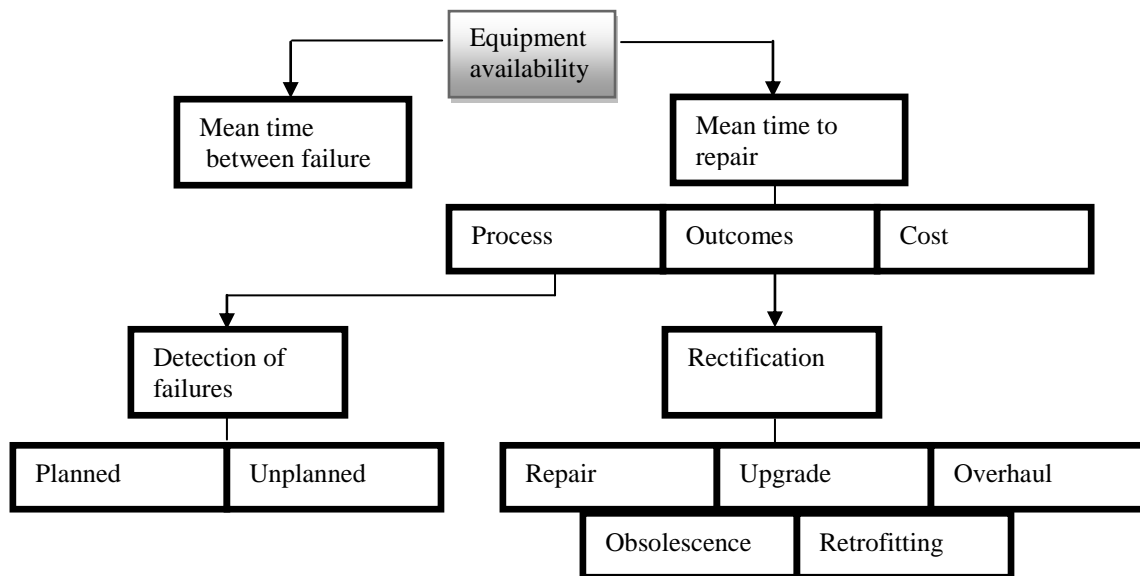


Figure 2.5 Factors influencing equipment availability

### 2.3.1 Demand Uncertainty

Service complexity and the delivery urgency have commonly been considered to contribute to uncertainty. This relates to the fact that, a service cannot be transported, the consumer must be brought to the service delivery system or the system to the consumer (Sasser, 1976). For instance, urgency may be in terms of time, where customers may require support within days, hours or minutes. Interestingly, although the consumption of goods can be delayed, as a general rule services are produced and consumed almost simultaneously (Sasser, 1976). The ability to satisfy demand in a set time scale depends on the ability to predict demand. Unsuccessful forecasting may inhibit support due to the inadequate level of capacity. By developing an uncertainty framework Lee (2002) compared demand for functional and innovative products in relation to supply characteristics, which may be stable or evolving. The paper highlights the importance of employing the correct supply chain strategy for the product offering. In this framework demand uncertainty is linked to the predictability of the demand for

the product. Furthermore, functional products are considered to have long life cycles, and stable demands. On the other hand, innovative products have short life cycles.

### **2.3.2 Supply Uncertainty**

Supply uncertainty involves managing resource availability, capacity and capability along the service supply network. The major challenge derives from the fact that services are direct; they cannot be inventoried due to the perishability of services (Sasser, 1976). Furthermore, since influencing demand appears to be more uncertain than managing resource capacity, managerial focus has tended to be put on the supply chain (Armistead and Clark, 1991; Sasser, 1976). Service capacity refers to the maximum level of value added activity over a period of time that the service process can function under normal operating conditions (Johnston and Clark, 2001). Furthermore, assessing capacity level is difficult as most services are provided within bundles. Also capacity levels need to vary from one location to another, which is not a simple task. Finally, the intangible nature of services also makes it harder to put a value on required capacity (Armistead and Clark, 1992), which is increasingly becoming important to determine required capacity level early on for an IPS<sup>2</sup> context. There is a need to allocate the right resources at the correct location with the appropriate number of resources. Frameworks to apply suitable supply strategies were not found in the service literature, although suggestions exist for products (e.g. Lee, 2002; Fisher, 1997).

### **2.3.3 Identification of sources of uncertainty in service delivery**

Firms in the manufacturing sector, from a traditional perspective, focused on managing a supply chain that consisted of product and material flow (Lin and Vassar, 1992; Loomba, 1998). On the other hand, service supply chains require a larger set of aspects that needs to be considered (Youngdahl and Loomba, 2000). For instance, as well as materials (parts), people and equipment need to be allocated (Ellram et al., 2004). Furthermore, an infrastructure needs to be built, which varies from deterministic production models into one that copes with high variability. This infrastructure needs to cater for the material flow, storage, repair, transportation, communication and

information systems (Cohen et al., 2006a). Due to these reasons, it has commonly been suggested that delivering after sales service is more complex than products. The service delivery process is challenged by the uncertainties that arise from demand and supply.

The uncertainty in demand may occur from the complexity (dependent on know-how) of the delivered equipment, the machine usage conditions/environment, or usage levels, along with the customer willingness to pay level. On the other hand, the uncertainty in supply may be influenced by resource availability and the capacity across the service supply chain. Service quality is a function of the scale and scope of the customer demand and supplier capacity to respond to the demand. To be able to manage service quality it is necessary to develop forecasts to be able to plan. Though, difficulties arise due to lack of information on demand and on available resources. Service delivery in PSS is highly driven by human involvement in providing equipment availability. It is important to understand the most important features of service quality, as this will help to understand the most significant uncertainties. For instance, in Armistead and Clark (1992), these were considered to be reliability of service delivery, competence of the service organisation, attitudes of staff to customers, the ability to put things right when they go wrong, the time to deliver the total service.

OEM or service providers tend to provide a portfolio of services whilst each offering has its own network of participants that focuses on service delivery within the constraints of demand and supply. From a demand perspective, lack of homogeneity creates the challenge for supply to develop a complex infrastructure to react to return, repair and disposal, in order to account for the variation in time of arisen, different demands, and the significance of requirement. For this purpose, the OEM needs to effectively deploy parts, people and equipments at many locations, while supporting all sold products/equipments (Cohen et al., 2006a). The complexity is coupled as each generation of equipments/technology has different parts and vendors. Along with this, compared to a typical product sale, the nature of a support business is typically unpredictable and inconsistent due to the characteristics of demand and the lack of information sharing. Whilst humans play a critical part in service delivery, sustaining the required knowledge/skill set over long durations is a challenging task, where

concerns such as obsolescence in knowledge have increasingly grown (Romero et al., 2009). The nature of uncertainty refers to the sources of uncertainty and in Table 2.1 these are classified for elements associated to service demand and service supply. Across the elements typically the epistemic characteristics are prevalent, where lack of data for the activities taking place in the in-service phase creates uncertainty to forecast events. Examples include human involvement and fault freeness. However, there are some uncertainties such as mean time between failure and required reliability level that adopt aleatory characteristics.

Table 2.1 Sources of uncertainty in service delivery

<b>Sources of uncertainty</b>			
<b>Service demand uncertainty</b>		<b>Service supply uncertainty</b>	
<b>Type</b>	<b>Nature</b>	<b>Type</b>	<b>Nature</b>
Reliability	Aleatory	Mean Time to Repair	Aleatory-Epistemic
Availability	Aleatory	Supply Chain: Capacity, Capability	Aleatory-Epistemic
Mean Time Between Failure	Aleatory	Human Involvement	Epistemic
Scope of Service	Epistemic-Aleatory	Fault Freeness	Epistemic
Delivery Urgency	Aleatory	Responsiveness	Aleatory
Differences Across Customer Demand	Aleatory	Repair Time	Aleatory
Maintainability	Epistemic-Aleatory	Maintenance requirement	Aleatory
Obsolescence	Epistemic-Aleatory	Stock level	Epistemic

Based on the literature review, the author has recognised that there is an emphasis to classify uncertainty for service delivery based on supply and demand sources. Though, additional examples of uncertainty sources were also realised including the information flow and technology management, organisational culture, and the interaction between the supplier and the customer (Armistead, 1990).

## 2.4 Service Cost Estimation

According to the Association for the Advancement of Cost Engineering (AACE), Cost Engineering is defined as “the area of engineering practice where engineering judgment

and experience are used in 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” (Hollmann, 2006). It is a methodology being used for predicting/forecasting/estimating the cost of a work’s activity or output (Stewart et al., 1995). The application of CfA has further promoted the concept of life cycle costs, which is the total cost over a product’s life cycle span (Xu et al., 2010). The industrial business processes have moved from delivering spares and repairs to total care packages, which encompass the whole lifetime of a product (Roy et al., 2009). It requires consideration of design cost, manufacturing cost, operating and service cost, and disposal cost. Along these lines, the aggregate representation of cost has been referred to as Life Cycle Cost (LCC). Other terminologies for LCC are Whole Life Cycle Cost (WLCC) and Through-Life Cost (TLC). The overall growth in the adoption of LCC has been relatively slow, due to various reasons such as scepticism towards new techniques and independence among the life cycle stages. The particular case of service cost estimation considers various activities, e.g. maintenance, repair, asset and operation management service, supply chain management and engineering service and training, that enable or enhance the operational life of given equipment (Asiedu and Gu, 1998). Though, without appropriate consideration of uncertainty, the chances of actual cost outcomes being within cost predictions diminishes.

#### **2.4.1 Cost uncertainty analysis**

This section focuses on explaining literature on ways to conduct uncertainty analysis for cost. As project phases have become more complex and costly the requirement to perform risk analysis has grown. In a typical project the primary areas of uncertainty include cost, schedule and technical performance. Cost uncertainty analysis aims to understand the influence of uncertainties on cost drivers associated with a systems technical definition and cost estimation methodologies (Boussabaine and Kirkham, 2004). More specifically, cost uncertainty modelling refers to the quantitative assessment of the impact of uncertainty on cost estimation with the goal of comparing across different options.



There has been an increasing emphasis on understanding the link between uncertainty and cost since the Second World War, which has resulted in numerous approaches to assess cost uncertainty. The initial focal point was on defining the sources, scope, and types of uncertainties that impact the cost of future systems (Garvey, 2000). The main focus of the literature was particularly on understanding costs of military systems with long range decisions. However, the cost estimates were often lower than the actual cost estimate or an estimate developed at a later phase, where the cause was referred to as uncertainty (Fisher, 1971). Recent literature focuses on issues such as improvements to risk quantification, forecasting accuracy and data collection (Bernstein, 1998; Emblemsvag, 2003; Thunnissen, 2004b). Risk assessment in most projects tends to focus on three main areas: cost, schedule and technical performance, which are all quantitative in nature (Stewart et al., 1995; Boussabaine and Kirkham, 2004). They may also involve intangible targets such as corporate image and employee satisfaction (Ali, 2005). From a more concentrated view, some researchers have suggested the necessity of studies that can address unresolved issues relating to the uncertainty assessment methodology (Chapman and Ward, 2000). The following section presents an overview of the cost uncertainty analysis methods.

#### **2.4.2 Overview of cost uncertainty analysis methods**

Uncertainty analysis, typically referred to as risk analysis, in common aims to systematically aid decision making (Stewart et al. 1995). This means that a major goal of the process is to firstly identify major risk and uncertainty areas, and subsequently to analyse the outcome of various decisions (Curran et al., 2004). It is necessary to build in the stochastic nature of uncertainty when making such decisions, as this aspect has commonly been ignored. As illustrated in Figure 2.6, uncertainty evolves as time passes; while imprecision is dominant earlier, variability is important in later stages. The process is governed by the timeliness of data availability.

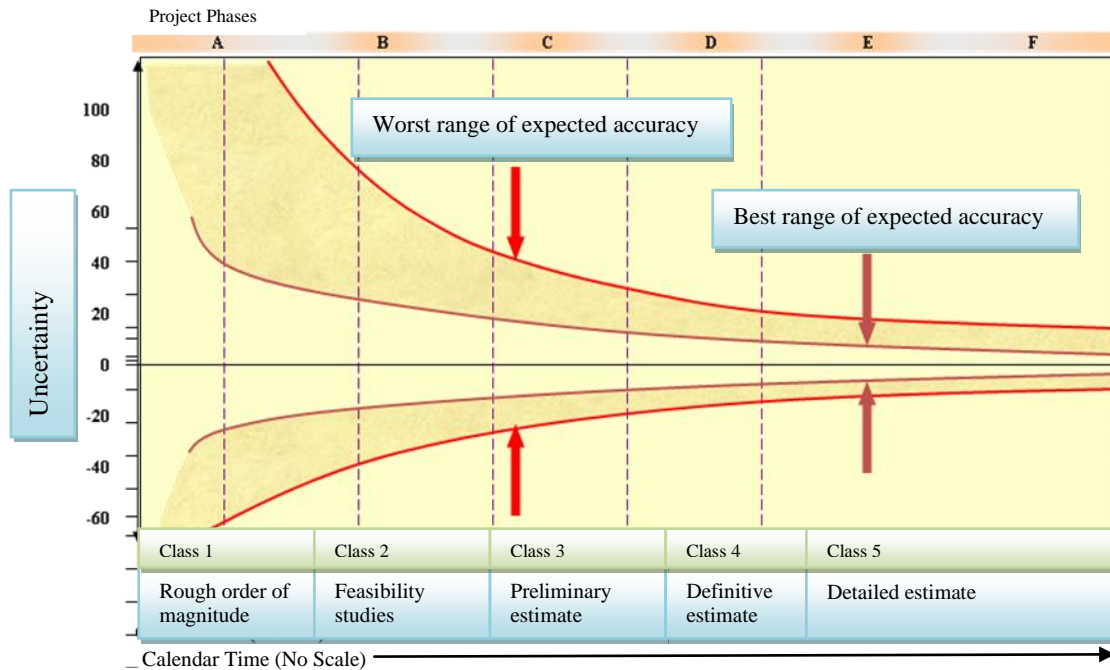


Figure 2.6 Estimating accuracy trumpet (Woodward and Chen, 1999)

In order to achieve effective decision making, appropriate uncertainty assessment methods need to be selected for the given context, while bearing in mind the final goals and objectives of the project (Chapman and Ward, 2000). Though, there are challenges in selecting the suitable approach due to lack of guidance. The selection of the uncertainty quantification approach is largely dependent on data characteristics, which influences the nature of uncertainty for a project. Furthermore, in cases where data represents the variability in a system (i.e. mean time between failure or repair time) this creates aleatory uncertainty. On the other hand, ambiguity in data due to multiple interpretations creates epistemic type of uncertainty that is influenced by the knowledge state of the decision maker. This particular uncertainty derives from expert judgement, which is commonly utilised when limited data exists. This may cause difficulties when justifying and retrieving data over long lasting projects.

Figure 2.7 depicts the suitable uncertainty modelling approaches for a given nature of uncertainty based on the epistemic and aleatory classification. Aleatory uncertainty tends to occur when there is tangible data available; however uncertainty occurs due to system variability. Typically a probabilistic or deterministic approach has commonly

been suggested in literature. Application of probability theory has been the common approach, where uncertainty in a cost estimate has been considered in three scenarios which takes an optimistic (minimum cost), most likely and pessimistic (maximum cost) view of the likely cost estimate (Curran et al, 2004). Within this area application of deterministic approaches and regression analysis is also common. However, in many cases there is lack of tangible data, where the nature of uncertainty is typically epistemic. Research in modelling such uncertainty has grown, while various approaches can be considered including possibility, fuzzy sets, evidence theory and imprecise probability. In cases where the nature of uncertainty is both aleatory and epistemic (i.e. vagueness deriving from linguistics or statistical error due to lack of data) the common approach involves the second order probability theory.

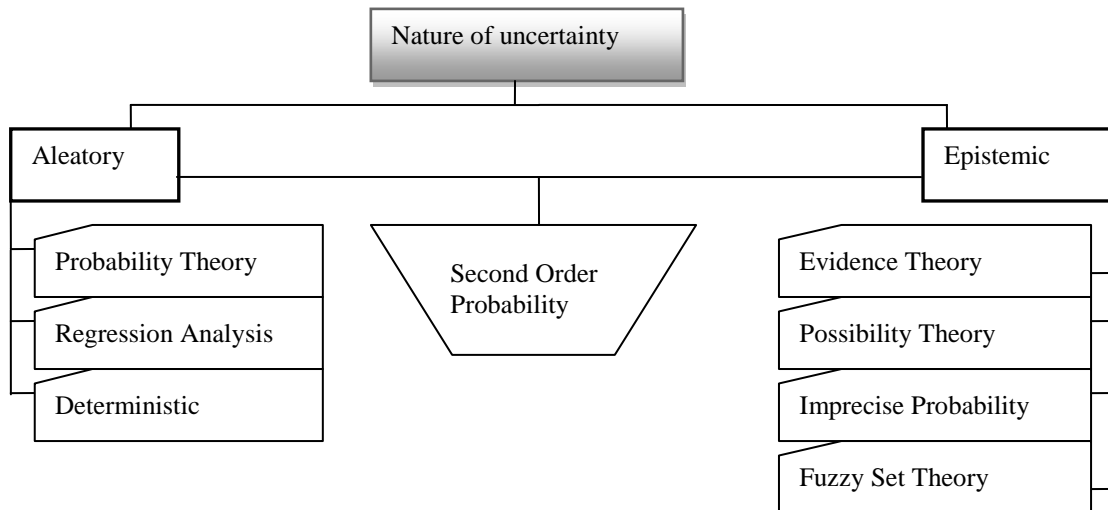


Figure 2.7 Uncertainty modelling approaches for natures of uncertainty

Traditionally differences between the influence of aleatory and epistemic uncertainty were not recognised (Mey Goh et al., 2010). Oberkampf et al., (2001) argues that homogeneous consideration of the two natures of uncertainty causes significant under estimation of the influence of uncertainty over cost. There is a growth in research that aims to address this issue. For instance, Kishk (2004) develops methodologies to integrate both aleatory and epistemic uncertainty. The paper proposed two methods: the hybrid number approach and transformation techniques. The first approach, through the hybrid numbers concept considers the two categories of uncertainties in a separate manner. The latter method, aims to transform uncertainties into a single form (Kishk,

2004). Table 2.2 summarises uncertainties that are typically found in cost data and models in order to reflect the considered areas within service.

Table 2.2 Classification of uncertainties in cost data and models

	<b>Classification</b>	<b>Source</b>	<b>Type</b>	<b>Example</b>
<b>Data Uncertainty</b>	Variability	Inherent randomness	Aleatory	Repair time, Mean Time Between Failure
	Statistical error	Lack of data	Epistemic and aleatory	Reliability data
	Vagueness	Linguistic uncertainty	Epistemic and aleatory	The component needs to be replaced about every 2 to 3 months.
	Ambiguity	Multiple sources of data	Epistemic	Expert 1 and expert 2 provides different values to end-of-life costs.
	Subjective judgement	Optimism bias	Epistemic	Over confidence in schedule allocation.
	Imprecision	Future decision or choice	Epistemic	Supplier A or B
<b>Model Uncertainty</b>	Intuitive/expert opinion	Judgement	Epistemic	Similar manufacturing process will be used but geometrical changes are made
	Analogical	Selection of benchmark model (qualitative characteristics)	Epistemic	The system will have 20% higher capacity than existing system and consumes 10% less fuel
	Parametric	Cost drivers/parameters CER choice Regression fit Data uncertainty Extrapolation	Epistemic and aleatory	Missing key cost drivers Unsuitable CER function form
	Analytical/engineering	Scope Level of details Available data	Epistemic and aleatory	Simplification in WBS due to lack of time
	Extrapolation from actual costs	Changes in conditions Limited data	Epistemic and aleatory	Maintenance procedures are revised

The uncertainty analysis methods can alternatively be classified into deterministic, qualitative, and quantitative techniques following Boussabaine and Kirkham (2004), as represented in Figure 2.8. The deterministic approach refers to numerical computation of risk or uncertainty. Qualitative approaches use subjective scoring techniques and the quantitative technique covers statistical and probabilistic approaches to quantification.

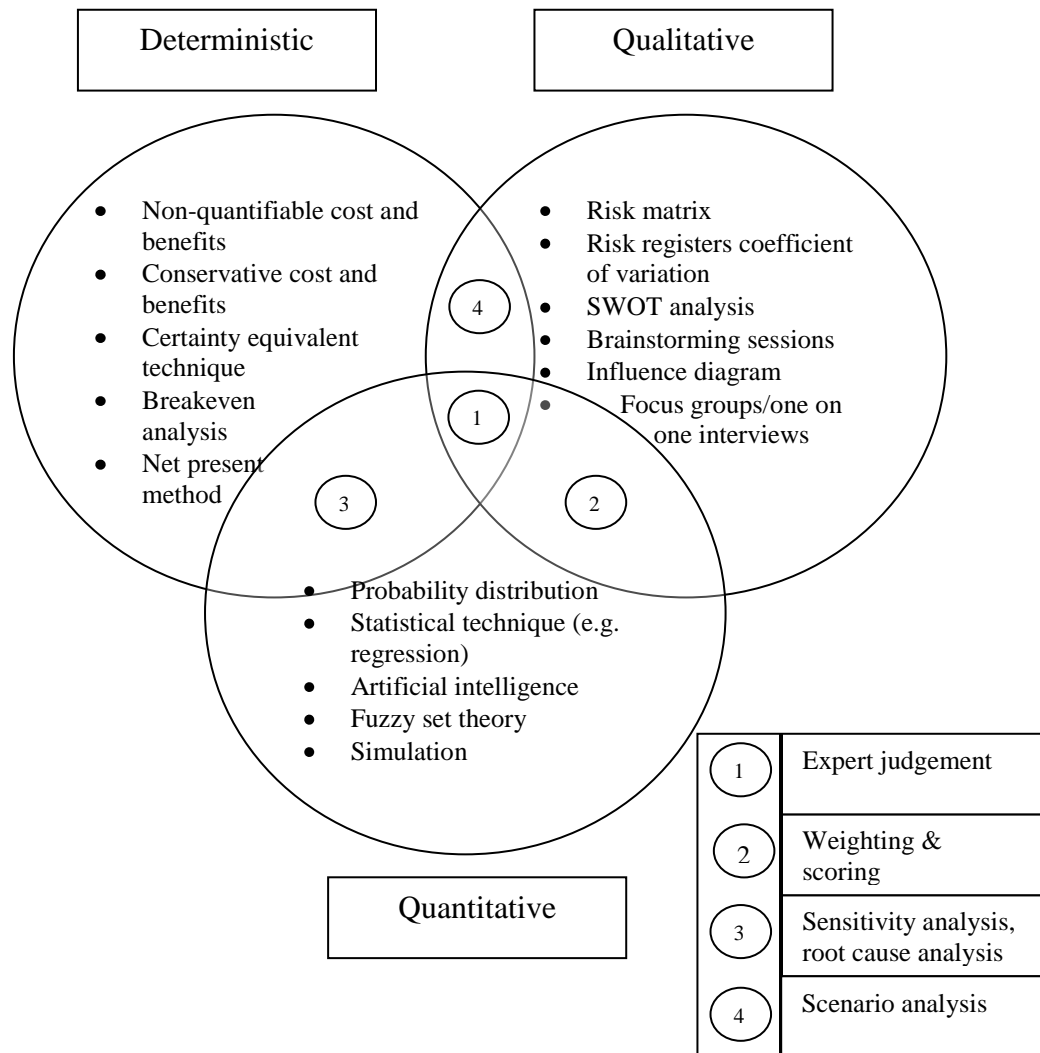


Figure 2.8 Uncertainty assessment methods

The most common deterministic approach, sensitivity analysis is popular in financial applications, risk analysis, and any area that models are developed (Datta and Roy, 2010). The ability to conduct probabilistic assessments in sensitivity analysis makes it a quantitative approach as well. Sensitivity analysis tests the influence on individual options by varying the projected value of important variables. The approach enables to show the impact of changes in assumptions on net present value and option rankings (Lefley, 1997). The goal of sensitivity analysis is to understand the likely range variation in a particular cost/benefit element. The main limitation of the approach is related to the possibility of only changing one variable at a time, although a number of variables may be interdependent. Other deterministic approaches include non-quantifiable cost and benefits, conservative benefit and cost estimating, certainty

equivalent technique, breakeven analysis, risk adjusted discount rate, benefit-cost analysis, and the net present method (Datta and Roy, 2010).

Qualitative analyses are beneficial to risk analysis as they aim is to bring together apparent uncertainties (Boussabaine and Kirkham, 2004). The magnitude of the risk or uncertainty is expressed in qualitative terms and the approach helps to get a general indication of the level of risk or uncertainty in a project. As a result of this analysis areas that need detailed analysis (e.g. quantitatively) can be identified. The method is particularly suitable when there is a lack of data to conduct quantitative analysis. There are a number of approaches that fit into this category including risk matrix, checklists, scorecards, risk registers coefficient of variation, SWOT analysis, brainstorming sessions, influence diagram, and focus groups/one on one interviews (Durugbo et al., 2010). The emphasis of such approaches is on the identification of uncertainty rather than its analysis as is the case with quantitative techniques. Qualitative analysis is commonly integrated into any other application of risk assessment; whether it is deterministic or quantitative. For instance, scenario analysis is a combination of deterministic and qualitative approaches. The approach involves adaptation of sensitivity analysis with the goal of combining individual tests into plausible scenarios and results for the “best case” and “worst case” scenarios are produced.

There are a wide range of well developed quantitative techniques which have existed for some time, however their application are not widespread in practice (Kishk, and Hajj, 2003). Furthermore, it is generally accepted that quantitative approaches can provide more information and can further facilitate decision making. Quantitative methods can be grouped into statistical (e.g. standard deviation, variance) and probabilistic approaches (e.g. probability distribution functions, simulation techniques). The selection of the quantification approach is largely dependent on data characteristics (Bedford and Cooke, 2001). Some of the well known quantitative approaches include probability distribution, mean variance criterion, simulation (e.g. Monte Carlo), statistical techniques (e.g. regression), artificial intelligence, fuzzy set theory, event or fault trees, behaviour modelling, and method of moments (Oberkampf et al., 2001; Garvey, 1999; Boussabaine and Kirkham, 2004; Bernstein, 1998). In probabilistic

methods, uncertainty in the cost data are represented by probability density functions (triangular and normal being most popular) and then propagated through cost models in order to assess the uncertainty in LCC. Analytical and computational methods such as the Monte Carlo simulation are used for uncertainty propagation according to probability theory. However, probabilistic methods although suitable for characterising aleatory uncertainty, may be less useful when statistical data is seriously lacking or when the uncertainty is caused by lack of knowledge (epistemic uncertainty) (Xu et al., 2010). This drawback has led to the investigation of the possibilistic and fuzzy set approaches (Kishk 2004; Oberkampff et al., 2001; Dubois and Prade, 2003).

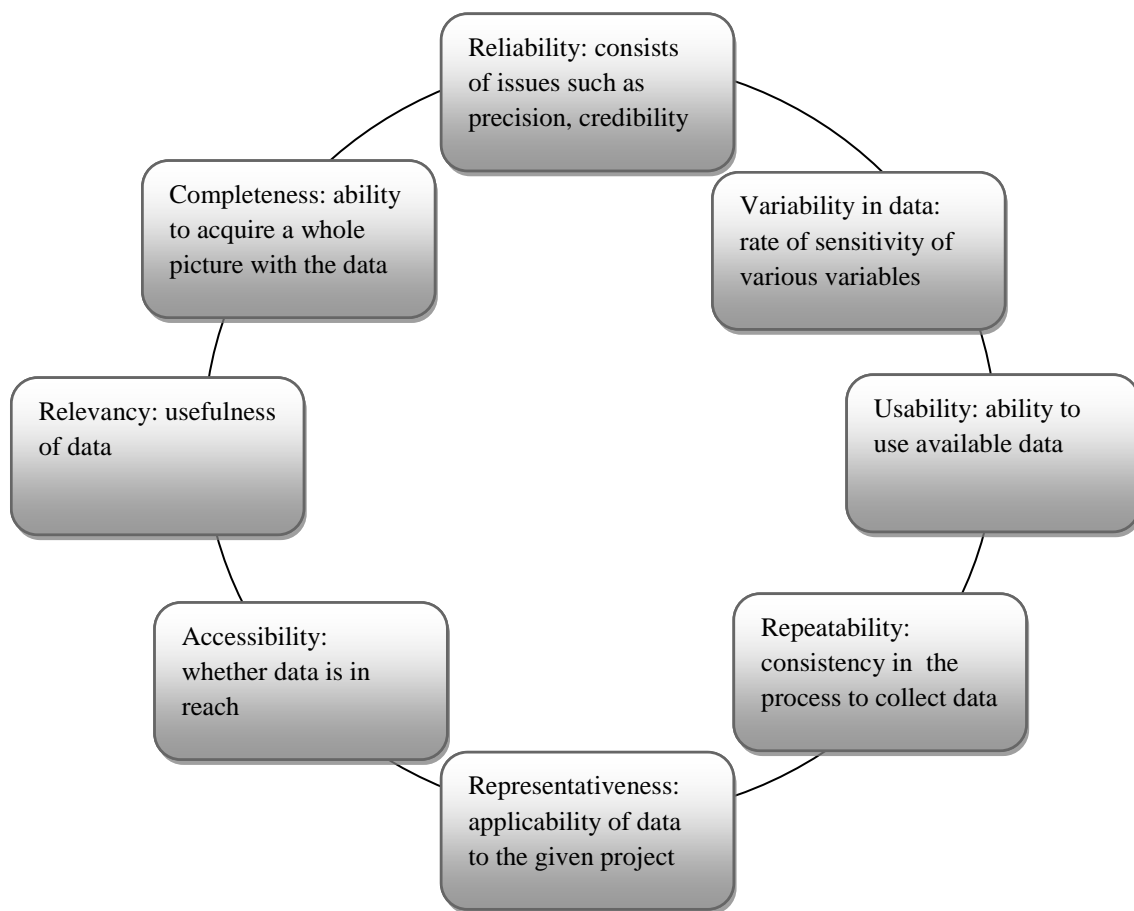


Figure 2.9 Sources of data uncertainty (Durugbo et al., 2010)

A summary of the typical data associated issues are represented in Figure 2.9. Data collection is a major requisite for uncertainty analysis and cost estimation. In order to achieve the desired level of quality in cost estimates, good data whether based on historical analogies or engineering understanding is necessary (MoD, 2009). Once the

key objectives of the program (e.g. requirements, scope, and schedule) have been established, then it is necessary to specify the data requirements to build cost estimates (GAO, 2009). For instance, this involves identifying all potential variables in the cost model affected by risk and uncertainty and identifying the potential data sources for estimating risk and uncertainty for each of these variables (e.g. specifying probability distributions). An important challenge in facilitating the transition towards service orientation is driven by the ability of the customer to transfer data to manufacturers and/or ability of manufacturers to make use of historical data.

## **2.5 Cost Uncertainty Modelling**

Service delivery has typically been constrained to maintenance in the literature (e.g. Ling et al., 2006). The focus of maintenance cost modelling addresses uncertainty in cases of impact of testing and maintenance activities on equipment unavailability through deterministic and probabilistic models (Sanchez et al., 2009). During the past 30 years, applications of classical probability theory to understand uncertainty has continuously been challenged by new methods such as, evidence theory, interval analysis, possibility theory and imprecise probability (Oberkampf et al., 2001). In common all of these methods concentrate on issues that arise from data. Some of the data issues may include vagueness, lack of data and structure. Recent methods are also capable of combining subjective (source of epistemic uncertainty) and statistical data (source of aleatory uncertainty). As a result challenges that derive from epistemic uncertainty have become increasingly manageable with recent developments. These methods have become more powerful than traditional methods in determining the influence and understanding types of epistemic uncertainty (Oberkampf et al., 2001). However, the most common application involves the development of complex probabilistic models, typically through Monte Carlo simulation, to explore the role of uncertainty (Datta and Roy, 2009). This approach uses random numbers to sample from known input probability distributions to determine a likely range of outcomes from a random simulating process. Its application has been rather diverse including physics, economics and engineering.



Usually cost drivers and cost estimating relationships (CERs) are stochastic, where uncertainty or the random nature of these variables is typically represented as a probability distribution (Daneshkhah, 2004). A CER refers to a mathematical equation where cost is expressed as a dependent variable of one or more independent cost variables, or as a function of one or more technical parameters (NASA, 2004). In order to get an aggregate perspective of the many cost drivers that get considered across defence projects, typically Monte Carlo Simulation has been used. This means that by taking a random sample from the probability distribution associated to each cost driver and CER the approach enables to obtain a single point estimate, which represents a project level output (Dienemann, 1966). The single point estimate represents the deterministic cost expectation, and by specifying the likely range including the minimum and maximum a boundary is reflected for costs. This is the single observation or experimental result out of an infinite number available. The approach relies on random number selection, while the process is repeated many thousands of times to develop a frequency histogram (or probability distribution) of total system cost. The random sampling process is repeated a large number of times, while combining different input values from the specified probability distributions. Expert opinion is necessary to define relationships between uncertainties and cost drivers, to develop probability distributions, to define the distributions' shape and to generate the Three-point estimates (MoD, 2007a). However, the subjectivity particularly for defining the range for cost drivers and the lack of availability of guidelines for this purpose has created challenges to consider (O'Hagan and Oakley, 2004).

There are two major issues that affect the integration of uncertainty to cost within the CfA context. Firstly, service delivery is typically influenced by issues that arise from lack of data, which creates epistemic uncertainty. Secondly, the stochastic nature of service delivery creates challenges arising from aleatory type uncertainty.

### **2.5.1 Approaches aiming to handle data related issues**

In order to tackle various issues that arise from data a wide range of approaches have been proposed including possibility theory, fuzzy set theory, neural networks (NNs) and

evidence theory. Possibility theory and fuzzy set theory are forms of artificial intelligence, which can be considered to be extensions to probability theory (Dubois and Prade, 2003; Harding et al., 1999). These approaches are capable of representing uncertainty with much weaker statements of knowledge and more diverse types of uncertainty (Oberkampf et al., 2001). Fuzzy set theory has, in many occasions, been proposed to substitute the traditional probability theory (Smith and Mason, 1997). The advantage of using this method lies in its capability to assign probabilities to ambiguous events or vague knowledge, which suits whole life cycle applications (Boussabaine and Kirkham, 2004). Fuzzy techniques have the ability to exploit the tolerance for imprecision and uncertainty while representing the real world (Emblemsvag, 2003).

For cost estimating purposes, the main idea of using NNs is to make a computer program that learns the effect of product-related attributes in relation to cost (Roy, 2003; Cavaliari et al., 2004). To be able to achieve this it is necessary to train the system with data from past case examples. Artificial neural networks learn and generalize from examples, to understand changing circumstances (Stewart et al., 1995; Emblemsvag, 2003). Their advantages over traditional methods lie in their capability to handle non-linear problems. Additionally, they do not require prior assumptions about the distribution properties of the underlying whole life cycle data (Curran et al., 2004). The user takes advantage of input-output maps that make the process easier to understand. These have been used in a range of areas, such as forecasting maintenance cost and running cost, forecasting use demand, ranking WLCC attributes, analysing WLCC risks and establishing non-linear relationships between WLCC centres (Boussabaine and Kirkham, 2004). However, application of artificial intelligence is threatened by its “black box” characteristic. These methods operate independently and do not provide adequate information for users (Boussabaine and Kirkham, 2004). Additionally, they have difficulties when changes appear drastically (Roy, 2003).

Application of NNs has been in a wide variety of areas including management, economics and engineering (Boussabaine and Kirkham, 2004). Furthermore, much research has also used these methods with a view to reduce the usage of regression analysis. Bode (1998) argued that NNs produce better-cost predictions than

conventional regression methods, based on their ability to detect obscure relationships in database. A comparison between probabilistic methods, regression analysis and neural networks are outlined in Sonmez, (2005).

Shackle's evidence theory has become increasingly popular in the field of artificial intelligence. Driven by increasing complexities in environments, traditional utility oriented decision making processes have been found limited by some researchers. The evidence theory simply neglects deterministic decision making systems; by keeping an open eye to new information that is received (Menzies and Hihn, 2006). Evidence theory simply, brings together all information received from different sources and evaluates them to understand whether the provided evidence is compatible or contradictory (Fioretti, 2004). It is governed by a belief system, which dictates the possibility measures.

Regression analysis has commonly been suggested when cost data is available. There is a clear norm that capabilities of this approach with available data are sufficient (Smith and Mason, 1997). Though, an important advantage of NNs over regression analysis, relates to their advanced capability to depict existing relationships between variables (Roy, 2003). And, fuzzy set theory was stated to be applicable when there is sufficient project data, mainly subjective, and user requires relationships between cost and variables. In conclusion, to reduce limitations faced by regression analysis, in cases particularly where data is not appropriate to utilize, neural networks and fuzzy logic have been proposed to be alternative approaches (Smith and Mason, 1997). Callopy and Armstrong (1992) defined 99 rules to facilitate the selection of the appropriate method. The large number of rules illustrates the difficulties in method selection.

### **2.5.2 Approaches aiming to handle the stochastic nature of services**

Traditional models in maintenance cost uncertainty modelling typically take a static perspective by assuming that the system operates in a certain fixed time instant (e.g. Monte Carlo simulation). On the other hand, stochastic models use random variables to reproduce or visualise the possible occurrence of events or disturbances that are

unknown a priori. Thus, such models define a representation of stochastic phenomena, which is typically achieved through a set of probability distributions and/or a set of relevant statistical parameters to generate suitable values for the random variables over time. The supply chain literature has commonly applied stochastic techniques to represent dynamism in systems. Furthermore, three simulation approaches have typically been applied: discrete event simulation (DES), system dynamics (SD) and agent based modelling (ABM). Their applications have varied depending on the problem at hand whether it be at a strategic, operational or planning level (Chopra and Meindln, 2007). Strategic refers to issues such as deciding the structure of the supply chain over many years or modes of transport to be used. Planning, for instance involves consideration of which markets will be supplied from which locations. Finally, operational problems can be daily and the focus is on the supply chain configuration (e.g. allocation of inventory). In literature, SD and ABM have been used equally to address strategic and planning problems. On the other hand, the use of DES heavily focuses on planning problems, while it has also been used for the operational context (Owen et al., 2010).

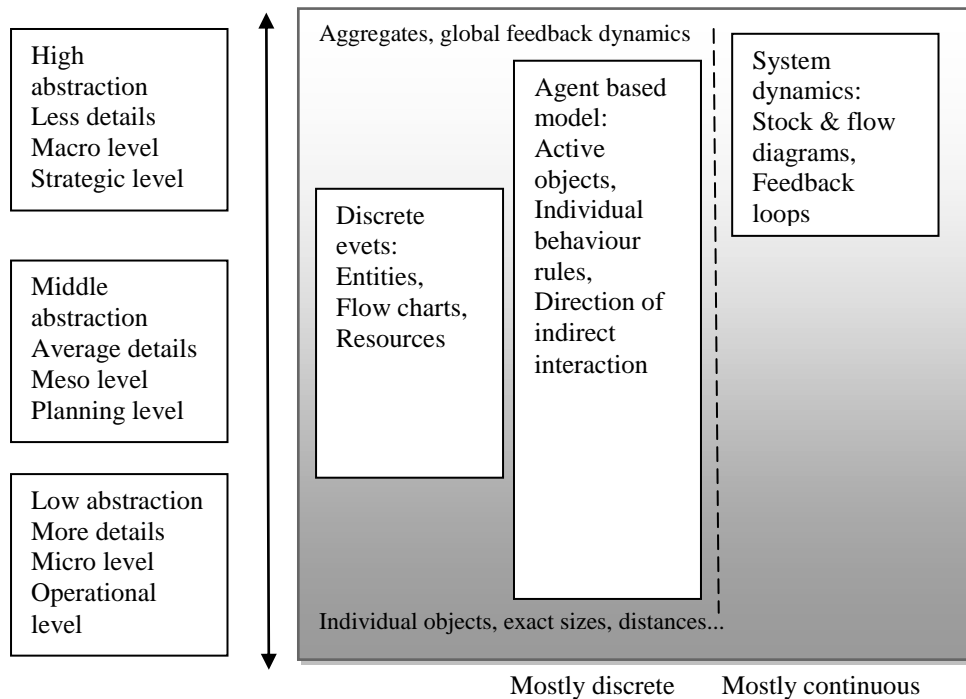


Figure 2.10 Simulation approaches for strategic, planning and operational problems (Buxton, 2010)

Figure 2.10, illustrates the areas of application of these simulation approaches. SD uses differential equations to model rates of change. Its use has typically been in causal loop diagrams where the relationship between the variables is explicitly defined. DE is a process centric simulation approach focusing on activities, such as queues and delays within a system. ABM involves bottom-up models where behaviour results from the aggregated activities of agents, where it is necessary to define dependencies across agents. For strategic problems, ABM and SD have commonly been applied due to their ability to capture different aspects of a system (Erkoyuncu et al., 2010b).

In literature ABM has mostly been used to define the engagement across a supply chain, but the approach has wide application including domains such as economics and manufacturing (Nilsson and Darley, 2006). In the supply chain literature there tends to be a set of fixed relationships and the effects of different patterns of decision making on overall stock levels is explored (Allwood and Lee, 2005). The main theme has been to capture the interaction with the customer. In defining an agent four key properties have been referred to including autonomy (e.g. function without user intervention), proactive (e.g. independently working towards a goal), reactive (e.g. respond to environment) and social (e.g. interact with other agents) (Wooldridge and Jennings, 1995). Across literature there is no general agreement on the term agent, whilst various definitions focus on different aspects such as software entity with thread of control over chosen operations (Parunak et al., 1998) or a self contained problem solving agent (Jennings et al., 1998). The fact that agents can react to changes, adapt and re-plan if a better approach is realised, based on information sharing between agents, makes it a dynamic system, which is key to representing a continuously changing world (e.g. CfA). In ABM the focus is on agents and their relationships with other agents or entities (Nilsson and Darley, 2006). In this research (Chapter 8) the agents are defined as real-life organisations identified in the context of interest, characterised with varying degrees of autonomy (i.e. execution ability and self-control), and characteristics based on policies, behaviours, states and constraints. Though, in other contexts such as in the manufacturing and logistics perspective an agent might represent a machine.

The application of ABM is widely growing due to a number of reasons. An important reason is associated to the growth in complexity across activities, which is driven by the increased interdependencies (Macal and North, 2006). Whilst this phenomenon is not new, traditional approaches have in some cases built in potentially unrealistic assumptions for modelling purposes. For instance, in the case of modelling economic markets notions of perfect markets have been relied upon, whereby assumptions such as homogeneous agents, and long-run equilibrium have made the problems analytically and computationally tractable. To the contrary, ABM provides the possibility of modelling processes out of equilibrium. Furthermore, the approach enables to model more fluid-turbulent social conditions when modelled agents and their identities are not fixed or given, but susceptible to changes that may include birth or death of individual agents as well as adaptation of their behaviour (Srblijinovic and Skunca, 2003). These models serve explanatory rather than predictive purposes, which is particularly suitable for the context of the early stages of the bidding phase. Other reasons for the growth of the application of ABM is associated to increased amount of data at lower levels of granularity and the enhanced computational power, which enables to conduct much more detailed analysis.

A commonly referred feature of ABM is associated to the adopted bottom-up approach, which enables to understand the root cause of interactions. The approach was compared to the traditional top-down oriented methodologies in Reaidy et al. (2003), which are represented in Figure 2.11. It is emphasised that top-down methodologies rely on the assumption that knowledge can be gathered outside the “system” and the observable phenomenon can be measured and analysed in order to decompose the information into different sub-units, whilst solving sub-problems separately (Nilsson and Darley, 2006). Subsequently, the partial solutions are combined to gather a single overall solution. However, the considered mathematical equations in this process tend to de-emphasise the relationships and dynamics (Parunak et al., 1998), which in reality exist particularly when considering interactions between organisations, similar to the generation of cost across the supply chain in the defence industry. Furthermore, the associated complexity increases with the growth in the number of suppliers and sources of cost. The issue of the traditional top-down oriented approach, which use global performance measures,

has been suggested to be the limitations in coping with the dynamics of the constituent parts, because the global measures are based on aggregated behaviours of the whole system (Swaminathan et al., 1998). This refers to the in-built assumptions, which focus on reductionism.

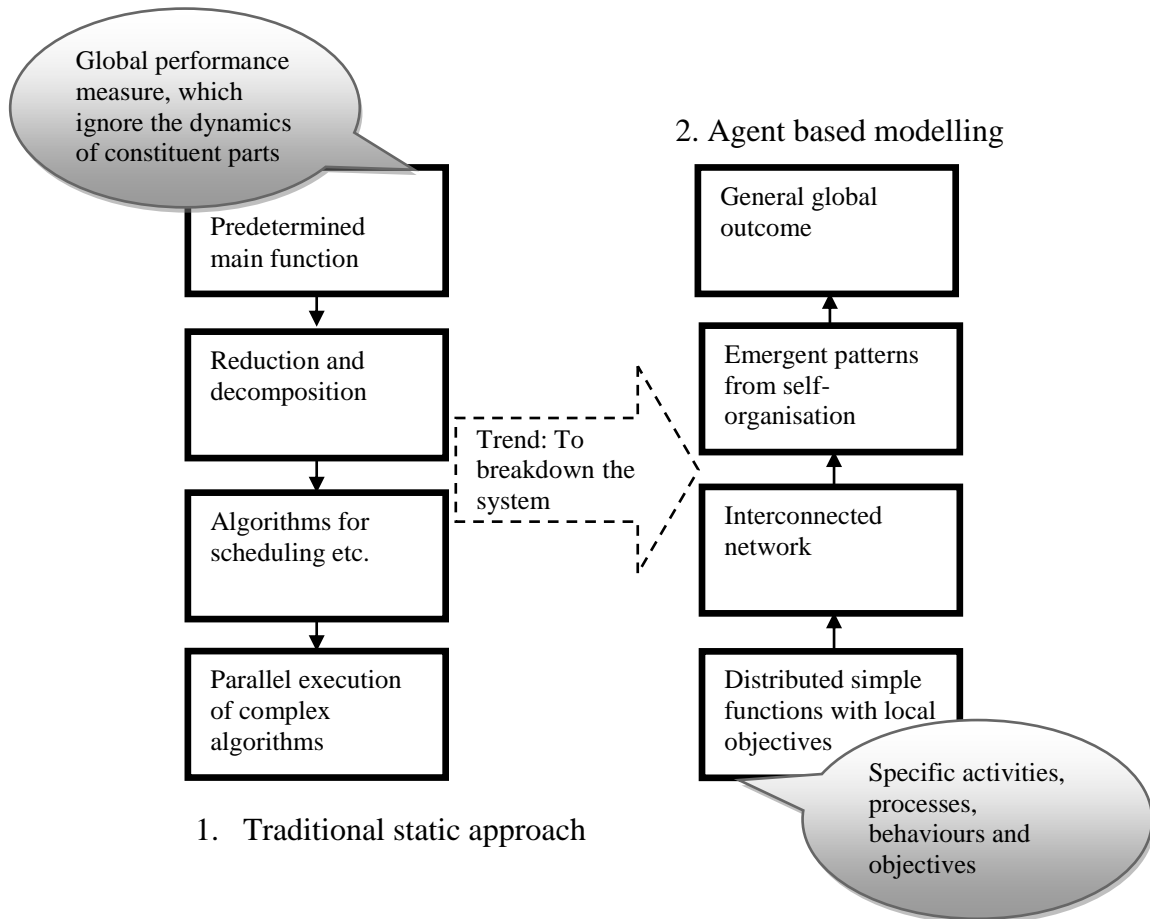


Figure 2.11 Comparison of traditional static modelling and agent based modelling (Nilsson and Darley, 2006)

Bottom-up methodologies focus on synthesising parts of complex systems, which have been broken down with the objective of achieving an understanding of simpler parts. This is driven by the user who perceives that the whole phenomenon of interest can not be observed unless; the focus is narrowed to the micro level, where specific activities, processes, behaviour and objectives can be defined. These sub-sections are referred to as agents, and interact and communicate with one another, whereby a coherent whole macro system is achieved as a result (d’Inverno and Luck, 2001). By defining

information processing rules each agent is provided with the ability to make decisions and have internal dynamics, which forms the behaviour of the system. The internal dynamics are particularly beneficial in capturing emergent behaviour that typically cannot be predicted upfront (Axelrod, 1997). The concept of emergent phenomena has received much interest in the ABM literature, due to it being a fundamental part of complex systems (Bonabeau, 2002). The emergence is driven by the interacting and interrelated networks of agents, where each agent interactively negotiates different goals in order to solve their particular problem. This also enables to focus on the local and unique parts of the system, whilst focusing on their own working principles, behaviours, states, and constraints, i.e. natural heterogeneity. The key difference of ABM from other simulation approaches was highlighted in Jennings et al. (1998) as:

“... it is the flexibility and high-level nature of these interactions (cooperation, coordination, negotiation) which distinguishes multi-agent systems from other forms of software and which provides the underlying power of the paradigm”

Based on literature review it was recognised that existing network approaches to cost estimation take a deterministic perspective, whilst in some cases taking the abstractions and assumptions limit representing reality. Furthermore, the implications of costs across the supply chain were understood in an isolated manner. The factors contributing to the complexity of supply chain uncertainty include scale, technological novelty, quantity of sub-systems, and the number of feedback loops (Datta, 2007). In order to manage these aspects organisations need to enhance the information system, configuration and organisational structure and the inherent processes related to supply and demand.

Tools such as AnyLogic (combines simulation approaches), WITNESS (discrete event), and Vensim (systems dynamic) have received increased interest. In common these tools enable better visualisation of the service delivery process through typically “what-if” type analysis.



## 2.6 Cost Uncertainty Management

From an academic perspective, researchers from economic, sociological and psychological schools have battled, but seem to have converged in recent times with a general agreement on the nature of uncertainty and risk and the impact of these on decision-making (Ward and Chapman, 2003). From a practitioner perspective, risk management permeates the worlds of strategy, finance, insurance, health, safety and environmental management, social policy and, of course, managed change through programmes and projects (Tummala et al., 2007). Researchers principally take two different main views of risk and the management of risk: optimisation and adaptation, as represented in Table 2.3. The optimisation principle refers to the quality of planning and the formalisation of planning problems. It fundamentally tries to answer the question of how to increase the quality of planning accuracy. Accurate planning is important for all projects. Research on planning mostly focuses on defining algorithms, heuristics and advanced planning systems. The contribution of planning is limited to providing the most accurate plan and to reduce state, effect and response uncertainty.

The adaptation perspective in contrast is associated with the question of the quality of intervening through actions. Those interventions are directed at increasing the ability to primarily prevent uncertainties from materialising and/or providing a cure for materialised uncertainties. The two perspectives of assessment and adaptation are not mutually exclusive. The foundation of 'good' decision making is based on the premise that we provide accurate predictions about threats, effects and response is adequate. As shown in Table 2.3, assessment refers to reducing the mismatch between perceived and actual risk. This involves increasing understanding of immeasurable uncertainty. The focus of adaptation lies on actions taken to prevent the risk from influencing project delivery. As an outcome of adaptation, reduced chance of failure is expected. If the mismatch between actual and anticipated risk is not closed, subsequent actions will deal with those threats that never existed on the first place or ignore threats that will materialise and adversely influence project performance. Thus, assessment serves the purpose of planning in order to capture uncertainty and adaptation refers to the actions that are taken to respond to risks. Furthermore, uncertainty management is considered to be an enabler of risk management. In order to achieve desirable risk management it is

necessary to have in place a sufficient uncertainty management process. Effective and efficient management of uncertainty requires a well balanced planning and control in order to achieve goals in a system (Koh and Saad, 2006).

Table 2.3 Assessment versus adaptation

	<b>Assessment</b>	<b>Adaptation</b>
<b>Input</b>	Uncertainty	Expectations
<b>Process</b>	Analysis	Action
<b>Output</b>	Reduced perceived uncertainty	Reduced threat

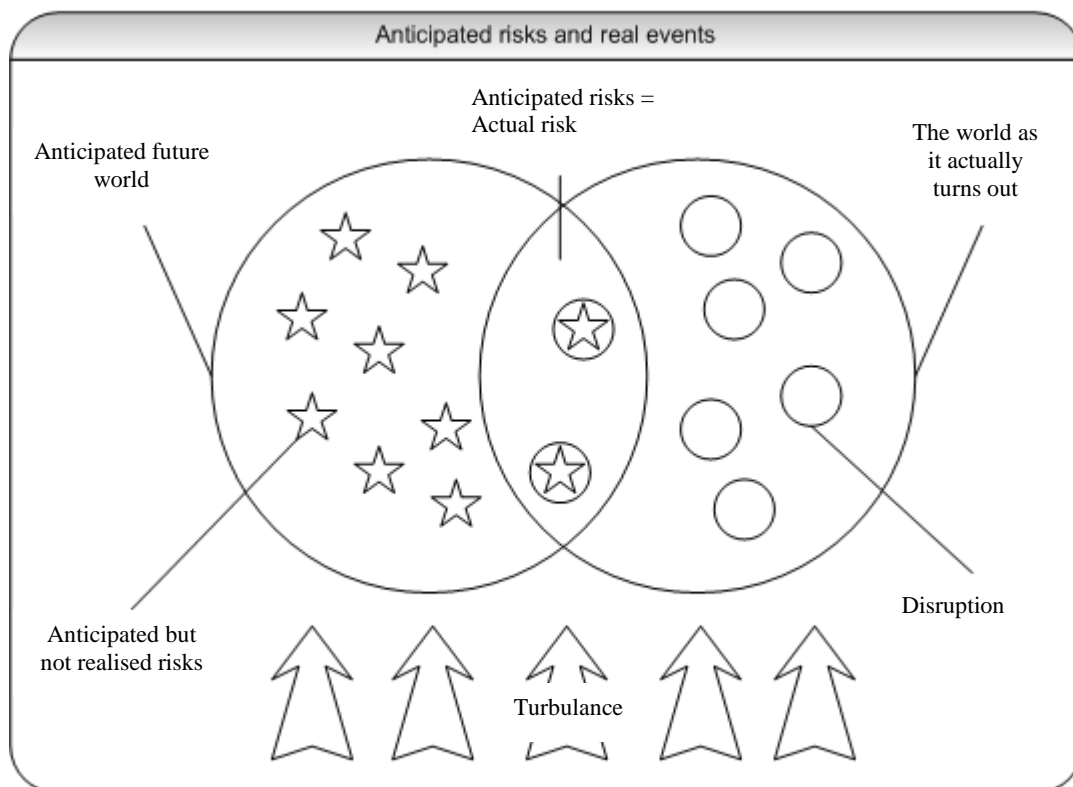


Figure 2.12 Planned risks and real events (adapted from Floricel & Miller, 2001)

It is not surprising that rules, processes, and procedures are defined to actively manage risks (e.g. Boehm, 1991). The majority of these project risk management as described in

the following section emphasise ‘action’ rather than assessing the quality of state, effect and response uncertainty, as represented in Figure 2.12.

### **2.6.1 Project risk management processes**

There are a number of best practice risk management processes and standards, all of which are largely similar in their advice. A comparison of these processes and standards can be seen in Hillson and Simon, (2007). In summary though, ‘best practice’ risk management processes can be deconstructed into five major stages (Erkoyuncu et al., 2009a), as represented in Figure 2.13 including planning, identification, analysis, response and management. Firstly, a project manager can apply risk management planning to define which activities should be taken to approach project uncertainties and to decide what risk impact areas are most significant in assessing and prioritizing risk. Secondly, risk identification allows project managers to single out uncertainties that may affect objectives. Thirdly, by using risk analysis a project manager evaluates quantitatively or qualitatively the likely consequences of uncertainties as well as the likelihood that uncertainties will become real. Quantitative modelling allows confidence levels in estimates to be ascertained, thus aiding managerial decision-making. Qualitative processes use subjective judgements to prioritize the risks identified for action. Fourthly, risk response planning focuses on planning and implementing actions to deal with the top priority risks. Lastly, all the processes stress the importance of keeping the process alive and learning lessons to build corporate knowledge for the future. An overlap between each of these steps exists due to their inter-linkage.

A continuous feedback mechanism guides firms to firstly identify uncertainties. Thereafter, uncertainties are assessed and analysed with a view to select the most significant threats. In accordance, based on the level of experience and the affordability to manage uncertainty suitable approaches to reduce their influence is selected, which leads to the process of controlling the influence of uncertainties.

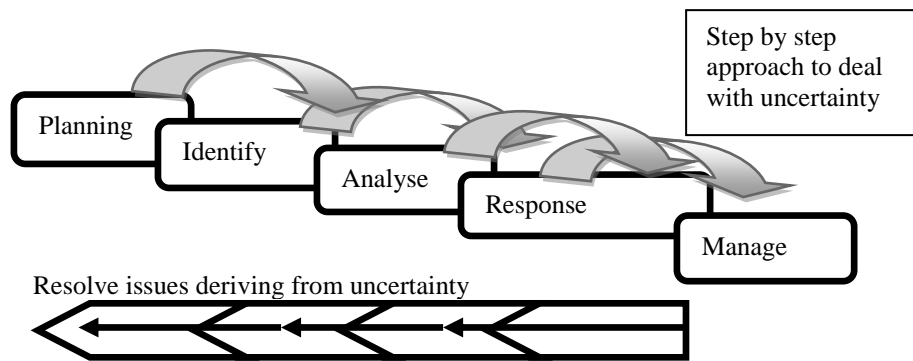


Figure 2.13 Managing uncertainty (Erkoyuncu et al., 2009a)

## 2.6.2 Project uncertainty management

An important claim and underlying rationale of the described risk management processes is the state of ‘perfect’ epistemic uncertainty possessed by risk actors (Jaeger et al., 2001), whilst additional assumptions include:

- A clear and unambiguous identification of the problem, its constituent elements and its causes
- Perfect information about the relevant variables concerning quantity and quality
- A well-developed model of the problem which incorporates all the variables likely to influence the decision outcome and a perfect understanding of the manner and scale of interaction
- An exhaustive list of all possible solutions
- An unambiguous statement of the objectives which is specific, quantifiable and internally consistent
- Perfect knowledge of the future consequences of each possible solution and their implications for the project (Ritchie & Marshall, 1993).

However, risk management as advocated by the Project Management Institute (2004) or the Association for Project Management (2005) is rarely conducted under these conditions. The management of risk is only as good as the predictive value of the risk estimates: “Some people believe when they plan that they introduce certainty, which is far from the truth. What they introduce is something to gauge their performance by.

Then when the gauge does not reflect reality, they fail to re-plan.” (Highsmith, 2004). The aspect of planning quality as a precursor for effective adaptation requires a wider view about risk management:

“Uncertainty management is not just about managing perceived threats, opportunities and their implications. It is about identifying and managing all the many sources of uncertainty which give rise to and shape our perceptions of threats and opportunities. It implies exploring and understanding the origins of project uncertainty before seeking to manage it, with no preconceptions about what is desirable or undesirable.” (Ward, 1999).

If our planning is poor, our decisions will be based on a distorted foundation- ‘propaganda’ and ‘lies’ (Smithson, 1989). Some research addresses this challenge and describe approaches to estimating and evaluating uncertainty (e.g. Chapman & Ward, 2000; Flage & Aven, 2009). Yet, surprisingly best practice standards pay insufficient attention towards the question of ‘historic data’ and the basis for calculating risks.

## **2.7 Research Gap Analysis**

A lack of connection between the research fields relevant to this study promoted the research to take an approach that combines a number of domains including IPS<sup>2</sup>, cost uncertainty management and modelling, and simulation. The literature search across these fields concentrated on capturing information regarding the definition of terms/concepts, the suitable techniques, and the experienced challenges.

From the IPS<sup>2</sup> perspective, Cohen et al., (2006) provides a comparison between the product and service supply chains in order to demonstrate the additional challenges that are experienced in the service business model. *To build on, there is a need to develop knowledge in classifying services and their associated activities/responsibilities for each kind of business model.* Also, Meier et al., (2010) emphasise that each IPS<sup>2</sup> solution requires an appropriate business model, whilst each contract creates different uncertainties. Along these lines, the paper suggests that the identification of

uncertainties is a major industrial challenge within the IPS<sup>2</sup> context. Hypko et al. (2010), presents the uncertainties that the solution provider and the customer faces at a strategic level. Though, the list contains a number of qualitative items that are challenging to include in cost estimation (e.g. uncertainty of customer dependence). Ng and Yip (2009) present the key challenges that are experienced in performance based contracts focusing on the defence industry in the UK (e.g. CfA). The paper classifies the challenges into: the implications of cultural shift, loss of control, lack of boundaries between organisations, reliance on supplier coordination, and the prediction of costs. Similar to Alonso-Rasgado et al., (2006), the paper suggests that the importance of life cycle costs is enhanced with the IPS<sup>2</sup> context. *Within the IPS<sup>2</sup> research domain there is an opportunity to enhance knowledge by identifying the types of uncertainties that are experienced across services delivered (e.g. training, health monitoring, and defect response). This also would need to address the shifts in uncertainties by adopting a CfA model. Additionally, there is a lack of research that lists the key components (e.g. cost drivers) of life cycle cost in IPS<sup>2</sup>.*

From the cost uncertainty management perspective, Arena et al., (2006) presents cost uncertainty analysis methods and recommends suitable approaches to utilise subjective opinion for improving the quantification (e.g. defining probabilities) and use of such information in cost uncertainty analysis. Along these lines, Tversky (1974) highlights that people judge the uncertainty in a subjective manner, which may create biases (e.g. psychology, experience). Kwakkel and Cunningham (2008), emphasises that there is little consensus on how to define uncertainty, what its characteristics are and how we should relate these characteristics to the appropriate treatment or management of uncertainty. *To build on from the referred literature, there is an opportunity to enhance knowledge that facilitates to reduce the subjectivity involved in prioritising uncertainties by offering systematic frameworks (e.g. scoring mechanism).* Ritchie and Marshall (1993) argue that risk management processes assume perfect knowledge (e.g. ability to determine the probability of occurrence and the impact), whilst considering the future consequences of each possible solution. *In order to extend this research, there is a need for frameworks that assess our understanding of the future, whilst also*

*developing an exhaustive list of solutions to the (e.g. prioritised) uncertainties through mitigation strategies.*

From the cost uncertainty modelling perspective, Mey Goh et al., (2010) present a critique of the current cost uncertainty modelling approaches. The paper classifies the key sources of uncertainty across the life cycle based on the nature of uncertainty (e.g. epistemic or aleatory). *To build on from this research there is a need for guidance on choosing specific uncertainty modelling techniques that would be suitable for particular uncertainties (e.g. failure rate).* Curran et al., (2004) provides a cost breakdown structure, which represents the key cost drivers along the life cycle. The paper additionally presents how the influence of uncertainty can be demonstrated through Monte Carlo analysis. *A further extension to this paper would be to specify the detailed cost drivers that are experienced in the defence industry in the in-service phase. Additionally, further research needs to define how specific uncertainties affect specific cost drivers by building relationships between the associated concepts.* Curran (1989) presents the use of Three-point estimating when measuring the influence of uncertainty. The paper suggests that such estimating provides the opportunity to take into account the probability of having a cost overrun, the degree of cost overrun and suggests elimination/removal strategies. Furthermore, given the difficulties experienced in quantitatively defining the Three-point estimates, often a qualitative assessment is considered to be supportive (Curran, 1989). Additionally, across a number of publications (e.g. Boussabaine and Kirkham, 2004; Asiedu and Gu, 1998; MoD, 2009) the qualitative nature of the Three-point estimating has been emphasised. *To build on from this body of research, there is a need for systematic frameworks to elicit expert knowledge to build a Three-point estimate.*

From the simulation point of view, the application of various simulation techniques including systems dynamics, discrete event and agent based modelling is widely growing across literature. Across these approaches the application of agent based modelling is attracting interest driven by the provided guidance in decision making associated to interactive and emergent behaviour that is experienced (Nilsson and Darley, 2006). The approach enables to generate robust and accurate results, whilst

assessing “what-if” scenarios for dynamic circumstances. Owen et al., (2010) highlight that the application of agent based modelling is highly flexible across operational and strategic problems. Cheeseman et al., (2006) applies agent based modelling to assess the design of the aftermarket service infrastructure. It was recognised that the importance of this modelling approach will particularly increase as the complexity of the maintenance solution grows (e.g. increase in number of suppliers or customers, scope of maintenance service). Within the cost estimation field only Ping et al., (1996) was found as an example application of agent based modelling. The paper presents a novel architecture whereby each agent represents a specific type of cost estimation method. The key benefit from applying the approach is highlighted as the representation of the communication while humans solve problems. With the enhanced dynamism in service delivery, the prediction of costs is increasingly becoming challenging, whilst agent based modelling offers a suitable means to tackle the emerging challenges. *Given the limited research that applies agent based modelling in cost estimation there is a need for research that presents how this modelling approach could be applied within the given context and to illustrate its advantages and disadvantages.*

## **2.8 Summary and Key Observations**

In Section 2.1, the author presents an overview of the research context by covering various aspects related to IPS<sup>2</sup>. These involve the applied business models, and the implications of the shift to IPS<sup>2</sup> in terms of cost and uncertainty. It is identified that in the defence industry the move to CfA has created major challenges in cost estimation particularly driven by the stochastic nature of service provision and the lack of experience in delivering holistic support packages.

In Section 2.2, the understanding in uncertainty is covered by explaining the various definitions and typologies for uncertainty. It is identified that whilst there are many definitions of the term uncertainty, largely driven by the context of interest, there is a commonality with regards to defining the nature of uncertainty. This refers to the cause of uncertainty in the variation between the expected and actual outcome. In Section 2.3,



literature for the concepts “Service” and “Uncertainty” were merged. It was identified that the classification of uncertainty into supply and demand sources is common.

In Section 2.4, the service cost estimation literature is introduced. The section presents an overview of the techniques that are available to tackle cost uncertainty. The techniques are classified into deterministic, qualitative and quantitative approaches. In Section 2.5, the current practice for cost uncertainty modelling in the defence industry is presented. Also the suitable methods for cost uncertainty modelling for the in-service context are presented based on the key challenges, including data issues and the stochastic nature of service delivery, which are experienced. In Section 2.6, the cost uncertainty management literature is presented and it is identified that there is an emphasis of risk management and a lack of research to manage uncertainty. It is highlighted that uncertainty can be considered as an umbrella term for both risk and uncertainty, whilst promoting the need for managing uncertainty.

In Section 2.7, the research gap analysis is presented, by considering each of the key research interests within this thesis, including: IPS<sup>2</sup>, service cost uncertainty modelling, service cost uncertainty management and simulation. In the following chapter the aim, objectives and adopted methodology is presented.



### **3 RESEARCH AIM, OBJECTIVES AND METHODOLOGY**

This chapter aims to present the aim, objectives and key research questions for this study. Furthermore, the Chapter also explains the rationale towards selecting a suitable research strategy. In Section 3.1 the research aim is presented, while also covering the derived objectives. Subsequently, the current research techniques, available research strategies and data collection techniques are covered in Section 3.2. Additionally, the approaches that were adopted to achieve research generalisability and validity are discussed. In Section 3.3, an overview of the methodology followed is presented for each of the steps that were pursued to fulfil the research objectives.

#### **3.1 Research Aim and Objectives**

The aim of this research study is:

To develop a framework for cost uncertainty management and modelling at the bidding stage of Contracting for Availability in the defence industry

The literature review in Chapter 2 enabled to set the basis for this research by capturing the current trends and research gaps. Furthermore, the findings and challenges observed from industry, as presented in Chapter 4, also supported in determining the scope of this research. In order to accomplish the aim of this study, a number of objectives have been defined. Within the bidding stage of the CfA context the research objectives are to:

- Define an uncertainty checklist to assist with the identification of uncertainties in costs and to explore the uncertainties that are explicitly experienced in CfA
- Develop an uncertainty prioritisation process to support in cost uncertainty management and modelling
- Build a framework that supports with formalising the subjective process of determining Three-point estimates, which are used in Monte Carlo simulation. In alignment, this objective also involves the development of a generic list of cost drivers within the scope of the defence industry

- Define a framework to manage cost uncertainties by applying an integrated approach, whilst suggesting a set of mitigation strategies
- Develop a framework, which can deal with dynamic uncertainty and can reflect the behaviour across the supply network
- Validate the frameworks through real life case studies and experts opinion.

The key research questions for the study are as follows:

1. How can major uncertainties be identified and prioritised at the bidding stage in a structured manner within the scope of the defence industry?
2. How can the potential impact of uncertainties be included to cost systematically at the bidding stage in a novel manner?
3. How can the bid development be supported to manage cost uncertainties in a generalisable manner across multi-platforms?
4. How can the dynamism in cost uncertainties experienced in CfA be modelled in a novel manner by applying an alternative approach to Monte Carlo simulation?

In Section 3.2, the author reviews the available research strategies, which have guided the development of the research methodology of this study.

## **3.2 Research Methodology Formation**

This section presents the elements that were considered in formulating the research methodology. Initially, the context of the research is described in order to guide the reader with the reasons for selecting the research strategy. Subsequently, the selected research strategy is discussed in light of the data collection techniques.

### **3.2.1 Research context**

This study focuses on the concept of uncertainty within the cost estimation research field. Furthermore, the bidding stage of CfA sets the contextual background of the study. The identified research gaps from literature review and the captured industrial challenges directed the research to reduce the subjectivity involved with uncertainty

considerations in cost estimation, whereby the focus is on cost uncertainty modelling and management. Due to the lack of research for the cost uncertainty concept within the in-service phase, the research built links across research fields such as “Industrial Product-Service Systems”, “cost uncertainty modelling”, “cost uncertainty management”, “cost estimation” and “simulation”. Since the study involves a domain with high industrial application, input from practitioners concerning the current practice and existing challenges have been required to offer innovative ways to tackle issues.

### **3.2.2 Overview for methods**

In order to define the term “research” a number of definitions have been proposed, while there appears to be limited agreements. Mertens (1998) defines research as one of the many different ways of knowing or understanding. The commonly agreed points regarding the definition of research includes, (1) discovery or creation of knowledge, (2) testing, confirmation, revision, refutation of knowledge and theory, (3) investigation of a problem for local decision making (Hemon, 1991). Bickman and Rog (1997, p.71) suggest that there are five essential components in conducting a research study: (1) purposes (e.g. goals), (2) conceptual context (e.g. theoretical and practical background), (3) research questions (e.g. attempted areas of interest), (4) methods (e.g. approaches and techniques for data collection), and (5) validity (e.g. validity threats). There are various purposes of a research including *Exploratory*, *Descriptive* and/or *Explanatory* (Robson, 2002). As represented in Figure 3.1, among these aspects, the research questions sit at the centre of the research design, while other elements can be considered as enablers. Furthermore, there are a number of factors that influence these aspects.

There is an emphasis that while building a research approach there are two main perspectives including deductive and inductive reasoning. The deductive approach relies on an initial basic premise, which is then logically applied to a specific case. On the other hand, inductive reasoning takes a bottom-up perspective of the world, by building from a particular case to general principles or from facts to theories. There are a number of ways to classify the wide range of methods that are available to design, carry out, and analyse the results of research.

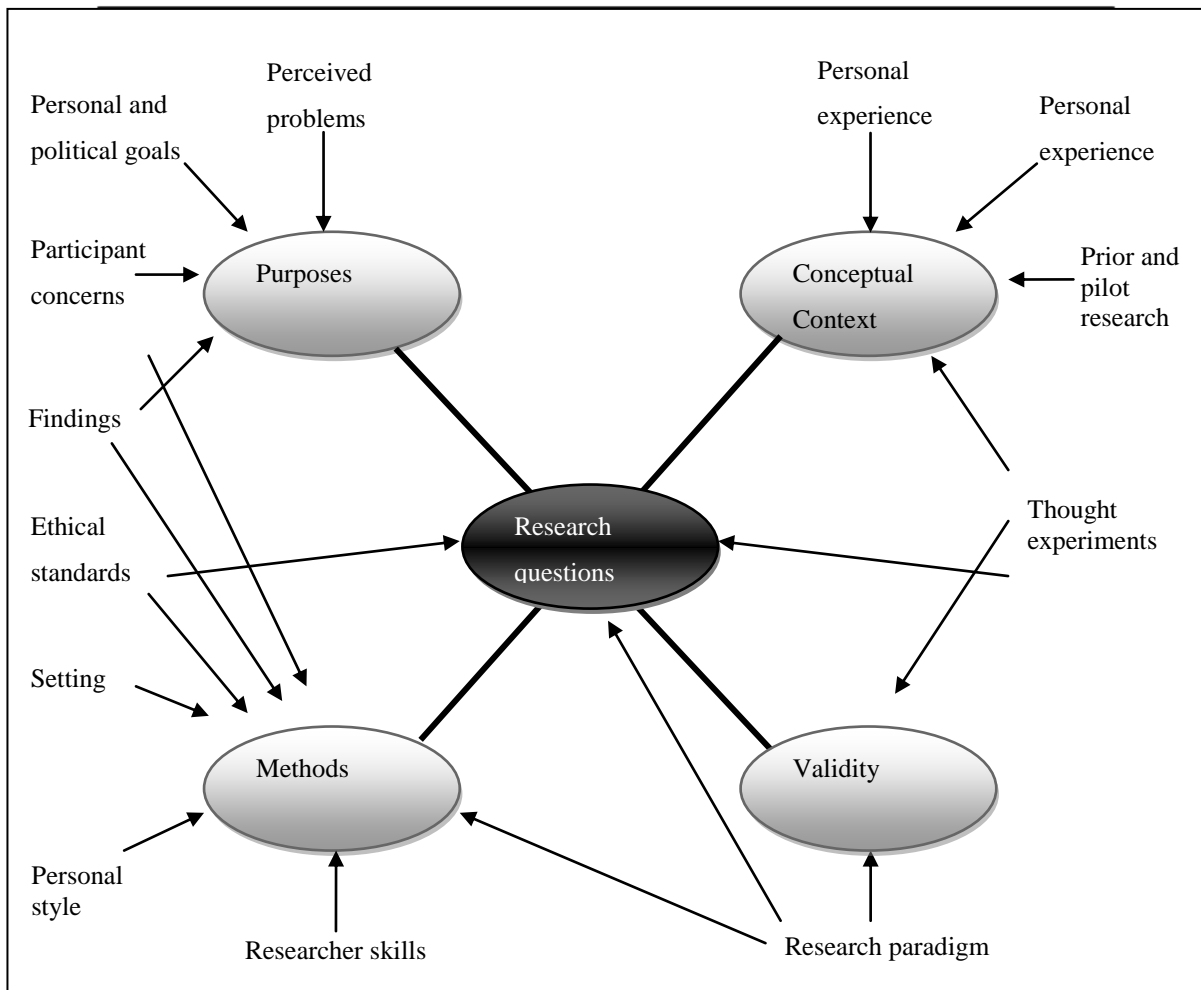


Figure 3.1 Contextual factors influencing research design (Bickman and Rog, 1997)

In Figure 3.2, in order to discuss research methods Blaxter et al. (1996) proposes three successive levels in terms of:

- *Families* which refer to two general strategies for doing research, whether it be qualitative or quantitative. These families have in some cases also been classified as fixed and flexible research designs (Robson, 2002). A classification in such a manner has been driven by the differences between the needs of the scientific and humanistic based research ways of approaching the real world
- *Research approaches*, which enable to design a research project, where a variety of approaches can be applied including action research, case studies, experiments, surveys, and workshops
- *Data collection techniques*, which cover a range of ways to elicit data including documents, interviews, observations and questionnaires

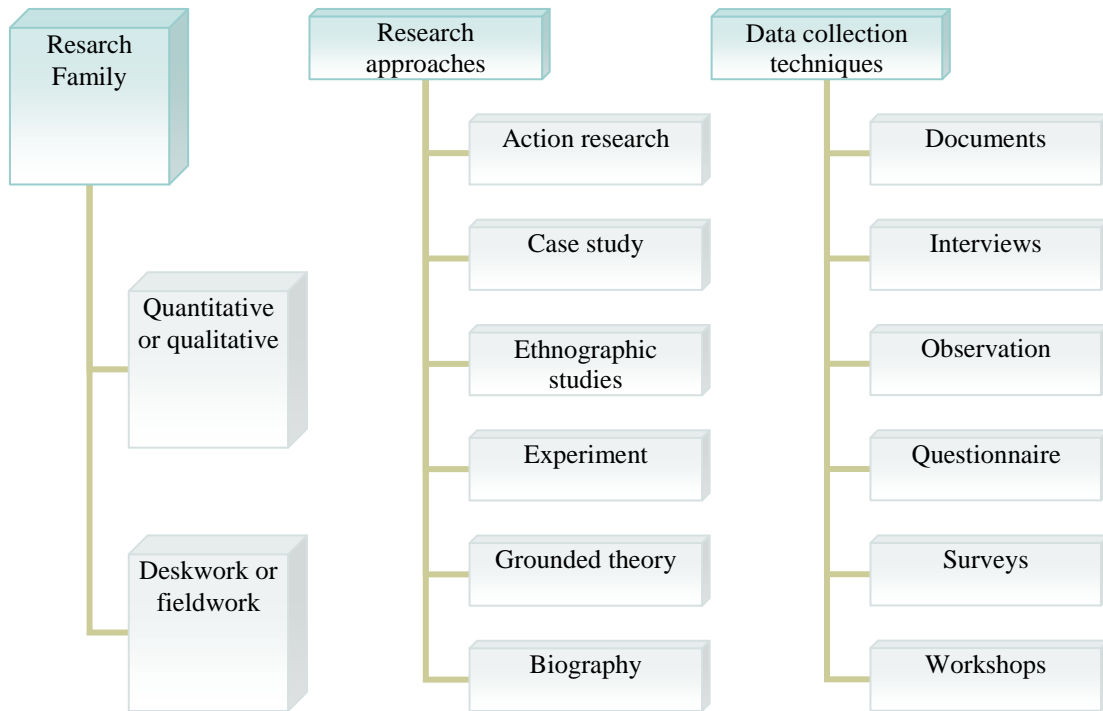


Figure 3.2 Research Methods

### Research family

The selection of a research design is driven by the needs of the particular fields' intentions to represent the real world. The quantitative perspective mainly focuses on collecting data from measurements and testing hypothesis in a deductive way. Quantification is a major theme in the approach, where the majority of collected data is of numerical format. The approach falls under the fixed design perspective, whereby a researcher can control the environment or the experimental conditions (e.g. laboratory).

The qualitative approach focuses on theory building, while taking an inductive approach. Cresswell (1998) describes qualitative research as: "an inquiry process of understanding based on distinct methodological traditions of inquiry that explore a social or human problem. The researcher builds a complex, holistic picture, analyses words, reports detailed views of informants, and conducts the study in a natural setting". It is also possible to apply a qualitative and quantitative approach in an integrated manner, which Robson (2002) argues that such an approach enhances the understanding of a topic due to the variation in the thinking involved in the inductive and deductive approaches.

## **Research approach**

A number of suitable research strategies have been considered in formulating the research design to this study. Throughout the research a range of research strategies were applied including, survey, case study, workshop and interview. The selection of these approaches has been driven by the research design, which took into account the industrial context of the study. The context necessitated in-depth interaction with industry to understand the current practice and to recognise the experienced challenges. Industrial input was also requested to validate the developed frameworks and tool.

### ***Case studies***

The case study is a research strategy which aims to understand the dynamics present in single or multiple settings in an in-depth manner (Eisenhart, 1989). The approach has been widely adopted across political sciences, sociology, urban studies, and other social sciences. The data collection procedure includes a range of ways such as documents, archival records, interviews, observations, physical artefacts. The evidence may be qualitative or quantitative. Furthermore, the data is analysed through descriptions, themes, and assertions. The selection of the case studies depends on the relevance of the participants to the investigated research domain. One of the main strengths of theory building from cases is the likelihood of generating novel theory. For this purpose, attempts to reconcile evidence across cases, types of data and different investigators and between cases and literature increases the likelihood of creative reframing into a new theoretical vision (Yin, 2008). A second strength is related to the resultant theory being likely to be empirically valid because there is such a level of evidence due to the intimate observation. The approach can have independence from prior literature or past empirical observation, which makes it a suitable approach to new research areas or research areas for which existing theory seems inadequate (Eisenhardt, 1989). As a weakness intensive use of evidence can yield overly complex theory (Yin, 2008). This is related to the fact that with a large amount of data it may be tempting to try to capture everything. Another weakness of adopting the case study approach is in relation to the results, which may be narrow and idiosyncratic theory (Eisenhardt, 1989). The approach



takes a bottom-up view and the specifics of data produce the generalised view. Table 3.1 illustrates a relationship between strategies and threats concerning research validity.

Table 3.1 Tackling threats to research validity (Robson, 2002)

<i>Strategy</i>	<b>Threat to validity</b>		
	<i>Reactivity</i>	<i>Researcher bias</i>	<i>Respondent bias</i>
<b>Prolonged involvement</b>	Reduces threat	Increases threat	Reduces threat
<b>Triangulation</b>	Reduces threat	Reduces threat	Reduces threat
<b>Peer debriefing</b>	No effect	Reduces threat	No effect
<b>Negative case analysis</b>	No effect	Reduces threat	No effect
<b>Member checking</b>	Reduces threat	Reduces threat	Reduces threat
<b>Audit trail</b>	No effect	Reduces threat	No effect

The validity of the research refers to the credibility of a study given the quality of research. There are a number of studies focusing on explaining the possible threats related to validity in qualitative research (e.g. Ahern, 1999). Lincoln and Guba (1985) propose three areas that emerge as possible threats to validity including reactivity, respondent bias, and researcher bias. Reactivity is in relation to the researchers' presence in the study, which may affect the behaviour of the involved people. Respondent bias may arise from obstructiveness or withholding information, due to the goal of providing information that the research specifically requires. Researcher bias focuses on aspects such as assumptions, and preconceptions, which are brought in to the study by the researcher. In contrast, Robson (2002) proposes a number of strategies to mitigate the influence of these threats to research validity. *Prolonged involvement* refers to interaction over a period of time. Triangulation uses multiple sources to enhance the rigour of the research. *Peer debriefing* aims to reduce researcher bias through debriefing sessions. *Member checking* involves checking transcripts, accounts, and interpretations made with respondents through various means (e.g. e-mail, face to face). *Negative case analysis* involves searching, for instances which will disconfirm a developed theory. *Audit trail* involves keeping a full record of the conducted activities during a study.

## **Data collection techniques**

The selection of the data collection technique(s) depends on the kind of information that is required, from whom and under what circumstances (Robson, 2002). The following data collection techniques have been utilised driven by the nature of the presented study.

### ***Literature review***

Literature review provides an understanding of existing research that covers current and the proposed future. In some cases the analysis of literature can provide as much intellectual and practical value as collecting first hand data. There are a number of reasons for conducting literature review including (1) identifying completed work, (2) preventing duplication of work, (3) avoiding pitfalls and errors of previous research, (4) supporting in designing the research, and (5) finding gaps in existing research (Hart, 2001). The main types of literature include books, articles, reports, conference literature, official and legal publication, and reviews.

### ***Surveys***

Across research domains survey has received much attention due to its ability to provide a quick, inexpensive, efficient and accurate means to gather information about a subject of interest (Zikmund, 1991). Most surveys involve the use of a questionnaire and three alternative approaches have been suggested, including self-completion, face to face interview, and telephone interview. Alternatively, as in the case of traffic survey, the data collection may rely on observation. The central features of a survey include (1) fixed and quantitative design, (2) collection of a small amount of data in a standardized form, (3) representative samples of individuals from known populations (Robson, 2002). Surveys tend to have a descriptive purpose and are not suitable for exploratory studies because follow on questions can not be gauged. There a number of benefits of the survey method, which have guided the author to apply it as one of the forms of data collection. Firstly, many questions can be asked about a given topic, whilst also offering considerable flexibility to the analysis. Secondly, there is flexibility in terms of how the questions will be administered (e.g. oral, written, electronic). Thirdly, by standardising the questions the author had the opportunity to compare results more precisely.

### ***Workshops***

Involve a relatively small number of participants exchanging information with potentially hands on exercises, usually lasting between 3 to 6 hours based on the workshops' focus. The basic advantage associated to workshops is the fact that through a single event the stakeholders dedicate all of their time focused on the concerned issue, also most of the relevant stakeholders being present at once, brings the advantage of taking certain decisions upfront, whilst saving time.

### ***Interviews***

Interviewing usually refers to personal interaction, whether it be face to face, by telephone, or through computers (e.g. Cisco WebEx), whereby the researcher asks questions and receives answers. There are three forms of interviews including structured, semi-structured and unstructured (Fellows and Liu, 2002). A standard set of questions are queried within the structured approach. The addition of individually tailored questions to a standard set of questions refers to the semi-structured approach. Lastly, unstructured interviewing refers to the in-depth problem identification or exploration of the subject usually at the initial stage of research. Interviews enable a structured approach to elicit information from a targeted audience and facilitate comparisons to be made. A major benefit of the method is associated to its ability to give the freedom to explore views or opinions in detail, including sensitive topics.

### ***Documents***

The analysis of a document refers to a written document, whether it be a book, newspaper, or magazine, notice, letter, or even non-written documents including the likes of films, pictures (Robson, 2002). During the research the author was provided with a number of documents that explain the current processes.

## **3.3 Research Methodology Adopted**

The presented research involves collaboration between the defence industry in the United Kingdom (UK) and Cranfield University through the 'PSS-Cost' project. The focus centred on addressing challenges that are faced in cost uncertainty modelling and

management at the bidding stage of CfA. The presented study combines theoretical and practical research in an applied manner in order to propose frameworks to solve industrial problems in managing and modelling cost uncertainties. The case of CfA creates a unique instance due to the unique uncertainty aspects that need attention. Furthermore, through literature review and industrial interaction it has been realised that these processes commonly follow ad-hoc procedures, which highly rely on expert judgment. Though, this promotes subjectivity which constrains uncertainty considerations to the individuals' experiences and achieving learning across projects is reduced. The uncertainty challenge is composed of five areas: (1) adequate and timely identification, (2) prioritisation, (3) reflecting justifiable ranges to the possible uncertainty, (4) defining responses to support uncertainty management, and (5) represent the dynamism in service uncertainty through a suitable modelling approach. The study was conducted in four stages, as represented in Figure 3.3.

The focus in Stage 1 is on understanding the context, which included literature review and attending industrial conferences. The literature review covered a number of areas including industrial product-service systems, service, uncertainty, cost estimation, cost uncertainty management and cost uncertainty modelling. A rigorous keyword search was conducted for each of these terms. The link between cost and uncertainty was the centre of attention. This phase also aimed to establish the available research approaches and to decide a suitable research strategy. Driven by the research objectives, the research followed an exploratory procedure, whereby both qualitative and quantitative approaches were considered. Furthermore, a qualitative approach was followed to assist the interaction with industrial collaborators. Semi-structured interviews, case studies and workshops facilitated the elicitation of expert knowledge for the purpose of this study. The main reason for the selection of these approaches is driven by the suitability of the features of these techniques to the presented study. Furthermore, the researcher has largely applied an inductive approach, while the deductive approach serves as a supplement to this approach.

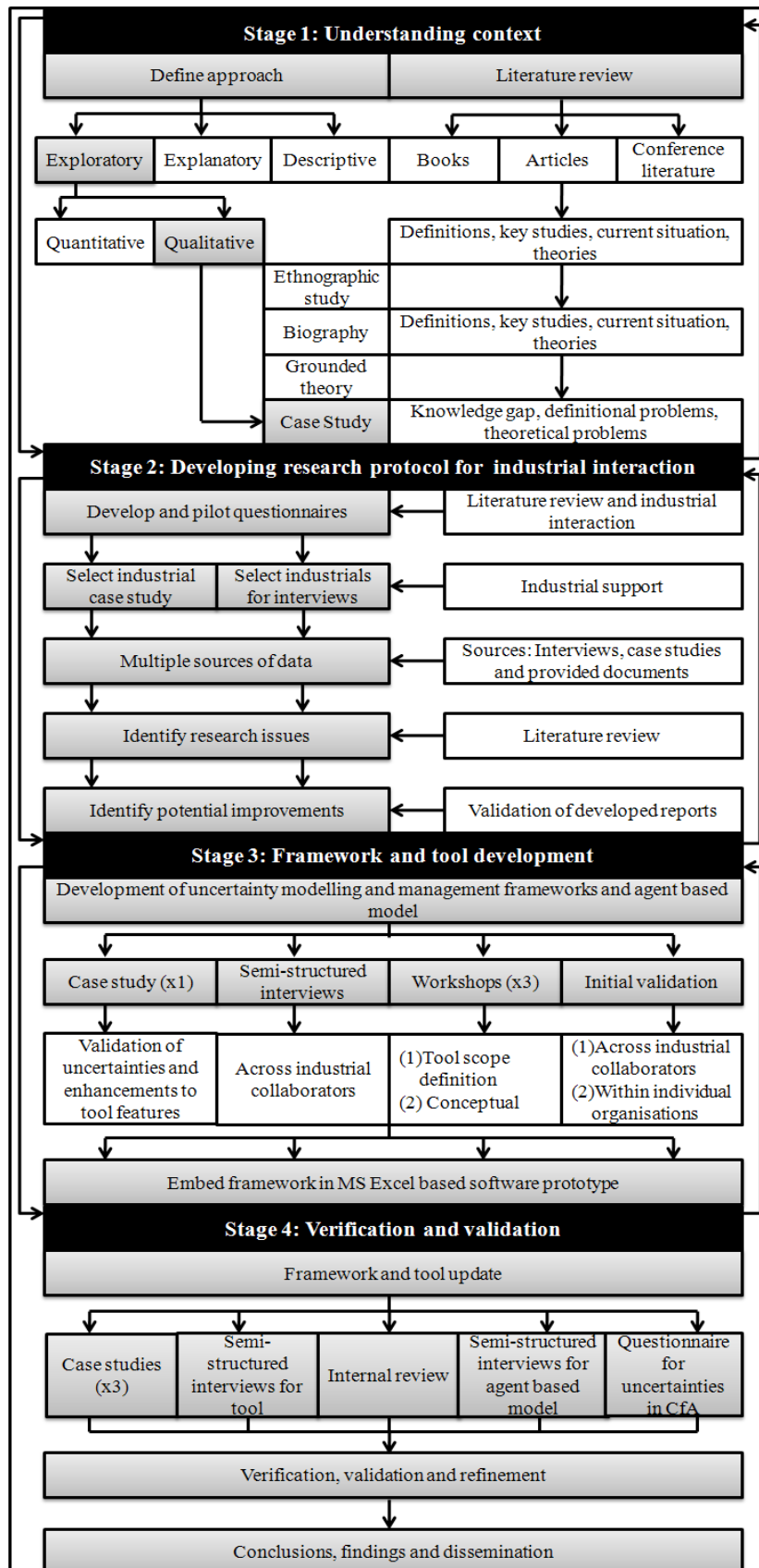


Figure 3.3 Research Method

In Stage 2 of the research, the main goal centred on data collection and ideas generation. Industrial interaction was achieved with three major defence companies and the defence customer in the UK. A research protocol was developed and followed in order to capture the current practice in terms of processes in cost uncertainty modelling and management. This involved conducting semi-structured interviews with all four organisations. The main benefit of this approach relates to the flexibility in capturing the required information. The method involved developing questionnaires prior to interviews and these were validated with one of the collaborating organisations. Initially, the focus was on the outcomes of the literature review and the aim was to compare the current processes with those that were realised from literature. The questions also aimed to capture the way in which the types of uncertainties change when moving into a CfA. Additional interest was to understand the challenges that existed in performing these processes and linking these with the research gaps that were identified in order to build ideas. This enabled the researcher to get an understanding of both the theoretical and practical challenges experienced. The full list of the questions is provided in Appendix A. Within this phase, the author also engaged with three case studies, which enabled to get a more detailed understanding. The case study approach enables to gain a rich understanding of the context of the research and the processes being performed. Furthermore, a range of data collection techniques may be employed and are likely to be used in combination, which offers the benefit of gaining a comprehensive understanding of a context of interest. The case studies concentrated on understanding the projects' characteristics, the cost model that had been developed, the set of cost drivers and the approach of capturing and managing uncertainty. Particular emphasis was put on drawing a link between the delivered services (e.g. spares, repair and training) and the types of uncertainty. The selection of suitable case studies was driven by both the availability of industrial support to the researcher at that time and the relevance to the presented study. As an outcome of this phase an overall framework was developed for the research, which integrates the uncertainty management and modelling considerations (see Chapter 5).

Within the second stage a total of over 100 hours of semi-structured interviews were conducted with cost engineers, project managers, support managers, engineering

managers, and functional experts (e.g. in risk and uncertainty). The contacts were reached by suggestions of key people in the business related to the research area, where functional experts primarily focused on. This set of expertise was considered to be sufficient for the conducted study. The triangulation approach was adopted to analyse outcomes from the semi-structured interviews, case studies and the provided documents. A range of documents including service content, current practice in cost uncertainty modelling and management were provided by one of the collaborating organisations. The triangulation involved transcription of the interviews, developing mind maps and writing reports to illustrate the learning to collaborating organisations. The reports were validated with the case studies based on the feedback that was provided. Across the case studies a cross-case synthesis was made to identify similarities and differences between the cases. This approach was taken in order to reduce the researchers' bias. Also it was considered suitable due to the focus of the research at the operational level rather than strategic. Throughout this process an audit trail has been kept in order to minimise researcher bias. This has involved keeping notes and audio records of interviews.

In Stage 3 of the research, framework development took place. The ideas identified in the second stage were further established through an initial workshop that aimed to define the scope for the framework development. Furthermore, the workshop aimed to establish a roadmap for industrial research requirements with regards to cost uncertainty. The workshop was attended by six participants across the collaborating organisations, while the experiences ranged between 10 to 25 years in various domains of cost engineering. The means to achieve solutions to the challenges was considered to be an MS Excel based software prototype tool, as it is commonly used across the defence industry. The tool has especially been developed for project managers, cost engineers, and uncertainty experts operating at the bidding stage of CfA.

The tool development process adopted a grounded empirical research approach. Along with input from previous stages in the research methodology, this phase also benefitted from analysis conducted on a case study, which provided contextual understanding. This case study was considered to be suitable due to its focus on spares and repairs in a

CfA in the naval domain. This supported in defining a suitable set of steps to consider the uncertainty management and modelling. In parallel, semi-structured interviews continued to further capture the current practice, where the interaction was largely with the naval domain. Furthermore, a survey was also distributed to collaborating organisations in order to elicit the types of uncertainties that emerge with CfA. Additionally two workshops were conducted in the air domain to enhance the generalisability of the research. The focus was on conducting an initial validation to assess the developed types of uncertainties for CfA, to define a comprehensive list of cost drivers for CfA and to define the sources of uncertainties within the suggested cost drivers. Within this phase a checklist of uncertainties for CfA, were developed. Literature review supported by defining the appropriate uncertainty prioritisation scheme, which was selected based on simplicity to understand guidelines and suitability to the given context. As an outcome of this stage the initial frameworks (including cost uncertainty management and modelling) were embedded in the software prototype. Some of the most important aspects to consider during the framework development process included generating reliable and useful results quickly and providing a user friendly tool. As a final element for this phase a workshop was conducted as an initial validation of the tool. This involved a presentation of the tool, and through a questionnaire feedback was collected, which assisted in making adjustments to the frameworks. The industrial interaction also provided information for the development of an agent based model. The kinds of information that was useful included: (1) contractual considerations, which (e.g. incentive and penalty) guide the interaction between the customer, OEM, and suppliers, (2) the main types of uncertainties, (3) the main types of cost drivers.

In Stage 4 the research verification and validation took place. An area of validation involved the identified uncertainties that were classified into emerging and transforming uncertainties for the CfA context (see Chapter 5). The validation took place through a questionnaire that was distributed internally to five researchers, and two industrial subject matter experts working within the Industrial Product-Service System domain. Within this session initially an overview of the uncertainties was presented, and explicit definitions for emergent and transformed uncertainties were provided.



The developed software tool was verified and validated for both of its embedded frameworks: cost uncertainty management (see Chapter 6) and cost uncertainty modelling (see Chapter 7). Semi-structured interviews were conducted with one of the collaborating organisations, which assisted in making modifications such as to the uncertainty list, the uncertainty prioritisation process. Also, three semi-structured interviews, using WebEx, were conducted to validate the tool. Additionally, three case studies were conducted within this process, while also internal verification activities took place. The case studies were participated by project managers, senior cost estimators and uncertainty specialists. Qualitatively, this involved conceptually assessing the coverage of uncertainties, the effectiveness of the uncertainty prioritisation scheme, range suggestion approach and the scope of uncertainty mitigation approaches. An iterative process was followed whereby modifications to the framework and the tool were made based on the received feedback. The results presented in Chapter 9, “Verification and Validation”, covers the outputs from the developed software tool based on inputs from the case studies. Also, various aspects such as generalisability and validity of results were assessed with each of the case studies through a questionnaire.

The final area of validation involved the developed agent based model, where four semi-structured interviews were conducted (see Chapter 8). This initially involved a presentation of the model by covering the relevant context, data requirements, assumptions, and outputs. Furthermore, with a pilot case study the applicability of the model was assessed and a number of implications were determined (see Chapter 8). As a result of these exercises a number of modifications were made to the model. The scope of the validation for this section was considered to be sufficient driven by the objective of contributing to the preliminary foundations of research in agent based modelling within the cost estimation literature. Throughout the research an iterative process was followed, which enabled to revisit findings. Information gathered from literature review during the first stage of the adopted research methodology fed into the second stage to build the questionnaires in light of the existing studies and research gaps. In contrast, feedback from the second stage into the first stage was achieved by gathering relevant industry based documents that further shaped the research gaps and current practice. The second phase of the adopted research methodology, which fed into

the third phase, built an understanding of the current practice and enabled to consider suitable measure to tackle challenges. Conversely, the third stage fed back into the second stage by further clarifying the current practice and in understanding the actual scope of existing processes. The third stage of the adopted research methodology enabled to provide the basis for the verification and validation that took place in the fourth stage. In contrast, the fourth stage enabled to refine the frameworks and tool.

The combination of case study, workshop, survey, and interviews as the means to collect data in the commercially sensitive research domain of cost uncertainty was considered to be suitable by the author for a number of reasons. Firstly, the approaches offered flexibility and a structured manner to elicit information from the industrial collaborators. Secondly, the approaches enabled to elicit information within the given time constraints. Thirdly, given the qualitative nature of the research application of such structured approaches enabled to elicit reliable information that can be generalisable.

### **3.4 Summary**

In Section 3.1 the aim and objectives to this research were covered. Section 3.2 presents an overview of the concept of research, by considering aspects such as research approaches and data collection techniques. Due to the industry oriented nature of the study a qualitative approach was taken, whereby through an explanatory perspective case study research has been conducted. The chapter explained various issues associated to the validity of qualitative research, whilst strategies to respond to issues were also covered. In Section 3.3, the adopted research methodology was explained, where each of the four phases were covered including “Understanding context”, “Developing research protocol”, “Framework and tool development”, and “Verification and validation”. An emphasis was put on explaining the steps in the research.

The following chapter presents the second phase of the research methodology, where through industry interaction results concerning the current practice in cost uncertainty management and modelling are presented.

## 4 CURRENT INDUSTRIAL PRACTICE

This chapter presents the current practice and the challenges highlighted across the industrial collaborators. Contracting for availability (CfA) is expected to become more prevalent with further transfer of responsibilities in the operational phase from the customer to the supplier within the defence industry (e.g. The Availability Transformation: Tornado Aircraft Contract-ATTAC). In parallel, with operational life spans covering several decades, the ability to deal with uncertainty in cost estimation for support activities is becoming critical at the bidding stage. The chapter initially provides an introduction to the current practice in uncertainty considerations in the CfA context. Section 4.1 presents the industrial interaction and the information that was collected for the current practice related to cost uncertainty modelling and management. Section 4.2 covers the challenges that have guided the development of the framework.

Increased involvement in equipment operation

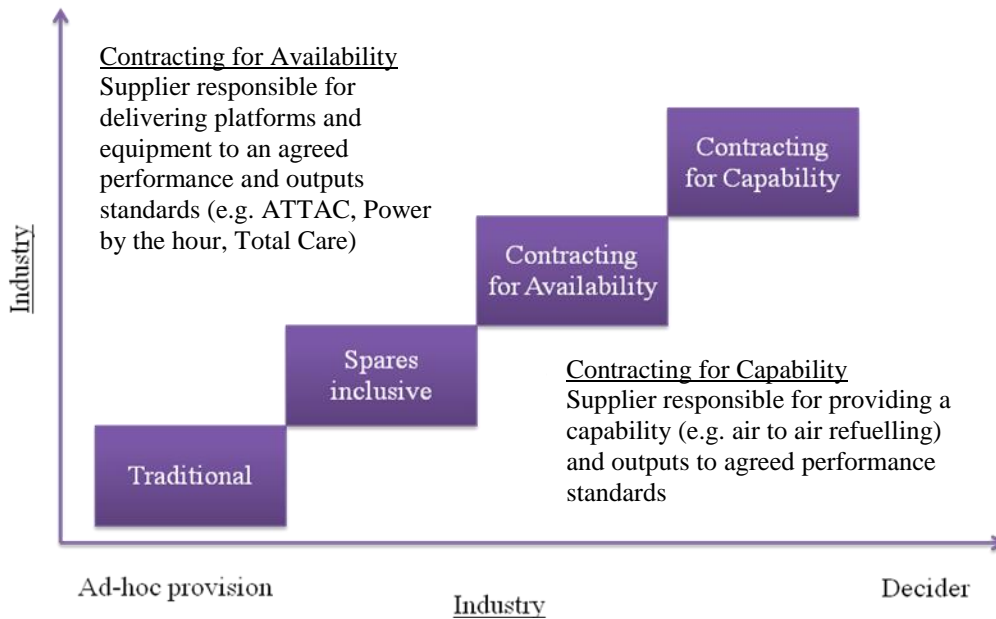


Figure 4.1. Transition of contractual approaches (Erkoyuncu and Cheruvu, 2010)

Based on the industrial interviews it was found that CfA are currently being awarded on the basis that they span the manufacturing and in-service phases of the CADMID lifecycle but the bids are often prepared and submitted in earlier phases (Erkoyuncu et

al., 2009a). The move towards CfA has followed an iterative transition, which has experienced a shift from providing the traditional business model into spares inclusive maintenance contracts, contracting for availability and contracting for capability, as represented in Figure 4.1. The traditional business model stands at one extreme where product and service is considered separately and service is considered to be ad-on features to sold products.

Under CfA the availability level is made the essence of the contract. The in-service phase for current contracts typically runs from ten to thirty years but there is often an ‘evergreen renewal’ arrangement in the terms and conditions which allows the contract to be re-baselined at shorter intervals, typically five years. At each iteration of this interval the estimating uncertainties become smaller as experience of cost outcomes increases and the time to contract completion decreases. Depending on the concept of the PSS solution, the individual equipments of which it is comprised may have a shorter design life than that of the PSS as a whole. This approach can mitigate problems such as obsolescence at the equipment level provided the successor equipment has the same form, fit and function. In these circumstances it can be helpful to consider uncertainties on two levels – first at the overall PSS level, and second at equipment level, whilst for each level a life cycle can be specified.

For a PSS of significant size (e.g. £100 million or greater in contract value), industry tends to start working on design solution and in-service support solution as long as three to four years before winning a contract, i.e. at the concept or assessment phase of CADMID. During these phases a number of technical and business reviews are conducted to assess the feasibility, affordability, and profitability of the potential project. These reviews, which take place on a cross-functional basis (e.g. engineering, procurement, operations, commercial, and finance) inform decisions such as “bid / no bid” and whether to accept an availability contract for the manufacturing and in-service support phases if offered. The bidding process begins with the completion of the concept phase where aspects such as cost, price, present value (P.V.) analysis, strategic alliance to objectives has been assessed and subsequently a request for a quotation (RFQ) or invitation to tender (ITT) has been received by the solution provider. During

the bidding process a number of areas such as cost, risk, uncertainty, and competition are assessed across many reviews that are typically undertaken within the 3-6 month duration. Furthermore, the bid estimate provides the initial project cost and timescales. However, at the bid phase the level of understanding of the final equipment usage will be at its lowest so cost estimate accuracy will also be low, which typically causes underestimation. With continual re-estimation at suitable phases across the lifecycle a greater level of accuracy of prediction can be achieved. As represented in Figure 4.2, the amount of available time to implement a rigorous approach to integrate uncertainties to cost estimation is limited (1b-2a). This further promotes the need for guidelines to support the process of considering uncertainty in cost.

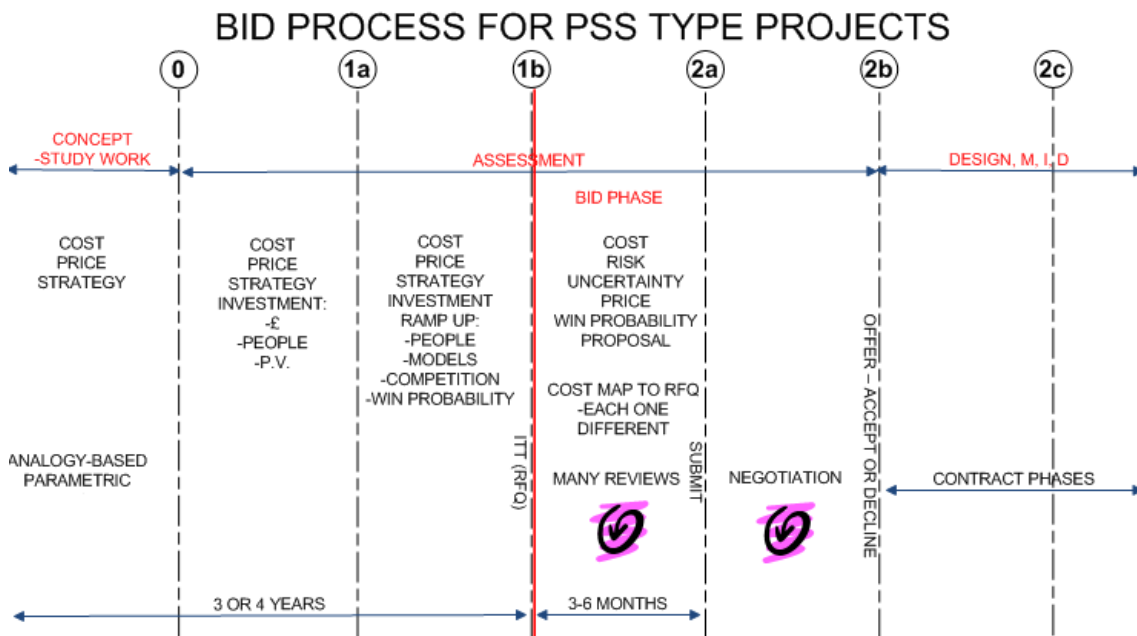


Figure 4.2 Typical bid process in PSS projects: Contracting for Availability

Cost models are established at the earliest possible phases of the CADMID lifecycle and are evolved as the lifecycle proceeds. Lower levels of detail are progressively added to the design solution and in-service support solution, e.g. by clarifying and elaborating requirements of the PSS with the customer, by performing trade studies to examine design or in-service support solution options, and by producing derived requirements to capture design decisions. Although it is usually possible to enumerate risks and

uncertainties early on in this process, the challenge for industry is to quantify them sufficiently, and with adequate levels of confidence, to support discussions on affordability (with the customer) and profitability (internally and with the supply chain). For example, cost estimates at the concept phase are based on high level assumptions and use parametric or analogy based tools. It is often not until the assessment stage or later, when the maturity of the design is progressing, that it becomes possible to quantify uncertainty by means of the more accurate estimating methods. This challenge can be characterised slightly differently for each of the bidding scenarios in the UK defence industry. These are (MoD, 2007b):

- The competitive situation: the price that the customer agrees is governed by the competition in the market
- The single bid situation: the price is established through negotiation between customer and supplier. This involves the customer having visibility of the supplier's costs and cost-to-price calculation including profit margin.

The trend from traditional contracting towards CfA sustains the challenge for suppliers to be confident in the affordability of their offering (e.g. to be assured of both winning the bid in the competitive situation, and of winning the value-for-money argument with the customer in the single bid situation). It has also increased the challenge for them to be confident in their own profitability as a result of the transfer of risk and uncertainty from customer to supplier, particularly in the single bid situation. The following section presents the industrial interaction that took place, while covering the findings regarding the current practice and the experienced challenges (Phase 2: Developing research protocol as represented in Chapter 3).

#### **4.1 Determination of the Current Practice and Challenges**

The research initially aimed to determine the current practice and existing challenges within the defence industry when considering uncertainty in cost estimation. Within the second phase of the research, where the current practice and challenges were determined, as represented in Figure 4.3, a number of forms of interaction took place with industry including semi-structured interviews, and case studies.

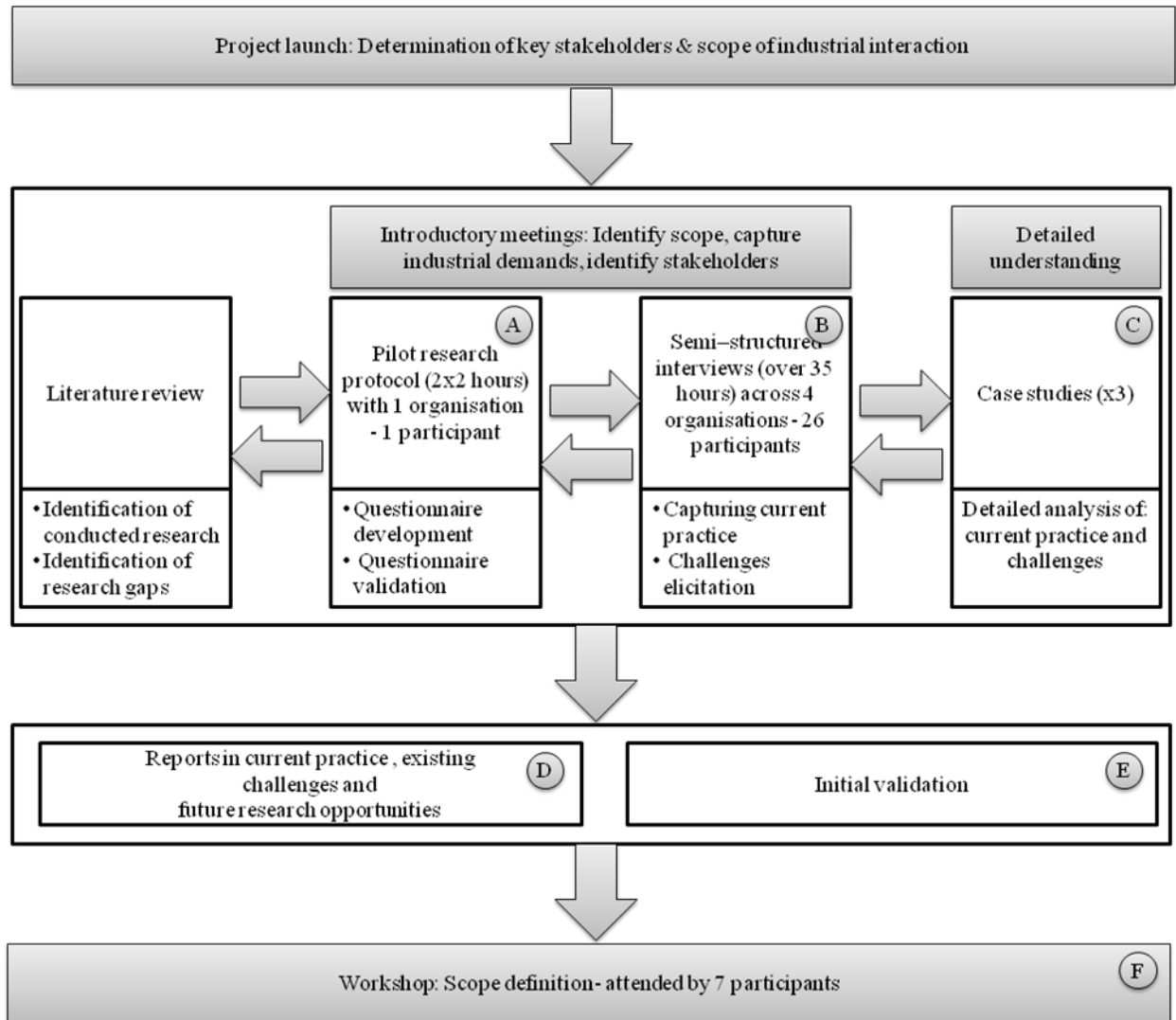


Figure 4.3 Overview of research methodology for Phase 2

The literature review facilitated by supporting with the development of questionnaires, which were based on understanding the research context and gaps. Also the review enabled to guide with selecting suitable measures to tackle existing challenges. The interaction with industry began with a project launch event, which was attended by participants from all pre-mentioned collaborators. The event consisted of presentations from three of the collaborating organisations, which focused on the context of the study and the industrial requirements. The goal of the event was primarily to meet collaborators of the project, to identify stakeholders and to capture an initial set of expectations. This led to setting up of initial meetings of 2 hours to further set out the expectations on an organisational basis.

#### 4.1.1 Pilot research protocol

Pilot research protocol refers to the initial set of interactions with a participant (Engineering Manager - 31 years of experience) from one of the collaborators. In total two meetings, each lasting 2 hours were conducted. In the initial meeting an unstructured interviewing approach was adopted in order to explore the conceptual scope of the questions. The respondent highlighted that there is increasingly a customer driven attitude with CfA, which has resulted in cultural implications over the organisation. This refers to the reorganisation of the business processes of this organisation in order to promote standardised processes across different departments (e.g. engineering, commercial, and finance). Within this structure the bidding team was determined to be the suitable stakeholders to this study, due to their responsibility in building cost estimates.

Based on the first meeting and literature review, a list of questions was developed for the interviews with industry. The second meeting focused on structuring the interviews and reviewing the questions. The goals of the questions were to realise how good the organisations are at cost estimating including the strengths and weaknesses, particularly from the perspective of integrating the influence of uncertainty. These also involved capturing existing processes used to consider uncertainty in cost estimation. The questionnaire was designed to elicit information within a two hour time frame. It was also agreed that the learning through each interview would be validated via developed reports provided to interviewed people. The activities undertaken during this process involved a collaborated effort with the members of the PSS-Cost project, whilst the analysis for uncertainty was conducted by the author. A sample of the key questions specified at the early stage of the research is provided below, whilst the full list is provided in Appendix A:

What are the factors that influence the process of agreeing CfA?

How is the supply network influenced by CfA agreements?

How is uncertainty defined?

What is the link between uncertainty and cost estimation?

How is the influence of uncertainty included in cost estimation?



### 4.1.2 Semi-structured interviews

Following the pilot research protocol, semi-structured interviews commenced. Based on the interested stakeholders that were realised at the project launch event, an initial set of people to interview were identified. In this process also support was gained from leading collaborators within each of the participating organisations in terms of finding and inviting suitable experts for the interviews. The list of potential experts to contact grew at each meeting driven by suggestions by interviewees. The interviews were typically arranged for the duration of two hours. Furthermore, the adopted process for eliciting information from the semi-structured interviews is represented in Figure 4.4.

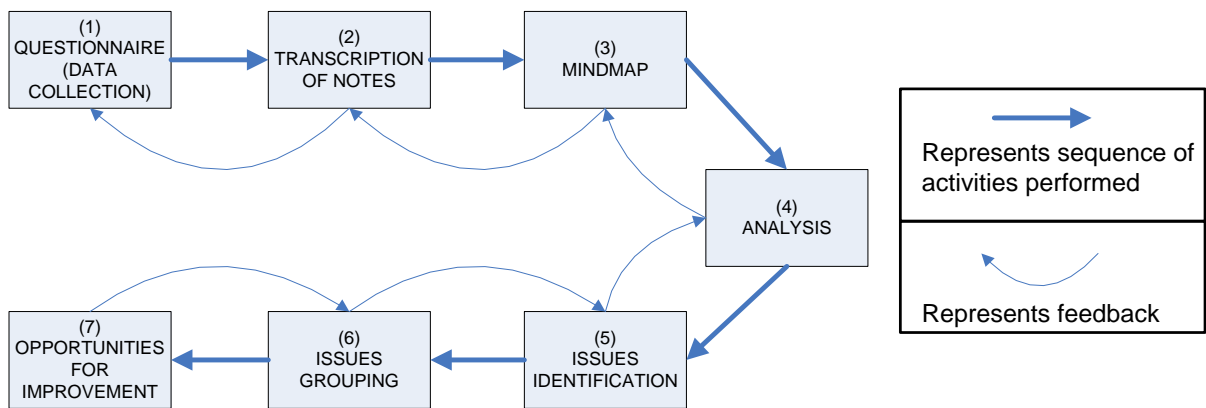


Figure 4.4 Process of eliciting information from industrial interaction

During the initial phases of the semi-structured interviews a collaborative approach with the other researchers in the PSS Cost project was conducted to elicit and to transcribe the gathered information. This approach was beneficial during the early phases as it enabled to further clarify the current practice and challenges internally. As the research matured the authors' research became increasingly independent. Activity ❶ focused on the data collection process, involving interviews, case studies and gathering documents. The questions were designed to elicit broad coverage of likely issues from each interviewee and case study. During the interviews, the author took notes and recorded the interviews. Appendix A lists the questions and key summary responses collated from interview notes (activity ❷). A sample of the response is provided below, where a sample for a complete response is provided in Appendix B:

How do you differentiate between risk and uncertainty?

Risk is an event, where things can go wrong. On the other, hand uncertainty relates to clarity of something, i.e. requirement. These may change from project to project and within the duration of a project. At the bidding stage, factors that affect cost and schedule are considered.

Examples: - What are the planning assumptions or are the requirements clear?  
- Technical specification?  
- For each activity different departments may produce performance attributes, these may contain holes and/or double counting

The triangulation approach was adopted to analyse outcomes from the interactions. This involved transcription of the interviews, developing MindMaps and writing reports to illustrate the learning to collaborating organisations. Appendix C shows a sample MindMap (activity ③), which was developed during this phase. This represents how MindMap techniques were used to analyse the summary responses (activity ④), identify the major issues (activity ⑤), and inform their grouping with issues on other projects (activity ⑥). Finally, a subset of issues was selected as opportunities for improvement (activity ⑦).

The following section provides a detailed explanation of the outcomes from the interviews with each of the participating organisations. During this process the author, along with asking the pre-mentioned questions, also detailed questions about uncertainty was also gauged, including:

How do you differentiate between risk and uncertainty?

What process do you follow to incorporate uncertainty into cost estimation?

What are the typical types of uncertainty in different life cycle stages of CfA?

How do you prioritise uncertainties?

What are the influences/ impacts of the uncertainties on costs?

What are the challenges in incorporating uncertainty to cost?

## Organisation A

With this particular organisation 11 semi-structured interviews were undertaken; seven of which was conducted in a face-to-face format, and four commenced as telephone interviews. An overview of the people interviewed (e.g. years of experience in cost uncertainty analysis), the number of meetings, meeting topics and their durations is provided in Table 4.1. Apart from the interaction (including three semi-structured interviews) with the risk specialist of the organisation the interviews did not follow a sequence of order and the intention was to capture a broad understanding of uncertainty in cost estimation from different perspectives.

Table 4.1 Overview of industry interaction with Organisation A

Meeting	Meeting Duration (Hours)	Main Topic	Job role of attendee(s)	Experience (Years)
Face to face, semi-structured interview – 1	3	Overview of uncertainty	Risk specialist	28
			Software specialist	24
Face to face, semi-structured interview – 2	1	Differences between risk and uncertainty Cost uncertainty processes	Risk specialist	28
Face to face, semi-structured interview – 3	1	Cost uncertainty processes	Cost estimator	4
Face to face, semi-structured interview – 4	1	Types of uncertainty in CfA	Upgrade specialist	17
			Support manager	14
Face to face, semi-structured interview – 5	1	Contractual considerations in building CfA	Supportability engineer	23
Face to face, semi-structured interview – 6	1	Cost uncertainty modelling	Bid team manager	29
Face to face, semi-structured interview – 7	1	Experienced differences when moving into CfA	Risk specialist	28
Telephone, semi-structured interview – 1	1	Differences in software and hardware uncertainty considerations	Software specialist	24
Telephone, semi-structured interview – 2	1	The role of the finance department with uncertainty considerations	Finance manager	18
Telephone, semi-structured interview – 3	1	The key types of uncertainty and process to structure uncertainty	Supportability engineer	17
Telephone, semi-structured interview – 4	1	Uncertainty management process	Engineering manager	31

Table 4.2 illustrates an overview of the key outcomes from the semi-structured interviews, which were conducted face to face. The table focuses on the current practice and the experienced challenges.

Table 4.2 Overview outcomes from the face-to-face interviews with Organisation A

Meeting	Current Practice	Challenges
Face to face, semi-structured interview – 1	<ol style="list-style-type: none"> <li>1. Increased emphasis on uncertainty in fixed price contracts compared to cost plus contracts</li> <li>2. Bidding team is responsible for uncertainty considerations and the customer judges processes</li> <li>3. Common application of Monte Carlo simulation</li> <li>4. Uncertainty analysis is conducted to get an understanding of the confidence level in the cost</li> </ol>	<ol style="list-style-type: none"> <li>1. Differentiating risk and uncertainty</li> <li>2. Dependency on experience in considering uncertainties and requirements for systematic elicitation processes</li> <li>3. Determining the time to retire risk (e.g. remove from project considerations)</li> <li>4. Organisational learning is not conducted in a systematic manner (e.g. to learn loops that cause under estimating)</li> <li>5. Lack of standardisation among individuals to consider uncertainty</li> <li>6. Balancing estimate quality &amp; effort</li> </ol>
Face to face, semi-structured interview – 2	<ol style="list-style-type: none"> <li>1. Emphasis on cost and schedule when considering uncertainty influence</li> <li>2. Risk defined as events, where things can go wrong</li> <li>3. Uncertainty defined as lack of clarity</li> <li>4. Uncertainty varies from project to project and throughout a project</li> <li>5. The work breakdown structure is used to structure service uncertainties</li> <li>6. The risks and uncertainties get classified in a risk register</li> <li>7. Monte Carlo simulation enables to derive spreads for confidence level</li> </ol>	<ol style="list-style-type: none"> <li>1. Need to store data in a systematic manner, in order to support “Lessons learned” initiatives</li> <li>2. With the scale of operations reaching 14 to 15 sites difficulties in standardising uncertainty considerations, causing challenges in e.g. estimate boundaries</li> <li>3. Functional activities (e.g. maintenance) are proving to be more challenging</li> <li>4. Insufficient consideration of uncertainty causing under/over estimates</li> <li>5. In order to prioritise uncertainty subjective expert opinion is used</li> </ol>
Face to face, semi-structured interview – 3	<p>The following order of activities were suggested to consider uncertainty:</p> <ol style="list-style-type: none"> <li>1. Uncertainties are qualitatively identified (e.g. checklists, brainstorming, experts reviews, and cross functional workshops)</li> <li>2. Assess the cause and influence of uncertainty</li> <li>3. Quantify the influence on cost, through Three-point estimate</li> <li>4. With the realisation of the impact, uncertainty is managed</li> </ol>	<ol style="list-style-type: none"> <li>1. Engineers may have characteristics such as impatience or/and limited time available to make the uncertainty considerations, as these processes tend to be considered at the end of the cost estimating procedure</li> <li>2. The current process of thinking of uncertainty follows the traditional considerations, but the sources vary within the CfA context and require sufficient understanding (e.g. a checklist)</li> <li>3. The solution provider needs to be able to justify the uncertainty considerations</li> </ol>
Face to face, semi-structured interview – 4	<ol style="list-style-type: none"> <li>1. Uncertainty defined as a measure of maturity for conducting a given task</li> <li>2. No standard list of uncertainty categories exists, but commonly the WBS gets considered</li> <li>3. The key set of uncertainties for the given project: maintenance, escalation value, transition, arising rate or failure rate, IT, and exchange rate</li> <li>4. Performance measures were</li> </ol>	<ol style="list-style-type: none"> <li>1. Data integrity, whilst some cases cost estimates are developed for activities with no historical experience</li> <li>2. Enhanced scope where a lack of prior knowledge exists (e.g. supply chain)</li> <li>3. Uncertainty prioritisation is a major aspect that needs adequate consideration, particularly due to the fact that a WBS can be detailed at such a level (e.g. thousands of components) that a need for prioritisation</li> </ol>

	established, focusing on value, availability of equipment (e.g. aircraft), spares availability, training, technical support, and affordability	emerges
Face to face, semi-structured interview – 5	1. Typically workshops were conducted to identify and classify uncertainties	1. Lack of understanding in meeting performance requirements as performance tended to be internally determined and managed by the customer 2. Inexperienced staff can cause learning to diminish, which can affect information flow 3. Determining when a risk can and whether it should be turned into an uncertainty 4. Lack of time available for risk and uncertainty analysis, which the degree may vary based on experience
Face to face, semi-structured interview – 6	1. Software support packages such as Crystal Ball and PERT Master widely used to define probability distributions 2. Variation in approaches to consider uncertainty (e.g. expert opinion, Three-point estimates)	1. Further consideration of uncertainty in baseline activities (e.g. maintenance) 2. Capturing differences between risk and uncertainty and the link with opportunity 3. Review uncertainty after bid acceptance
Face to face, semi-structured interview – 7	1. Product breakdown structure: What is the equipment? 2. Work breakdown structure: What sequence of activities is necessary (e.g. how the equipment is assembled)? 3. Cost breakdown structure: What will the cost for each of the activities be? 4. Risk or uncertainty breakdown structure: What are the key challenges? 5. Historically the component level availability was focused on, with CfA the focus is on system level reliability	1. In order to better understand uncertainty, consideration of the work, cost and product breakdown structure

The key outcomes from the telephone interviews are covered in Table 4.3.

Table 4.3 Overview of outcomes from telephone interviews with Organisation A

Meeting	Current Practice
Telephone, semi-structured interview – 1	1. Within the software context, source lines of code are used focusing on 50 to 100 components 2. Three-point estimate is developed for the required effort (e.g. fixed time for defects) 3. Software packages such as COCOMO was highly used due to the in-built uncertainties, cost drivers and the source lines
Telephone, semi-structured interview – 2	1. The financing teams do not get involved in cost estimation 2. The key uncertainties to consider in cost estimation were defined as obsolescence, spares, warranty and exchange rates
Telephone, semi-structured interview – 3	1. The cost breakdown structure supports understanding uncertainties 2. Key uncertainties: Equipment or hardware failure, range of costs (e.g. maintenance, upkeep, upgrade), software failure, uncertainty in design management (e.g. man power), change (e.g. technology refresh), supply chain issues
Telephone, semi-structured interview – 4	1. The uncertainty associated to the completion of a task represented through Three-point estimating 2. Within a risk register, the specific and identifiable uncertainties represent the tolerances of the task

## Organisation B

Two sets of semi-structured interviews were conducted with this particular company. At the initial meeting a general observation over the given context was captured. Subsequently, a follow on meeting was set up to get a detailed understanding of the uncertainty related processes and existing challenges. An overview of the interacted people and the format of interaction are provided in Table 4.4.

Table 4.4 Overview of industry interaction with Organisation B

Meeting	Meeting Duration (Hours)	Job role of attendee(s)	Experience (Years)
Face to face, semi-structured interview – 1	2.5	Logistics engineering manager	26
		Director for Global Marketing Systems Customer Service	18
		Proposal Director in Military Customer Management Systems Customer Services	14
		Business development manager	22
Face to face, semi-structured interview – 2	2.5	Logistics engineering manager	28
		Military programmes manager	25
		Proposal Director in Military Customer Management Systems Customer Services	14
		Business development manager	24
		Supportability engineer	18

The key areas of query at the introductory meeting were on understanding the given scope of CfA agreements and an initial understanding of the relevant types of uncertainties. The respondents provided the following explanations in order to compare across the various contracting options that the organisation has been involved in:

- CfA: This could relate to a part, system or whole aircraft availability
- Capability contract: The means of achieving the goal is irrelevant as the result is the focus (e.g. for easyJet getting to a destination at a specific time)

- Reliability contract: Involves the case when the solution provider is contracted to manufacture equipment and it must be able to offer the reliability requirement

At the second meeting, in order to gather information concerning uncertainty processes a series of meetings were arranged with the participants, which each lasted for thirty minutes. The focus of these interviews was to get an understanding of the key uncertainties that were experienced within this organisation. The list of key uncertainties across the respondents: (1) assumptions, reliability, testability (e.g. no fault found), (2) failure, repair cost, escalation of material costs, obsolescence, (3) failure, (4) the reliability of the equipment, exchange rate and materials costs and government indices, and (5) performance of ground field workers, pilots, spares availability and affordability.

Regarding the shift to CfA, Respondent 2 highlighted that the key issue with CfA agreements relates to differences between the considerations for costs at the design stage where the contract is agreed and in the in-service phase where actual requirements are realised. Across the respondents, commonly an emphasis was made on the importance of failure rate in delivering CfA. Furthermore, Respondent 4 highlighted that failure rates are hard to predict, though not due to a lack of availability of methods to conduct analysis. Instead it was suggested that the issue was in the uncertainty as to when and what will fail. Respondent 5 emphasised the potential that CfA offers in accumulating stable returns, whilst the role of penalties has commonly become an important part of the bidding process. It was also suggested that a range of post-design services (e.g. obsolescence management) are increasingly offered to facilitate the transfer of risk from the customer. Though, Respondent 1 set a scope to the transfer of risk, by specifying that the reliability is the solution providers' responsibility, whilst other matters such as equipment usage are still the customers' responsibility. Furthermore, it was also highlighted that CfA promotes the need for better transfer of information from the equipment and suggested that better prognostics (e.g. what will go wrong, when?) and diagnostics (e.g. understanding the problem) are required.

## Organisation C

Two sets of semi-structured interviews were conducted with this particular organisation. At the initial meeting a general observation over the given context was captured. Subsequently, a follow on meeting was set up to get a detailed understanding of the uncertainty related processes and existing challenges. An overview of the interacted people and the format of interaction are provided in Table 4.5.

Table 4.5 Overview of industry interaction with Organisation C

Meeting	Meeting Duration (Hours)	Job role of attendee(s)	Experience (Years)
Face to face, semi-structured interview – 1	2	Program manager	25
		Risk specialist	29
		Commercial manager	7
Face to face, semi-structured interview – 2	2	Program manager	25
		Risk specialist	34

At the initial meeting the emphasis was on explaining the scope of the research to Organisation C participants, whilst also eliciting their understanding of CfA agreements and their implications on cost uncertainty. It was identified that this organisation has limited experience in delivering CfA. It was emphasised that CfA is typically agreed for peace time, whilst explicit clauses are defined to build a level of readiness for a potential war time. The respondents suggested that in building a cost model the uncertainties to consider are in relation to logistics, equipment reliability and spare parts requirements. It was suggested that with CfA the importance of understanding equipment utilisation grows for the solution provider. Furthermore, the WBS is followed to construct the Three-point estimate, as used in the Monte Carlo simulation.

At the second meeting a detailed understanding of uncertainty considerations was captured. Some of the areas of interest included, differentiating between risk and uncertainty, and processes to manage and model uncertainty in cost estimation. In order to illustrate the difference between risk and uncertainty an example was provided;



uncertainty was defined as the time it takes to get to work, and risk was defined as specific events such as an accident or traffic lights. The respondents highlighted that a standard list of uncertainty categories had not been specified within this organisation. Furthermore, it was emphasised that uncertainty considerations get reflected in a risk register, and the experts get to compare among the defined elements of the list, typically using expert opinion. This process was reflected to be generally qualitative and challenges were suggested in standardising these processes across projects. The key uncertainties in CfA were suggested to be reliability, whole life cycle cost, lines of maintenance, operation of equipment (utilisation), vibration or temperature, training, handling and customer involvement. Based on this list it was suggested that uncertainty for the solution provider is largely driven by external sources.

From the uncertainty modelling side it was indicated that software packages such as Predict or Active Risk Manager were commonly used for Monte Carlo simulation, whilst the considerations vary across projects. Challenges were suggested in modelling performance and quality requirements as the characteristics of component or subsystem change for various reasons (e.g. customer requirements) over time. On the other hand, the uncertainty management stages were suggested to be classified into four stages (1) identification, (2) analyse (e.g. understand), (3) planning (e.g. what to do), and (4) manage (e.g. sustain control). From a strategic point of view the respondents referred to four potential strategies to respond to the influence of uncertainties, including: tolerate (e.g. ignore or sustain), treat (e.g. take actions), transfer (e.g. supplier involvement), and terminate (e.g. avoid task). The respondents also emphasised the importance of lessons learned initiatives, which enable to improve the understanding of uncertainty.

## **Organisation D**

With this particular organisation a knowledge elicitation event was organised consisting of 5 hours of semi-structured interviews. The session was classified into two sections, whereby initially the focus was on understanding differences between the agreed contractual forms including availability and capability contracts, WBS and cost estimation techniques. Secondly the uncertainty considerations were queried by

gathering definitions, and modelling and management processes. An overview of the respondents is provided in Table 4.6.

Table 4.6 Overview of industry interaction with Organisation D

Meeting	Meeting Duration (Hours)	Job role of attendee(s)	Experience (Years)
Face to face, semi-structured interview – 1	5	Through life analysis expert (assurance)	25
		Supplier Management and Strategic forecasting (land and sea systems)	24
		Supplier Management and Strategic forecasting (Software, aircrafts)	26

A classification of the risk and uncertainty definitions is provided in Table 4.7.

Table 4.7 Defining risk and uncertainty based on interaction with Organisation D

	Uncertainty definition	Risk definition
Respondent 1	Sure something will happen, not sure what level (e.g. mean time between failure-influence rate to fitters)	Probability of impact (e.g. 20 % chance, breaks will need changing and costs will arise)
Respondent 2	Statistical variation which comes from the method (regression gives confidence limits)	1. Cost or time implication of specific events e.g. impact and probability 2. The probability of occurrence can be looked at in e.g. skewed, binomial distribution
Respondent 3	Persists in our understanding of the future	Probability of occurrence

Respondent 1 highlighted that for uncertainty and risk, the Integrated Project Team manager nominates risks and uncertainties. This person asks questions such as “what could be risk? How could this risk be mitigated? Which elements should be considered in the risk register?”. All this information is stored and updated, on a monthly basis. Furthermore, all reasons that are considered are inputted into a master data storage, which is called a Master Data and Assumptions List (MDAL). Using Three-point estimates, the uncertainty is added to the cost model on a spread sheet in a stochastic manner at 10, 50 and 90 percent confidence levels, which is typically represented through a cumulative distribution. A description of these levels is provided below:

- The *10% confidence point*: an outcome of only a 10 percent chance of achieving

- The *50% confidence point*: the unbiased estimate or expected outcome. This point is where the actual outcome of the development work is equally likely to be above or below that point as shown in the above diagram
- The *90% confidence point*: an outcome of 90% chance being achieved. Typically the 10% and 90% confidence points are chosen as the tolerances

Respondent 1 also highlighted that the biggest area of concern in uncertainty analysis is related to overheads, as they tend to be one of the biggest cost drivers (e.g. in some contracts it is only possible to become profitable after the fifth year due to these costs). Furthermore, for some ships up to a third of all costs may constitute overhead costs. Respondent 3 emphasised that there were two types of models that were used. Firstly commercial off the shelf type products including Galorath, Price, HVR models can be used. These provide a range and a distribution, which is used in the Monte Carlo simulation that is run through for costs. The organisation suggested that curves are typically represented for the confidence levels of 10, 50 or 90%. In this process MS Excel is an integrator and adds risks and uncertainties in. So, all costs are viewed in terms of influence over total cost and time. For instance, on an S curve, increasing or diminishing costs are linked to the risks and uncertainties, which are well reasoned in the MDAL. This helps to understand the situation with uncertainties. The second type of models were suggested to concentrate on the application of analysis in MS Excel, where a cost model is inputted into Excel, and all ranges for costs are considered and as a next step Monte Carlo analysis is made. In this process the risks and uncertainties get drawn out from the risk register.

In defining the types of uncertainties relevant for CfA, Respondent 1 emphasised that this is the responsibility of the Integrated Project Team (IPT). In this process, aspects such as pattern of usage and the manner of equipment utilisation (e.g. location of usage) are critical to consider. Respondent 2 indicated that considerations with planned maintenance were straight forward, whilst unscheduled maintenance required an in-depth assessment of things that could go wrong and affect operational targets. As a result of the shift to CfA, Respondent 3 suggested that with the transfer of

responsibilities from customer to suppliers, created visibility issues regarding the activities that a supplier undertakes.

Organisation D also provided and suggested published material that was of relevance. Some of the areas included the process of cost estimation, integrating uncertainty and the used tool to apply cost estimation. Table 4.8 illustrates the range of tools that can be used across the life cycle, whilst the in-service phase is the focus of this research.

Table 4.8 Current tools and models (MoD, 2007b)

<b>Hardware Toolset</b>	<b>Pre-concept</b>	<b>Concept</b>	<b>Assessment</b>	<b>Demonstration</b>	<b>Manufacture</b>	<b>In-Service</b>	<b>Disposal</b>
Rule of Thumb <sup>4</sup>	✓	✓	✓	✓	✓	✓	✓
CER <sup>4</sup>	✓	✓	✓	✓	✓	✓	✓
FACET <sup>4</sup>	✓	✓	✓	✓	✓		
NAFCOM <sup>3, 4, 8</sup>	✓	✓	✓	✓	✓		
PRICE TrueConcepts <sup>4</sup>	✓	✓					
PRICE H/ TrueH <sup>4</sup>	✓	✓	✓	✓	✓		
PRICE HL <sup>4</sup>						✓	
Price TP <sup>7</sup>	✓	✓	✓	✓	✓	✓	✓
Propricer <sup>7</sup>		✓	✓	✓	✓	✓	✓
SEER H <sup>3, 4</sup>	✓	✓	✓	✓	✓		
SEALECT <sup>3</sup>						✓	
OSCAM (Air, Land, Sea) <sup>4</sup>						✓	
Disposal model (Excel)							✓
<b>Software Toolset</b>	<b>Pre-concept</b>	<b>Concept</b>	<b>Assessment</b>	<b>Demonstration</b>	<b>Manufacture</b>	<b>In-Service</b>	<b>Disposal</b>
Rule of Thumb <sup>4</sup>	✓	✓	✓	✓		✓	
CER <sup>4</sup>	✓	✓	✓	✓		✓	
PRICE True S <sup>3</sup>	✓	✓	✓	✓		✓	
PRICE True IT <sup>3</sup>	✓	✓	✓	✓		✓	
SEER SEM <sup>3</sup>	✓	✓	✓	✓		✓	
Cocomo <sup>3</sup>	✓	✓	✓	✓		✓	
VERA <sup>3, 4, 8</sup>	✓	✓	✓	✓		✓	
R <sup>2</sup> Estimator <sup>2,3,8</sup>	✓	✓	✓	✓		✓	

SSCM <sup>3</sup>						✓	
Detail Estimates				✓		✓	✓
<b>Risk Toolset</b>	<b>Pre-concept</b>	<b>Concept</b>	<b>Assessment</b>	<b>Demonstration</b>	<b>Manufacture</b>	<b>In-Service</b>	<b>Disposal</b>
Palisade @Risk	✓	✓	✓	✓	✓	✓	✓
Predict <sup>5</sup> (schedule only)	✓	✓	✓	✓	✓	✓	✓
Crystal Ball <sup>3</sup>	✓	✓	✓	✓	✓	✓	✓
ARRISCA	✓	✓	✓	✓	✓	✓	✓
<b>Trend Toolset</b>	<b>Pre-concept</b>	<b>Concept</b>	<b>Assessment</b>	<b>Demonstration</b>	<b>Manufacture</b>	<b>In-Service</b>	<b>Disposal</b>
Price KM <sup>3</sup>	✓	✓	✓	✓	✓	✓	✓
CONTEXT (comparison tool)	✓	✓	✓	✓	✓		
MS Excel <sup>7</sup>	✓	✓	✓	✓	✓	✓	✓

Table 4.8 highlights that there are a number of tools, models and cost estimating relationships (CERs) available for use on forecasting tasks. These tools are either software bespoke developments (e.g. FACET, OSCAM), commercial products (e.g. MS Excel, @Risk) or generic commercially available cost models (e.g. Price, Seer). Notes on the available tool set associated to Table 4.8 are presented below (MoD, 2007b):

1. The ticks indicate software listed has a capability to forecast costs within the particular UK MoD project phase.
2. None of the models provide phase outputs comparable to the CADMID phases
3. This item is not available as a networked model/ tool at present
4. This item should not be used as a primary tool for all labour or material cost elements, the analyst should seek advice if no other model/ tool is available for the particular forecasting task or task sub-element
5. Predict should be used only for schedule risk/ variability calculations. The tool provides no active linking to Excel based cost models and cannot provide sensitivity analyses that are correct
6. There are no developed schedule estimating tools (commercial or bespoke). Some hardware and software models do provide schedule durations for contractor work content (e.g. Seer, Price, Facet)
7. Excel, Price TP (the framework, not included catalogues) and Propriicer are “cost aggregators” using inputs taken from other estimating methods
8. Must not be used as a primary tool, analysts must seek advice before using

### **4.1.3 Comparative analysis between organisations**

This section presents a comparison across the organisations by focusing on the current practice in terms of cost uncertainty modelling and management. The similarities, differences and the unique aspects associated to each organisation concerning the uncertainty considerations is discussed below.

#### **Similarities across the organisations**

- Three-point estimating and application of Monte Carlo simulation
- Dependency on experience for identification, prioritisation, management and defining degree of uncertainty in cost drivers. This also causes difficulties in standardising terminologies and associated processes
- Applied steps for uncertainty management, whilst the terminologies can vary
- Differentiation of risk and uncertainty in order to conduct separate analysis
- A standard set of uncertainties do not exist for CfA
- Application of in-house developed tools for cost uncertainty analysis, whilst using commercial tools for validation and verification purposes.

#### **Differences across the organisations**

- Definitions of uncertainty vary, whilst all organisation concurred with the concept that uncertainty causes a difference between actual and targeted levels
- Variation in defining the Cost Breakdown Structure (CBS) and WBS, which is driven by the equipment requirement that follows bespoke characteristics
- Terminologies for the types of uncertainty and in defining the types of uncertainty in the risk registers

#### **Unique characteristics**

- Each organisation was observed to have a different level of experience in CfA. This was recognised to cause a variation in the perception of uncertainties. A comparison of the key uncertainties that were specified are illustrated in Table 4.9. Organisation A and D, which appeared to have a higher degree of

experience in CfA, focused on the failure rate as a key issue affecting the delivery. On the other hand, Organisation B and C, which appeared to have lesser experience in CfA, focused on challenges associated to pricing and the process of whole life cycle cost estimation.

- Lessons learned initiatives are applied at various degrees across the organisation. By applying such initiatives organisations intend to improve existing practices

Table 4.9 Comparison of the defined key uncertainties across the organisations

	Organisation A	Organisation B	Organisation C	Organisation D
<b>Key types of uncertainty</b>	Obsolescence, supply chain, failure rate	Pricing, flying hours, obsolescence, failure rate	Reliability, whole life cycle cost, lines of maintenance, equipment utilisation, training	Pattern of equipment usage, equipment utilisation, failure rate

The high degree of similarities across the organisations were considered to be associated to the provided guidance by the customer, which aims to conform the approaches in order to improve decision making by unifying the decision making process.

#### 4.1.4 Case Studies

In total three case studies were conducted during the second phase of the research methodology, while an additional project supported by providing documents in relation to the service contents and the cost uncertainty modelling methodology. The information provided below for Projects A, B, and C represents outputs from the case studies. The research method followed the activities as illustrated in Figure 4.4.

##### Project A

Project A is at the in-service stage of the CADMID lifecycle having just received a 30 year contract to support a number of training equipments. The contract involved developing and providing most of the training capability, where 50 percent had already been delivered. The project is in the delivery phase, and the agreement is until 2037. An overview of the interaction and participant related information is provided in Table 4.10.

Within Project A, the training service involves (1) provision of a complete training solution, which includes simulation application and courseware for the Navy, (2) availability of facilities (e.g. buildings), (3) training equipment. The offered services focus on (1) Submarine Command Team Training, (2) Weapon Handling and Loading Training, (3) Other Weapon Related Training and (4) Non Equipment Related Training. The responsibilities of the solution provider include the provision of:

- A team trainer (within a coordinated team)
- Two classrooms (e.g. for 8 trainees) and equipment availability (e.g. computers)
- Pneumatic and hydraulic equipment which deals with explosives and ammunitions handling including health and safety issues

Table 4.10 Overview of industry interaction with Project A: First phase of the study

Meeting	Meeting Duration (Hours)	Job role of attendee(s)	Experience (Years)
Face to face, semi-structured interview – 1	2	Project manager	18
		Assistant to project manager	8
		Subcontract manager	6
Face to face, semi-structured interview – 2	2	Project manager	28
		Assistant to project manager	8

During the course of interaction with this case study heavy emphasis was put on capturing the existing processes for uncertainty management. It was highlighted that these processes get treated as an integral part of the life-cycle management process. It was also identified that such processes get implemented in a continuous manner throughout the bidding stage of a project. The uncertainty management processes were suggested to include a cycle which includes uncertainty identification, analysis, evaluation and mitigation, as represented in Figure 4.5. The identification phase involves a review of the uncertainties. The analysis and evaluation phases are concerned with defining a response. Based on the selected response measure the mitigation procedure is informed. The *identification of uncertainty* is the responsibility of the



project team where uncertainties and any proposed control measures that lie within their expertise will assume ownership of that measure until it is reassigned at a subsequent stage of the management process. Furthermore, various group activities such as project meetings or reviews may be undertaken to identify the uncertainties. The *analysis of uncertainty* refers to qualitative assessment involving a risk and uncertainty specialist for each of the identified uncertainties. In this process consistency of interpretation and a valid criticality index of uncertainties plays a critical role. The *evaluation of uncertainty* involves a quantitative assessment. Line by line the role of uncertainty is assessed through models that enable an understanding of the collective consequence of the uncertainties on objectives or to meet requirements. Simulation is a common route that enables project management to respond to changing circumstances. The *mitigation of uncertainty* refers to the mitigation of uncertainties and realization of opportunities. Within this phase strategies and plans are devised and followed to reduce the influence of uncertainty and to promote opportunities. The *reporting process* enables to record, manipulate, modify and report uncertainties.

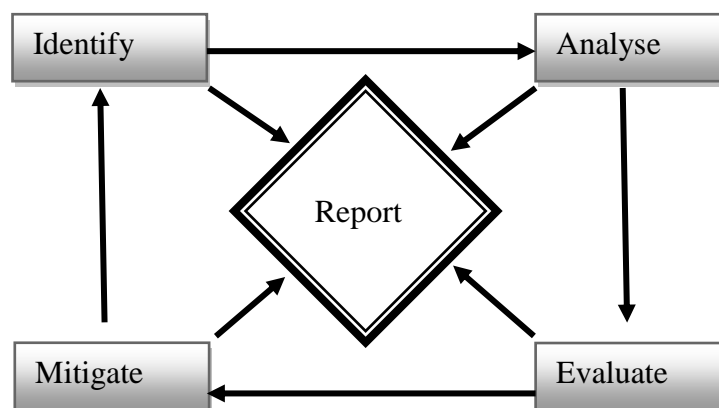


Figure 4.5 Components of Uncertainty management

### Project B

Project B is for a new naval radar sensor and is at the assessment stage of the CADMID lifecycle. The overall project is for the replacement of 18 legacy radars, integration of the new radars with the existing ships systems and services, and in-service support for an initial 10 year period. While the product life is considered to be 25 years, the support has initially been agreed to be 10 years. There is continuous disposal in subsystems at the

lower level. Within this project the “Evergreen principle” has been applied, which means the contract would be renewed every 5 years and there is opportunity for renegotiation. An overview of the interaction and the participants is provided in Table 4.11.

Table 4.11 Overview of interaction and participants in Project B

Meeting	Meeting Duration (Hours)	Job role of attendee(s)	Experience (Years)
Face to face, semi-structured interview – 1	2	Design Analysis Diagnostics Engineer	28
		Supportability engineer	22
Telephone, semi-structured interview – 1	1	Design Analysis Diagnostics Engineer	28

In the interview an explanation was covered concerning the uncertainties that arise in each service offering and the key considerations for each of these areas, including:

- *Spares services*: Involving frequency of support and range of requirements
- *Repair services*: The trade off between the costs of new spare parts and repair is considered. The uncertainty relates to how many times failures occur, which makes it challenging to determine required effort. These services also take into account the influence of obsolescence (e.g. resultant unrepairable component)
- *Defect response*: Based on the likelihood of occurrence of defects in components appropriate management procedures are developed. These responses depend on the priority of the defect
- *On-call service*: Related to support that is provided on unplanned basis. Though, some requirements may not be included in the contract
- *Health checks*: Involve regular checks on equipment in a planned process
- *Performance assessment*: Measurement of the performance (e.g. availability).

On the other hand, from the modelling perspective a range of approaches were highlighted for the bidding stage for the mentioned services, as highlighted below:

- For spares usage, off the shelf tools such as OPUS 10 or RAM Lock are used
- For repair service, meantime between failures are considered. There may also be issues that arise from unrepairable kit. Offering repair service(s) highly requires human involvement, which can highly influence the uncertainty

- For defect response, significant interest is put on the number of failures
- Costing health check operations involve consideration of inflation and fuel costs
- Performance check necessitates managerial activities, which focus on aligning delivery of support to customer requirements

## Project C

Project C is a very large military system-of-systems project (value £100s million) involving over 60 functional sub-systems of which only a minority are sourced in-house. The project is now anticipating the need to engage with the customer on in-service support. Some of the key services offered within this project include, technical support (e.g. operation defect analysis and management), spares (e.g. spares management responsibility), management (e.g. efficient delivery of support), design authority (e.g. continuous assurance of the system performance and safety in-service), quality assurance (e.g. application of systematic quality assurance), and continuous improvement. Table 4.12 presents an overview of the interaction with Project C.

Table 4.12 Overview of interaction in Project C

Meeting	Meeting Duration (Hours)	Job role of attendee(s)	Experience (Years)
Face to face, semi-structured interview – 1	2	Integrated Logistics Support Manager	18
		Business Development Manager	12
		Systems Engineering Manager	16
Face to face, semi-structured interview – 2	2	Integrated Logistics Support Manager	18
		Business Development Manager	12
		Systems Engineering Manager	16
Face to face, semi-structured interview – 3	2	Integrated Logistics Support Manager	18
		Assistant manager	22
		Engineering Manager	31

Through the interaction it was recognised that estimating costs for the in-service and disposal stages can be made in the design and manufacturing stages, where the level of uncertainty can increase drastically after the sixth year of the contract award. For this reason, Project C has set a review procedure for every 5 years, while the in-service phase may last between 30 to 50 years. Furthermore, the evolution of uncertainty for the in-service and disposal phases for the customer and the OEM is represented in Figure 4.6. 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 the supplier aims to charge the best price, while taking the costs, risks and uncertainties into account.

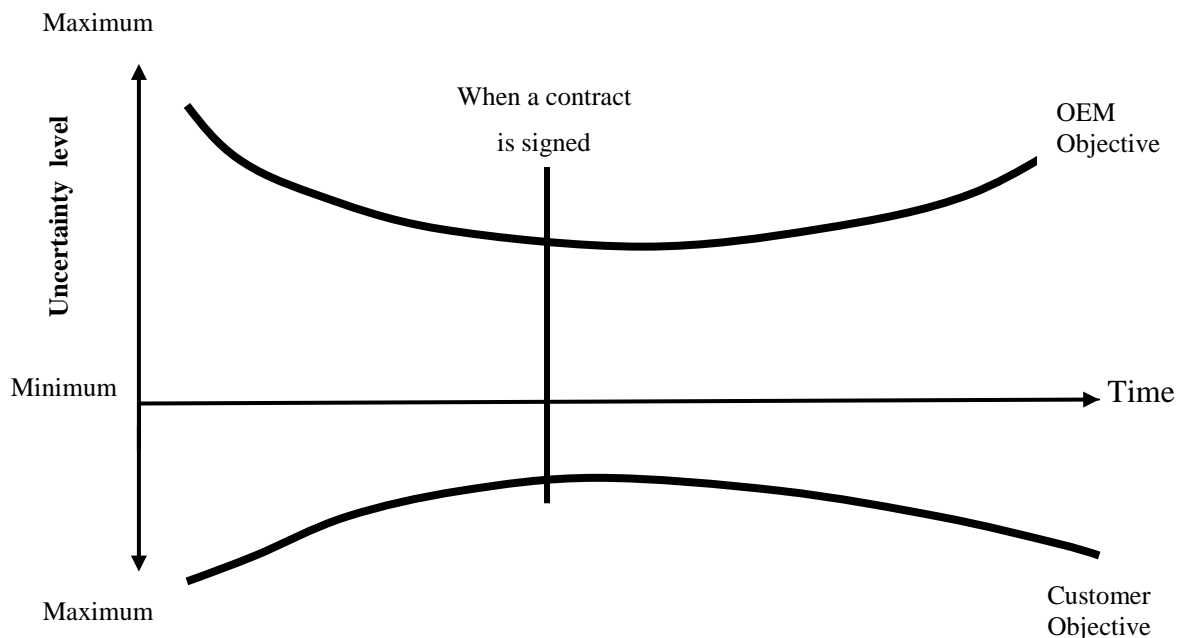


Figure 4.6 Evolution of uncertainty for OEM and customer

The participants indicated that in the design phase strong emphasis is put on materials and labour estimating. Labour is considered in terms of skill level and scale of labour requirements. Material estimates tend to be based on similar historical projects and follow the equipment breakdown structure. When considering the in-service phase the role of subcontractors are also considered in areas such as repair, maintenance and painting. In the bid phase all costs for the support stage are combined, within a detailed manner. Project C defines “labour costs” and “materials costs” as follows:

- Labour costs involve non-recurring engineering (NRE) activities at the system-of-systems level (e.g. requirements management, system engineering trade studies)

- Materials costs refer to the bought-in subsystems (e.g. commercial off the shelf (COTS) or military off the shelf (MOTS))

Considerations for both labour and material cost typically follow the work breakdown structure or product breakdown structure. For labour cost uncertainty, benchmarked metrics are used to develop NRE models, which derive a cost estimate for each section of the WBS. These represent the Most Likely cost data, which subsequently the Minimum and Maximum estimates get added to provide the full set of Three-point estimates. The Three-point estimates get used in a Monte Carlo simulation to generate a cost uncertainty curve representing the labour costs. The outputs provide information about the confidence level of the sum of the Most Likely costs and an overall confidence level of the cost estimate for the project. For materials cost uncertainty, a cost estimate gets considered for each bought-in subsystem, which is populated from suppliers' quotes. Each supplier gets challenged to negotiate their Most Likely values. Overall, the case studies enabled to get a broad understanding of the uncertainty related considerations. The focus of Project A was in delivering support for a number of training equipments and a heavy emphasis was laid on uncertainty management. Project B offered a range of services for new naval radar sensor. The case study enabled to recognise the cost uncertainty modelling approaches. Project C involved a large military system-of-systems project and the cost uncertainty modelling was the focus.

#### **4.1.5 Initial validation**

The initial validation was achieved through developed reports, which aimed to provide an overview of findings obtained through interviews, case studies and documents on cost estimation at the bidding stage of CfA in the defence industry, whilst the focus of the presented material is on uncertainty. A sample report is provided in Appendix D. The following section provides a summary overview of the understanding of uncertainty across the defence industry:

In CfA the customer predominantly aims to transfer responsibility, in other words risk and uncertainty, to the OEM. Uncertainty is an issue of clarity, which is most influential

during the bidding stage. This also means that the occurrence is certain, though the magnitude is uncertain. As a result, many assumptions are developed due to the limited information, which may relate to technical support, utilisation rates and/or programme requirement. These may also contribute to uncertainty. Each uncertainty and risk element is not static and may change during a project. This variability causes difficulties in assigning risks and uncertainties into separate buckets. Furthermore, many interviewees mentioned that risk and uncertainty are commonly allocated into the wrong pools. The manufacturing stage contains more risks than uncertainties, while support is considered to hold more uncertainty. The sources of uncertainty may originate from:

- Estimating costs for the in-service are typically made in the design and manufacturing stages. At such early stages, information is highly limited, making it challenging to make accurate cost estimates for operational and support activities. This source of uncertainty is driven by *limited information*
- There are difficulties in estimating costs also due the *limited time* that is available. This causes immature design of life cycle contracts
- In traditional contracts OEM responsibility was constrained to component reliability, though with CfA the focus is on system level reliability. This necessitates additional knowledge in equipment utilisation, though driven by *lack of knowledge* OEMs are finding difficulties

The interaction with industry also aimed to identify a set of uncertainties that are typically experienced with CfA. At a broad level, uncertainties for CfA arise from the process of sustaining system level capability. This highly relates to the capability and capacity of the OEM. Also, supplier sustainability becomes more important with the enhanced reliance. Also, the role of the customer as a source of information was defined as a major area of uncertainty. Some of the key areas of uncertainty were suggested as:

Equipment utilisation, economic conditions, availability of kit, equipment refresh rate, rate of technology change (e.g. upgrade, obsolescence), supporting COTS equipment, affordability, spare parts and material costs, receiving the spare parts, and human error

The industry has commonly embraced Three-point estimating, which may be constructed in different ways (e.g. depending on required effort). Monte Carlo

Simulation is the most commonly used estimation method that produces spreads and helps to understand the confidence for a price. This approach relies on engineering judgement and/or historical extrapolation. On the other hand, commercial models tend to be used for validation purposes, as the provided data may not fit into requirements. Each service offering has a different approach to model uncertainty. Furthermore, specific areas of interest and tools used are highlighted below. In common, participants across organisations highlighted difficulties arising from limited data, though no firm complaint was directed to the utilised methods.

#### **4.1.6 Establishing the current practice and challenges**

Given the developed report and the collected feedback from industrial collaborators, the author also reviewed processes published by organisations to gather a comprehensive understanding of the current practice and challenges. This section initially presents the current practice in cost uncertainty related processes. Subsequently, the aim is to reflect the challenges that were recognised across the case studies and the organisations.

##### **Establishing the current practice for cost uncertainty management and modelling**

The presented research across the organisations conforms to the developed industry based processes related to cost uncertainty. Figure 4.7 illustrates survey results from a NATO study, which indicates that when risk and uncertainty analysis is conducted the two most commonly used techniques seem to be expert opinion and sensitivity analysis (NATO, 2007). Detailed analysis, using e.g. Monte Carlo simulation seems to be undertaken with varying degree of frequency by only two to three countries, using typically in-house built models. This finding also followed across the collaborated organisations. Support costs in the in-service phase typically arise repeatedly. These are often aggregated using tools that can simulate the rate of occurrence. Examples include Vari-Metric (Zamperini and Freimer, 2005), OPUS 10 (OPUS 10, 2009), or Tecnomatix

PSST (Tecnomatix, 2009), which contains a suitable database developed in collaboration with BAE Systems<sup>3</sup>.

Risk		Mission need	Pre-feasibility	Feasibility	Project definition	Design & development	Production	In-service	Disengagement
Methods	Expert opinion	●	●	●	●	●	●	●	●
	Monte Carlo simulation					●			
	Sensitivity analysis	●	●	●	●	●	●	●	●
Models for risk analysis	In-house	●	●	●	●	●	●	●	●
	Commercial	●	●	●	●	●			
Models for uncertainty analysis	In-house	●	●	●	●	●	●	●	●
	Commercial	●	●	●	●	●	●	●	●

Legend: ● >3 nations; otherwise 2-3 nations

Figure 4.7 Cost uncertainty modelling approaches used across countries (NATO, 2007)

Estimating practitioners in both the supplier and customer communities have a preference for commercial tools in order to verify and validate cost models. Unfortunately, commercial tools are not always able to cope with specific circumstances, for example the phased introduction or withdrawal of platforms from a fleet concurrent with mid-life update and/or technology refresh and/or spares scavenging. In this case special-to-purpose models in MS Excel (or similar) are required and investment in verification and validation for these must be accommodated in the cost of bidding (Erkoyuncu et al., 2009a). An overview of some of the commonly used commercial packages is provided below:

- Predict (schedule only): Is a decision support tool that aims to enhance the management of risk and uncertainty in predicting cost and schedule
- @risk: Is the most widely used risk analysis tool that utilises MS Excel to perform Monte Carlo simulation
- Crystal Ball: Is used to predict software and service costs

There are a number of pre-requisites to considering risk and uncertainty in the cost uncertainty modelling process (MoD, 2009), as represented in Figure 4.8.

<sup>3</sup> The PSST tool in combination with the BAE Systems database was formerly known as RAMLOG.



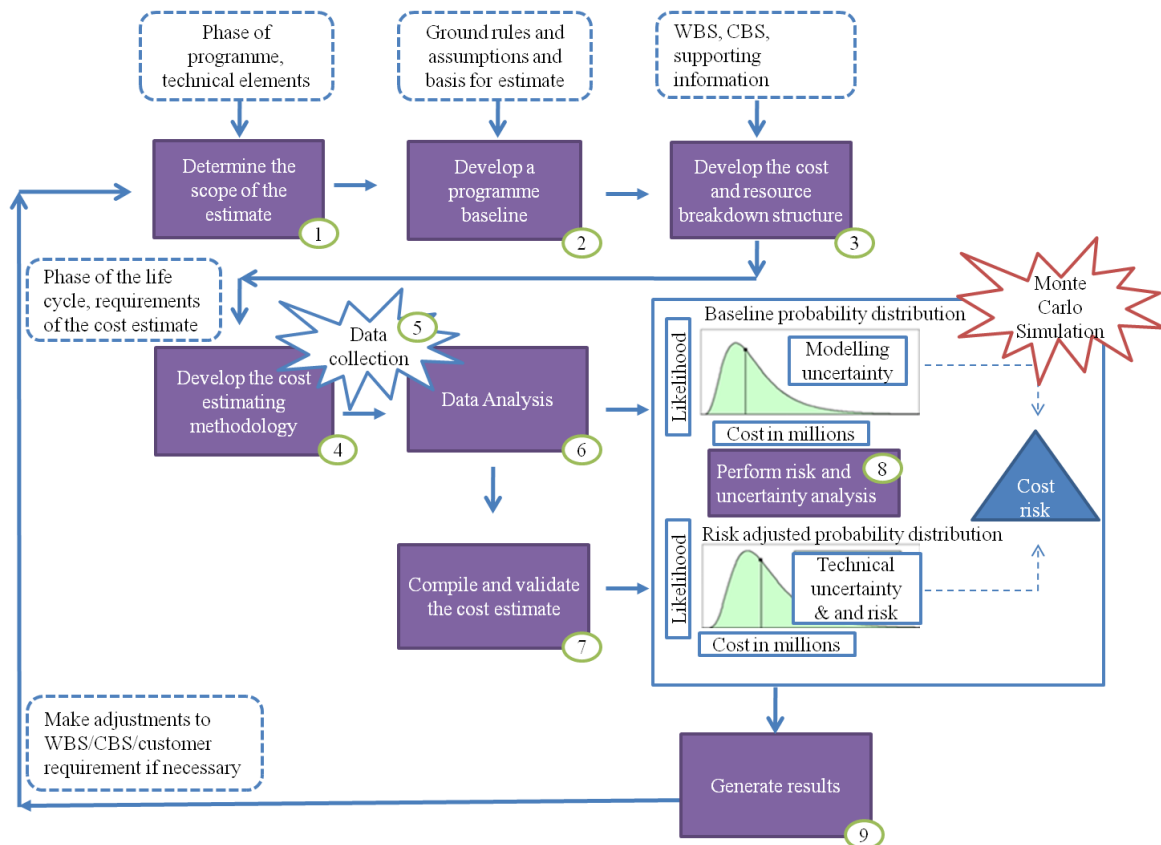


Figure 4.8 Cost uncertainty modelling process

Initially, the scope of the estimate needs to be defined, which leads to the development of a programme baseline and a cost and resource breakdown structure (Tasks 1, 2, and 3). Along this process information such as work and/or cost breakdown structure supports the development (Garvey, 1996). If cost for any of these elements is not clear, then uncertainty is considered to be influential. Subsequently, driven by the phase in the life cycle a cost estimating methodology is developed, whereby available data is collected and assessed (Task 4, 5 and 6). At this point based on the available data the single point estimate is developed and validated (Task 7). Also, the influence of risk and uncertainty is considered by compiling information generated in Tasks 6 and 7 (Task 8), whereby the cost uncertainty modelling procedure separates risks and uncertainties. Initially a baseline cost estimate is developed, which focuses on the influence of uncertainty and secondly the risk adjusted cost estimate includes the influence of risk as well as uncertainty. The cost uncertainty modelling process ends with the generation of results representing the cost/benefit and these can guide with making adjustments to the work and/or cost breakdown structure. Thus, probability distributions are developed for

each one of the work breakdown structures and capture the possible values that can be attained. The Monte Carlo simulation enables to sum these variables to produce an overall probability distribution of the system's total cost.

**Baseline cost estimate**

To generate the baseline cost estimate, a fixed value representing, for instance the equipment weight and performance are considered deterministically as a cost driver (NATO, 2007). Furthermore, for each of these cost drivers, the cost estimate is represented as a probability distribution and the focus is explicitly on cost uncertainty. Based on the provided distribution through Monte Carlo simulation a random number is selected for each of the cost items and subsequently each CER is aggregated after sufficient repetition of the random number selection. Figure 4.9 presents the way in which the cost of software development is driven by the Source Lines of Code and the evolution of the range estimates.

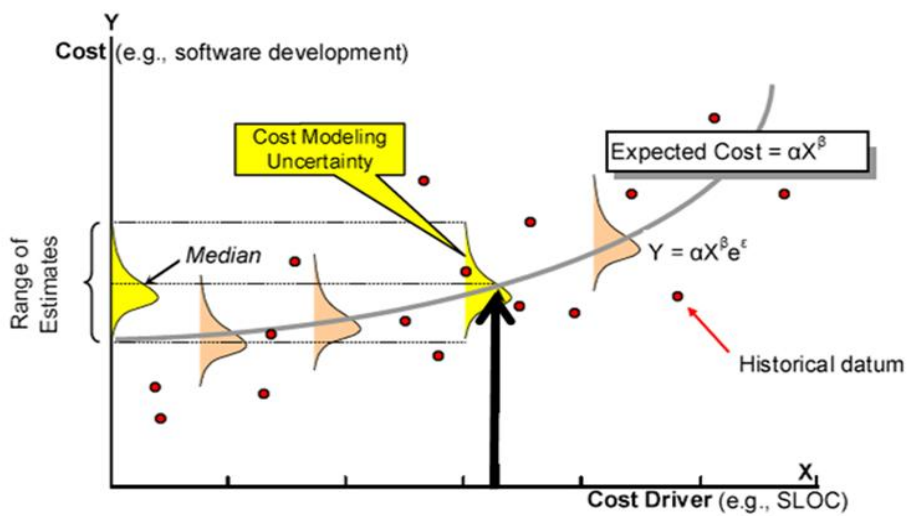


Figure 4.9 Baseline cost estimate (NATO, 2007)

**Risk-adjusted cost estimate**

Once the baseline cost estimate is developed the influence of risk is included in the risk adjusted cost estimate. This involves consideration of stochastic behaviour in the cost drivers, where the deterministic view considered in the baseline estimate is avoided (NATO, 2007). Thus, variability is also considered for instance in equipment weight

and performance and a suitable distribution for each CER needs to be defined. This leads to the Monte Carlo simulation, where initially the probability distribution for the cost driver is considered using the Three-point estimates.

### Establishing the challenges

The sub-section follows with the challenges that were captured across the case studies, while following with an overview of the challenges experienced across the collaborating organisations. The identified challenges set the major gaps experienced in particular with the adoption of CfA. Table 4.13 describes the list of challenges that were realised across the specified case studies.

Table 4.13 Overview of challenges across three case studies

	Challenges
<b>Project A</b>	<ul style="list-style-type: none"> <li>• Customer relationship and obtaining customer acceptance/credibility</li> <li>• Forecasting obsolescence cost</li> <li>• Estimating cost</li> <li>• Complexity and difficulty of methods</li> <li>• Bespoke nature of offerings</li> <li>• Accurate interpretation of historic data</li> <li>• Lack of commercial repository of data storage</li> <li>• Need to ensure delivered products and systems are aligned to meet the training requirements during technical refresh</li> </ul>
<b>Project B</b>	<ul style="list-style-type: none"> <li>• Need for obsolescence management</li> <li>• Dealing with sensitive material at the disposal stage and costing this process</li> <li>• Division between product and service oriented costs in the CBS</li> <li>• Work packages need to be more accurately described at the early stages</li> <li>• Information related issues: e.g. standardisation in storage, limited information</li> <li>• Developing portfolio contracts to be able to assess costs</li> </ul>
<b>Project C</b>	<ul style="list-style-type: none"> <li>• The supply chain is often the biggest cost driver in CfA, which creates uncertainties.</li> <li>• There is a need to standardise the CBS for comparing different projects as it would help to mitigate omissions and double counting when cost estimates are rolled-up</li> <li>• There is a need to standardise the cost estimating process in terms of considering uncertainty and risk in order to enhance learning across projects</li> <li>• In CfA agreeing the ownership of risks and uncertainties is more difficult than for conventional manufacturing or in-service support contracts because both the supplier and the customer find it more challenging to identify and quantify these and establish a mutually agreeable management approach.</li> <li>• The culture shift is an important aspect in CfA and affects the identification and quantification of uncertainty due to the reliance on expert opinion</li> <li>• Contractual framework is unclear and uncertainty considerations could help to structure the thinking</li> <li>• Need to be able to compare across projects in terms of the uncertainty influences</li> <li>• Lack of common terminology among departments for the terms risk and uncertainty</li> </ul>

### **Additional challenges realised from collaborating organisations**

The following list of challenges were gathered from collaborating organisation and represent an additional set of challenges that have not been referred to in Table 4.13.

- Lack of first line assessment causing an increase in system level uncertainty
- A commonly used framework that distinguishes between risk and uncertainty
- Assessing the influence of personal risk aversion/optimism level
- Systematic data flow from the customer to the OEM feeding into MDAL concerning usage level and conditions of usage
- Lack of alignment between customer and supplier uncertainties
- Analysing the productivity of individuals (e.g. faster/slower individuals)
- Measuring uncertainty that arises from the association between value and acquisition price over project durations
- Lack of feedback mechanisms to capture the difference between actual outcomes and estimates

### **Observation of existing challenges across collaborating organisations**

The following list of challenges summarise the key challenges and makes a comparison across the collaborating organisations.

- Sustaining the reliability level is very important in CfA, though, measuring this metric is difficult. All interviewed organisations agreed with this idea and suggested that improvements should be made to understand the concept of reliability. This will necessitate better understanding of equipment failure and obstacles such as technology maturity or obsolescence that may arise in the future
- All organisations that were interviewed highlighted the large reliance on the service network for bespoke parts. Also, issues related to quality of parts and timeliness of the supply chain was often mentioned. The need for better understanding uncertainties deriving from the supply chain was commonly referred.
- Three out of the four organisations that were interviewed on this topic, suggested that services lack standardisation and need an approach to reduce non-recurring

costs, which may originate from spare parts, obsolescence mitigation strategies and/or failure costs. This confirmed the difficulties experienced in support costs

- Two out of the four organisations mentioned difficulties in prioritising uncertainties at the early stages of the CADMID cycle. This means among uncertainties that are considered their influence over potential costs may not easily be captured
- Growth in service offerings has brought about new issues associated to responsibilities (e.g. who does what?). This is an issue of scope and was recognised by all four organisations that were interviewed, which implies that agreeing CfA is still contractually a challenging task
- Determining metrics in service offerings means that new areas are of interest to the OEM. For the OEM this refers to taking on new responsibilities, such as spares management, where new metrics will need to be considered in order to sustain high performances, whilst these create additional uncertainties and risks
- Large sources of unnecessary costs arise from repair requests that do not have any fault. This issue was raised by three out of four of the interviewed organisations.

#### 4.1.7 Scope definition workshop

To finalise this phase of the research a scope definition workshop was organised, which involved seven participants. An overview of the meeting in terms of duration and participants is provided in Table 4.14.

Table 4.14 Overview of the scope definition workshop

Meeting	Meeting Duration (Hours)	Job role of attendee(s)	Experience (Years)
Workshop	3	Supportability engineer	26
		Integrated Logistics Support Manager	18
		Engineering manager	31
		Assistant project manager	4
		Systems engineer	24
		Supportability engineer	27
		Project manager	16

The workshop aimed to raise potential research questions that required investigation and a scope for the framework and tool development. Some of the research requirements captured during the workshop s include:

- There is a need to better understand the uncertainty that originates from the customer and technology
- Need to understand the evolution of uncertainty over time
- Some of the key uncertainty areas associated to CfA include system design, component durability, support solutions, customer equipment usage, resource requirement, infrastructure, supplier base. Though, there is a lack of consistency and there is a need for a standardised list of uncertainties for guidance.
- Agreement of CfA has promoted behavioural issues such as changes in responsibilities, relationships with the customer, relationships with the supplier, which are qualitative aspects that are challenging to consider quantitatively
- Understanding the relationships between cost reduction and uncertainty
- Definition of factors to apply uncertainty in particular aspects of a model (e.g. an uncertainty capability audit)
- Provide a holistic uncertainty list in order to customise the uncertainty, which can help to understand the parts that are more uncertain. This could also potentially help as a language between the customer and the OEM.
- Need support in determining the assumptions in relation to the environment
- Need support in aggregating the influence of uncertainties
- Need support in turning uncertainties into certainties (and to retire risks)
- Need for an ability to reduce cost while increasing certainty
- Need a measure to see how there is a link between certainty and uncertainty
- Visualisation of uncertainty through customised tools

As a result of the workshop it was determined that some of the key questions of interest for the cost uncertainty domain for this research included:

- How does uncertainty differ across different types of system complexity categories (e.g. simple pump valve and complex computer sensors)?
- How to measure and estimate uncertainties over time?

- How to develop guidelines for cost uncertainties at the bidding stage in terms of identifying, prioritising and responding to uncertainties?

## 4.2 The Focused Challenges

The transition to CfA has shifted the sources of perceived customer value, while the service content has increased in the provision. Cost estimation has emerged as a major challenge due to the uncertainty that arises from the dynamic behaviour experienced in service delivery (e.g. changing usage conditions and equipment health) and the manipulation of customer requirements. The degree of uncertainty is associated to the length of the contract e.g. over 30 years. In order to deal with the cost uncertainty challenges a number of areas have been set the focus for this study, including:

*Firstly*, as the nature of the in-service phase has drastically changed for the solution provider by delivering CfA, there is a need for an effective mechanism to identify uncertainties. The challenge is coupled with the need to understand differences between projects, when establishing guidelines or checklists. This relates to the fact that there are no established types and categories of uncertainties. *Secondly*, prioritisation of uncertainties is a challenging task, due to the lack of standardised processes (e.g. metrics) in comparing cost uncertainties. So among uncertainties that are considered their influence over potential costs may not easily be captured. Also, a structured approach would enable to reduce the influence of optimism arising from engineers. *Thirdly*, a means to recognise the level of uncertainties is necessary because of the lack of understanding of the boundaries of a cost estimate not only across organisations but also across internal departments.

*Fourthly*, there is a need to consider the uncertainty in input variables when developing Three-point estimates. A structured and rigorous approach needs to be put in place in order to be able to justify the defined confidence in an estimate as this determines the level of uncertainty. The link between the confidence level in cost and affordability is also important in the process of agreeing contracts (e.g. over confidence may reduce affordability). *Fifthly*, since in the bidding stage there is substantial time pressure, it

would be beneficial to reduce the impact of the be-spoke nature of projects on adjusting processes by utilising a generic model through a tool that provides a standardised methodology to integrate uncertainty to cost estimation, while keeping a balance between time and accuracy of a cost estimate. Sixthly, in order to understand the dynamic nature of cost in relation to uncertainty alternative approaches to the Monte Carlo simulation needs to be assessed.

### **4.3 Summary**

In this chapter, initially the main changes with regards to cost uncertainty that occur with the adoption of CfA are explained. The applications across the CADMID cycle were presented and it was recognised that with CfA the amount of uncertainty increases for the solution provider, whom needs to further understand the role of uncertainty.

In Section 4.1, the process of interaction with industry is presented, whereby a step by step approach is followed to explain the results from interviews, workshops and case studies. Across industrial collaborators it was observed that cost estimation tends to be made with in-house tools, while commercial of the shelf tools tend to be used for validation purposes (mainly due to visibility issues). The most common approach to integrate uncertainty into cost estimation was recognised to be Three-point estimating, which requires considerations of the most likely, minimum and maximum levels of costs. Some of the key challenges that have been identified include:

- There is not a standard consideration of uncertainty in cost estimation, though considering the WBS helps to structure the thinking. This relates to the identification, prioritisation and linkage of uncertainties and cost drivers
- There is much difficulty in estimating costs of functional/service offerings due to the variability over time (e.g. stochasticity and unexpected arising). This is associated with e.g. the lack of experience/data in estimating
- The supply chain tends to produce the largest amount of costs for a service delivery. Furthermore service providers are reliant on receiving requirements on time and with the required quality



Section 4.2 narrows the range of identified challenges to the scope of the research by specifying the specific areas to be considered in the developed overall framework.

Within the following chapter an overview of the framework that has been adopted within this thesis is presented. Furthermore, the chapter focuses on describing the types of uncertainties that are experienced in CfA is presented. Furthermore, the chapter also covers the unique uncertainties associated to CfA.



## **5 OVERALL FRAMEWORK DEVELOPMENT & UNDERSTANDING UNCERTAINTIES IN CONTRACTING FOR AVAILABILITY**

Sufficient consideration of uncertainties is essential for successful delivery of Contracting for Availability (CfA), due to their potential impact over cost, schedule and performance. This chapter begins by presenting an overall framework of the research covered in this thesis, whilst presenting three phases, including “Uncertainty Management”, “Three-point estimating” and “Dynamic cost estimation”. As part of the input to the uncertainty identification in “Uncertainty Management”, this chapter serves the purpose of structuring complexity in CfA delivery by presenting the main categories and types of uncertainties and their impact on the delivery of the use oriented model of Industrial Product-Service Systems (IPS<sup>2</sup>) at the bidding stage. The findings have been derived from the industrial interactions with seven major organisations in the defence industry and critically analysing the literature. The uncertainties that are explicitly associated to the service delivery are classified into emergent and transformed uncertainties, which represent a unique set of uncertainties for the CfA context. Emergent refers to the uncertainties that specifically arise in CfA (e.g. equipment availability, payment based on performance). Transformed is associated to uncertainties that were existent in the traditional model, though have changed, due to various factors (e.g. failure rate for hardware, spare parts storage). Validation results indicate areas that make CfA unique in terms of uncertainties.

In Section 5.1 the overall framework for this research is presented. In Section 5.2 the detailed methodology and initial results that was captured related to the types of uncertainties is presented. An iterative process is presented, which leads to the finalised list of uncertainties as covered in Section 5.3. Based on further analysis the author presents the emergent and transformed uncertainties in CfA in Section 5.4 and Section 5.5, respectively. The implication of the classification of uncertainties into emergent and transformed across the supply network is covered in Section 5.6. Subsequently, the potential impact of uncertainty in CfA is discussed in Section 5.7. Finally, in Section

5.8 the results from the validation concerning the emergent and transformed uncertainties for CfA are demonstrated.

Based on literature review the author has not come across a set of uncertainties that enable to understand the uncertainties that are experienced explicitly within the context of CfA. Driven by this gap and the industrial need to understand the relevant uncertainties in CfA, this chapter aims to enhance the understanding of uncertainties within the given context. Understanding the types of uncertainties may enable to improve processes associated to:

- project management by recognising the uncertainties influencing service delivery
- cost uncertainty modelling by recognising the influences on cost drivers
- cost uncertainty management by recognising the sources of variability in cost drivers that need to be managed

The presented comprehensive list of uncertainties represents a set of uncertainties that are likely to be experienced within the CfA context. Though, in order to understand the unique characteristics associated to CfA, the author conducted further analysis. It was acknowledged that the manner in which service is delivered is the differentiating factor from other forms of equipment support based interactions. Along these lines, it was acknowledged that there are emergent and transformed uncertainty outcomes from the interaction achieved in CfA.

## **5.1 Framework Development**

Research in the management of uncertainty as opposed to risk has received lesser interest. Although, an integrated approach across uncertainty identification, analysis, evaluation and mitigation has been proposed in literature (as covered under Case Study A in Section 4.2.3), its application has been limited. There is little consensus to define the relevant sources of uncertainties, their characteristics and how the characteristics can be related for uncertainty to be treated or managed. Uncertainty management is not just about the management of perceived threats; it also involves opportunities and their implications. The process involves the identification and management of all the many

sources of uncertainty which derive and drive our perceptions of threats and opportunities. This necessitates the exploration and the understanding of the origins of uncertainty before seeking to manage it. Key concerns are understanding where and why uncertainty is important in a given project context, and where it is not (Ward and Chapman, 2003). To be able to establish reliable cost estimates and sustain efficient and effective project management, it is necessary to select the appropriate management approaches for all the sources of uncertainty.

Only through an iterative process can the management of uncertainty be addressed, because initially identification of significant uncertainties and methods to manage uncertainty are unknown (Chapman and Ward, 2000). Along with this, as more information becomes available it is necessary to revisit earlier steps, test decisions and assumptions and make revisions as appropriate (Chapman, 1997). Each phase has its own objectives, which varies in terms of identifying the relevant uncertainties, their significance and the approach to respond and control over a given project duration. Taking a step by step approach aims to enhance effective use of time and other resources throughout the uncertainty management process. However, there is a need to take a systematic approach along the iterations, which avoids the assumption of linear information acquisition (Chapman and Ward, 2000). Furthermore, there is a need to consider how uncertainty evolves over the project duration or equipment life cycle. For instance, while imprecision is dominant at the conceptual stage, where limited data is available, in latter stages such as support or disposal the influence of variability grows.

Uncertainty management has not traditionally been considered in cost estimation (Boussabaine and Kirkham, 2004). The integration would enable consideration of the dynamic nature of uncertainties over the project duration. The common practice considers uncertainty management and service cost estimation independently. The integration would enable to consider the dynamic nature of uncertainties in cost estimates over the bidding process. Driven by these research challenges an overall framework has been developed. The framework consists of three phases as illustrated in Figure 5.1. In the first phase, uncertainty management involves the identification, prioritisation and mitigation of uncertainties, which directly influence the bidding

process. In the second phase, through Three-point estimating a confidence level is calculated to guide with the bidding. In the third phase, the dynamism in costs due to uncertainties is represented through agent based modelling.

The framework pays attention to the subjectivity involved in uncertainty considerations from a number dimensions including identification, prioritisation, management and Three-point estimating. The framework addresses the identified challenges by providing a standardised procedure that embeds flexibility to approach each of the specified areas, while enabling a structured procedure to follow. The novel contributions of the overall framework are in association to:

- the list of uncertainties to identify from for the bidding context of CfA
- the uncertainty prioritisation scheme
- the list of uncertainty mitigation strategies to select from
- sources of uncertainty in specific cost drivers
- process of turning a single point estimate to three
- dynamic cost estimation to recognise the behaviour in a supply network within the CfA context

The first two phases of the framework are implemented within an MS Excel based software prototype, which has been delivered to industrial collaborators. The tool has been named the “Uncertainty Tool for Assessment and Simulation of Cost” (U-TASC). The third phase takes input from the first two phases, however the agent based model is implemented using a software package called AnyLogic. Phase 1 focuses on reflecting a comprehensive set of uncertainties for CfA and the methodology to follow to manage uncertainties. Each of these aspects is presented in detail in Chapter 5 and 6, respectively. Considerations in Phase 2 focus on determining a link between uncertainties and cost drivers by establishing a bottom-up perspective in order to define Three-point estimates, which is presented in Chapter 7. As part of Phase 3, an approach for dynamic cost estimation using agent based modelling is presented in Chapter 8.

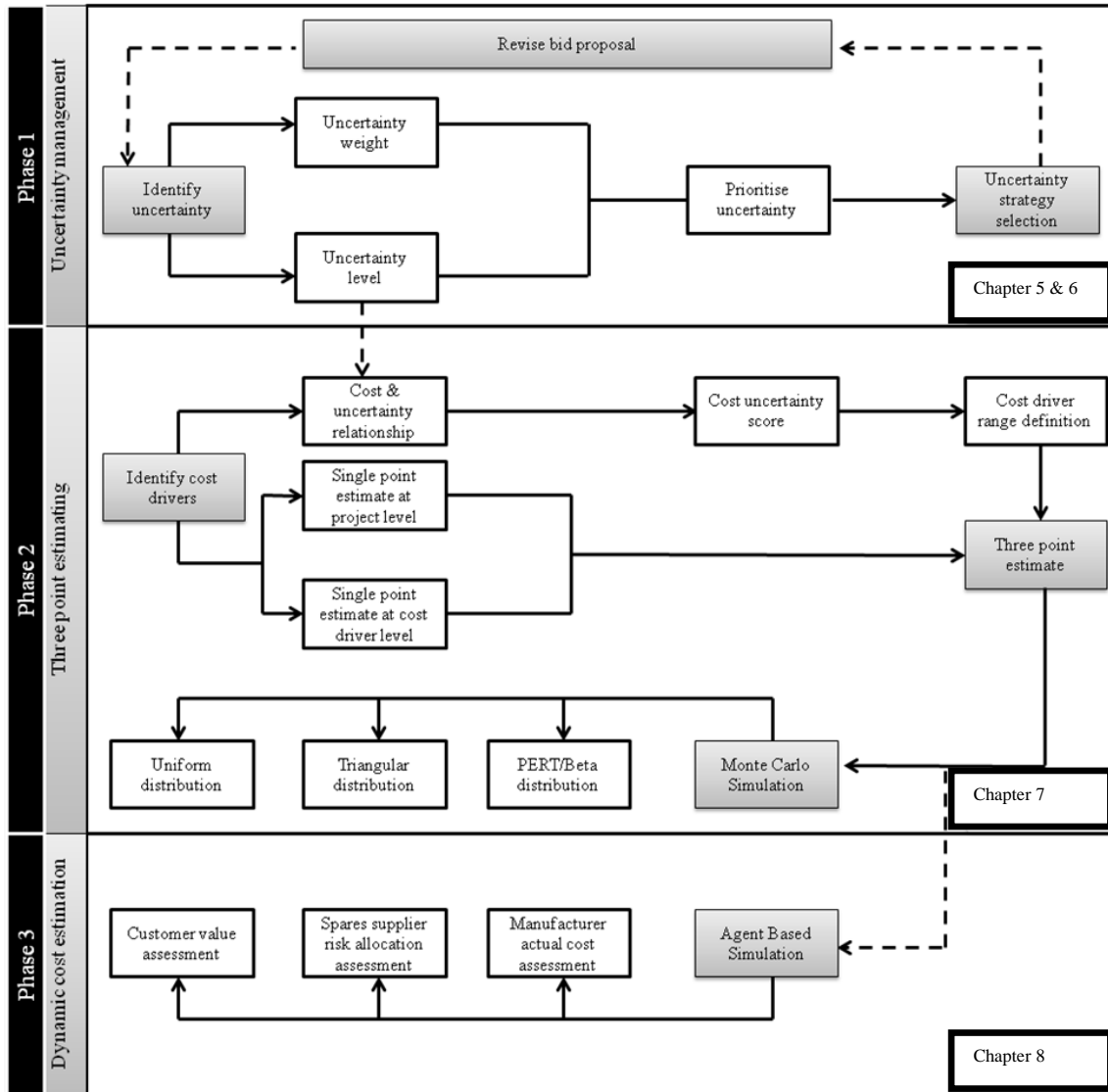


Figure 5.1 A framework for uncertainty management in service cost estimation

### Phase 1: Uncertainty Management

Phase 1 is concerned with the identification, assessment and evaluation of *major* uncertainties. This phase aims to address the level and the severity of uncertainty, while setting the context through qualitative questions such as what, when, where, how, and why. The answers to these questions support the identification of uncertainties as well as its quantification and management. Firstly, to identify uncertainties it is necessary to recognize and document all associated uncertainties that are known. The identification of uncertainty may be achieved through semi-structured interviews, brainstorming

techniques, the nominal group technique, the Delphi technique, identification tools (e.g. systems dynamic models), identification aids (e.g. checklists), UML diagrams, SWOT (strengths, weaknesses, opportunities, threats) analysis (Ward, 1999) and Weidema pedigree matrix (Lewandowska et al., 2004). Uncertainty identification processes, typically, use expert judgment (Kishk, 2004).

## Phase 2: Three-point estimating

Within this phase the integration of cost drivers and uncertainties aims to establish a Three-point estimate that reflects the influence of uncertainty. An important characteristic of the phase is associated to collecting expert opinion in devising the Three-point estimates that get used in Monte Carlo simulation. Furthermore, it is important to select the suitable probability distribution to represent the aggregated cost drivers. Table 5.1 illustrates the suitable distributions for given scenarios. The process of selecting the suitable probability distribution can sometimes present difficulty to the modeller. Nevertheless, there are many software programs that enable the correct selection of the distribution from a given data set. Furthermore, manually, Flanagan and Norman (1983) specify three points to guide the selection of distribution: (1) List everything known about the variable and the conditions about the variable, (2) Understand the basic types of probability distributions, and (3) Select the distribution that best characterizes the variable under consideration.

Table 5.1 Comparison of distributions (Stockton and Wang, 2004)

Continuous probability density functions	Discrete probability density functions
Normal distribution: for inflation and discount rates	Poisson: for probability of a number of events occurring in a fixed period of time if these events occur with a known average rate and independently of the time since the last event.
Beta: for variability over a fixed range	Binomial: for number of successes in a sequence of $n$ independent yes/no experiments
Weibull: for life expectancy, life-cycle, future forecasting and deterioration of elements	Geometric: for either the number $X$ of Bernoulli trials for success or $Y=X-1$ trials for failures before first success
Gamma: for time between events when events are not completely random	Bernoulli: for cases that have two possible outcomes (e.g. coin tossing)
Exponential: for modeling random points in time	
Lognormal: for positively skewed data sets	



### **Phase 3: Dynamic cost estimation**

The agent based approach is a disaggregate method that uses local rules for individual computational entities representing each member of the service network. The suitability of Agent Based Modelling (ABM) for cost estimation can be considered from four dimensions including generation of individual cost element distributions, generation of additive distributions, generation of compound distribution and treatment of dependency between cost elements. It offers detailed representation of each uncertainty and cost driver. As agents can mimic the service delivery process, this provides a useful feature to consider uncertainty. Parunak et al., (1998) define five characteristics of agents that are particularly salient, including applications that are complex, modular, decentralised, changeable, and ill-structured. In order to develop the ABM it is necessary to establish: (1) an agent architecture that represents the context and purpose, (2) the rules to capture the evolution of the agents and their interaction and, (3) an environment that the agents live in and interact with. Within this phase the final task involves the determination of the suitable probability distribution to represent cost. To be able to link the major uncertainties and cost drivers the agent based modelling approach offers a number of advantages when considering uncertainties in service cost estimation, including (Datta, 2007):

- Agent based approaches offer increased robustness against unpredictability and the dynamic nature of uncertainties that arise when delivering services
- When the nature of the phenomenon studied is complicated and there is necessity to understand the influence of each uncertainty
- An agent-based model can represent many actors (e.g. uncertainties and cost drivers), in particular their intentions, internal decision rules and interactions

## **5.2 Methodology for Defining and Structuring the List of Uncertainties**

The case of CfA creates a unique instance of uncertainties and explicit recognition of each area is required in order to support the bidding process from the cost estimation

perspective. Through interaction with industrial collaborators it was recognised that the process of systematically capturing uncertainties in CfA is a major challenge. Thus, the research aimed to initially establish a list of uncertainties that typically affect an IPS<sup>2</sup> delivery. An overview of the steps that were undertaken to derive the comprehensive and final list of uncertainties and to understand the uncertainties that are typically experienced in CfA are represented in Figure 5.2.

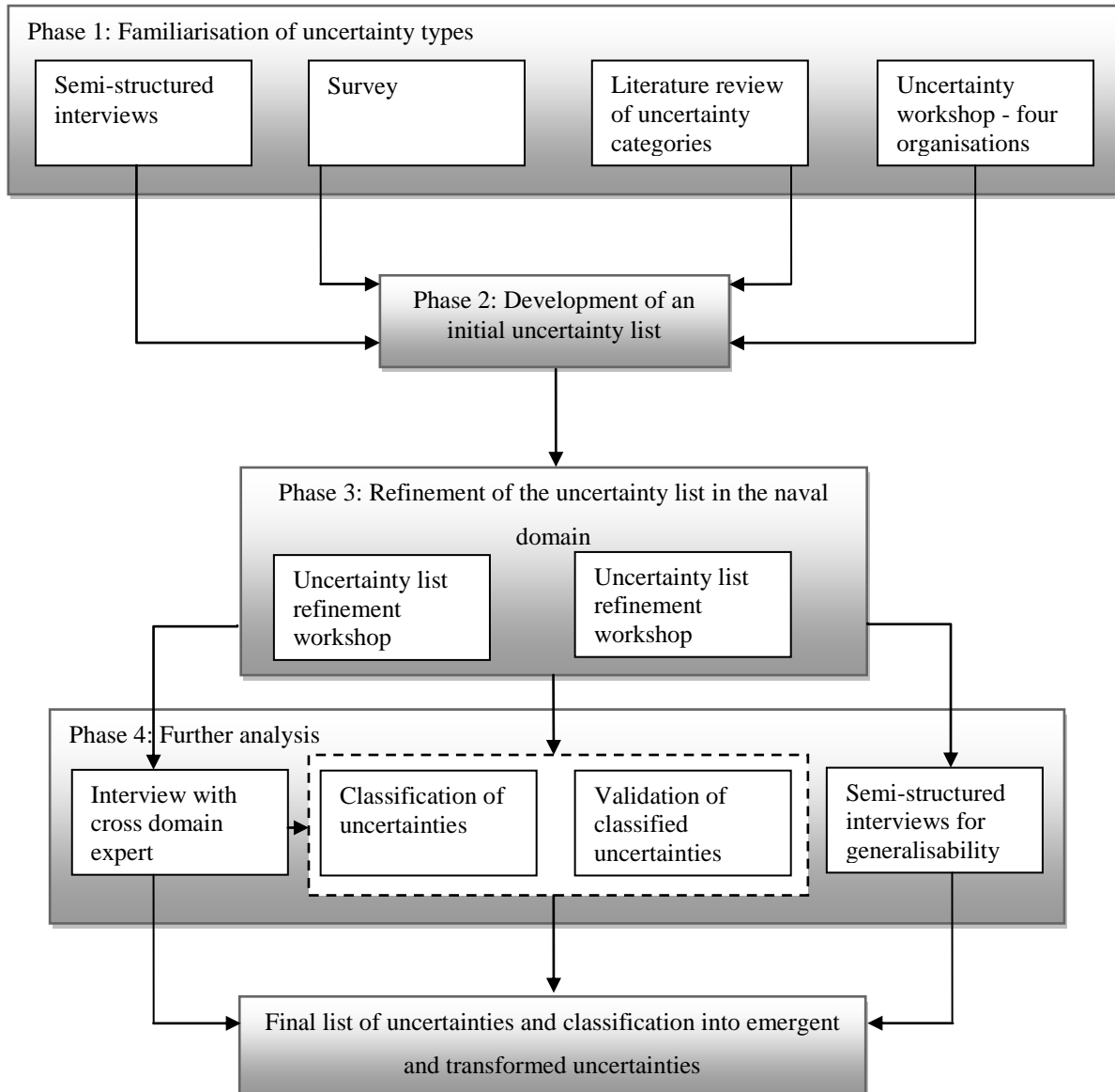


Figure 5.2 Research method to derive the comprehensive list of uncertainties

The presented research method in Figure 5.2 follows an iterative process. Whilst Phases 1 and 2 involved the development of the uncertainty list in Phase 3 and 4 the developed

lists were further refined through validations, which lead to the finalised list of uncertainties.

### **5.2.1 Phase 1: Familiarisation of uncertainty types**

The first phase combined literature review, semi-structured interviews, survey, and a workshop that was attended by industrials. Literature review for this part of the study focused on collecting and analysing types and categories of uncertainties from published material. In order to get an understanding of uncertainty the literature review concentrated on research that was conducted within the cost estimation domain. For this reason, studies by the MoD, Department of Defence (DoD), North Atlantic Treaty Organisation (NATO), USA Government Accountability Office (GAO), Society of Cost Estimating and Analysis (SCEA), European Aerospace Working Group on Cost Engineering (EACE), Society of Cost Analysis and Forecasting (SCAF) and NASA were highly relevant and supportive. A commonly agreed classification of uncertainty across DoD, NASA and SCEA includes (Government Accountability Office - GAO, 2009):

- business or economic: variation from business or economic assumptions
- cost estimating: variation in cost estimates despite a fixed configuration baseline
- program: risks outside the program office control
- requirements: variation in the cost estimate caused by change in the configuration baseline from unforeseen design shifts
- schedule: any event that changes the schedule-stretching it out may increase funding requirements, delay delivery, and reduce mission benefits
- software: variation from optimistic assumptions about software development
- technology: variations in technology maturity or availability

The highlighted list of uncertainties was determined to be unsuitable for the purpose of this research due to the lack of emphasis on service delivery, while schedule is considered to be outside the scope of the research. Furthermore, in order to fill this research gap in-depth interaction with industry was necessary.

The outcomes of the literature review, led to semi-structured interviews with all four mentioned organizations and the results were covered in Chapter 4. The uncertainty list was developed based on examination of what occurred on previous programs (e.g. WBS) and an overall understanding of the issues that are likely to arise on future programs. Furthermore, the list was generated bearing in mind their influence over cost drivers, which are influential during the bidding process. The author took notes during interviews concerning the suggested types of uncertainties and collated the results. The analysis of the interviews aimed to realise similarities, differences, and unique aspects.

Table 5.2 Overview of participants at the workshop

Organisation	Job role of attendee(s)	Experience (Years)
A	Engineering manager	31
A	Software specialist	24
A	Project manager	18
A	Subcontract manager	6
A	Assistant project manager	22
A	Principal Reliability Specialist	20
C	Risk specialist	18
D	Through life analysis manager	33
E	Supportability engineer	26
F	Design engineer	16

Within Phase 1 also a workshop was conducted, lasting three hours, which was attended by ten industrial experts across five organisations, where three of which were industrial collaborators. The names of the organisations follow the characterisation in Chapter 4, whilst two additional organisations also attended this workshop. Organisation E is heavily involved in missiles and missile systems with a high commitment to delivering availability solutions. On the other hand, Organisation F is heavily involved in providing in depth consultancy for the design and manufacturing phases for cost estimation in the defence industry. The aim of the workshop centred on three areas: (1)

the types of uncertainties in CfA, (2) cost uncertainty management approaches, (3) cost uncertainty modelling approaches. The emphasis within this chapter is on the first point, whilst results for the second and third points are covered in Chapter 6 and 7 respectively. Table 5.2 presents an overview of the attendees.

The workshop was structured whereby the researcher initially presented findings for each of the areas of interest. Subsequently the following questions were directed to the attendees in order to gather cross organisational information in the defence industry that represented industry best practice:

- How do uncertainties change when moving from a traditional model into CfA?
- How can uncertainties be managed at the bidding stage of CfA?
- Are there cost uncertainty modelling methods that are more suitable for CfA?
- What is your current approach to include uncertainty to cost at the bidding stage?

Participants of the workshop highlighted that CfA is designed to transfer the service and support responsibilities and the ownership of various uncertainties transfer from the customer to industry. It is expected that better operational knowledge of the OEM will facilitate better management of uncertainty. Furthermore, the OEM is incentivised to minimise transactions. Some of the other major changes were suggested to include:

- The ranking of various uncertainties change as a proportion to the overall uncertainty level. For instance, with the increasing responsibility of the OEM in support activities uncertainty in maintainability (e.g. better handling of mean time between failure (MTBF)) is reduced while service provision uncertainty has grown (e.g. supplier performance)
- The customer controlled the scope and timing of requirements in a product oriented context, while in an availability context the OEM has a larger responsibility to manage the life of the equipment
- The industry is expected to enhance the ability of sustaining required availability, however the co-creation of value depends on the interaction between the customer and the OEM

As the operational uncertainty is reduced by transferring responsibilities to the OEM, the challenges in uncertainty have become particularly driven by the service delivery process. The major uncertainty areas that were realised in the discussion are illustrated in Figure 5.3 and represent the very initial categorisation of uncertainties:

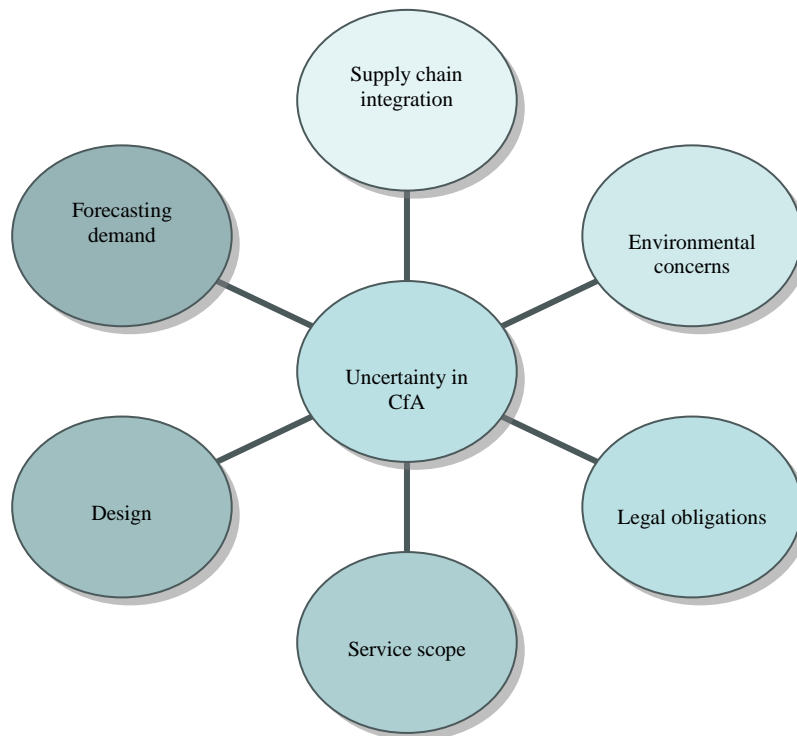


Figure 5.3 Initial categorisation of uncertainties in Contracting for Availability

- Supply chain integration refers to the efficiency in resilience. To be able to manage this process the importance of supplier relationships is very high
- Design, challenged by predicting the service provision prior to product design
- Demand forecasting considers the ability to plan for labour and spares requirements. Considering that in CfA the customers' usage is outside the control of the OEM, forecasting demand in many cases is challenging
- Necessity to enhance scope and scale of service offerings in areas that limited experience exists for the OEM (e.g. training, obsolescence management)
- Legal obligations that are encountered due to availability targets or any other form of performance requirement

- Environmental concerns refer to the impact of industry on environment and in association the growth in concerns of the public

Within Phase 1 also a survey was distributed to industrial experts. The questionnaire requested participants in the defence industry to select three services that have been the most challenging to deliver for a given project. The aim of this approach was to gather a list of uncertainties that have a higher influence. Furthermore, based on the frequency and impact of uncertainties the respondents were requested to exhaustively fill the types of uncertainties within an allocated matrix in the questionnaire, as shown in Figure 5.4.

		Frequency	
		Low	High
Impact	Low		1
	High	1	5
			10
			10

Figure 5.4 Survey elicitation of the key uncertainties for key services in CfA

In order to elicit the information the questionnaire was initially e-mailed to 15 of the industrial participants of the study. Additionally, during the course of this particular study the author also queried interviewees to fill the questionnaire. In total four responses were gathered and an overview of the respondents is provided in Table 5.3.

Table 5.3 Overview of respondents of the survey

Organisation	Job role of attendee(s)	Experience (Years)
A	Integrated Logistics Support Manager	18
A	Integrated Logistics Support Manager	30
A	Systems Engineer	26
C	Program Manager	25

As a result of the survey, it was acknowledged that provision of services is rather diverse in terms of scope and terminology. Furthermore, lack of standardisation of service terminology creates difficulties to compare and contrast across provided services. However, it was recognised that the key services that are offered centre on the provision of spares, maintenance and training. It was also realised that the suggested uncertainties varied across the mentioned services. The list of challenging services across the respondents includes: (1) availability, utilisation, spares delivery, (2) support cost estimation, project modification cost estimation, obsolescence, (3) integrated system, and (4) repair of electrical equipment, analysis of customer data, post design services. The survey supported with the development of the uncertainty list, along with determining the scope of services to be considered with the research.

### 5.2.2 Phase 2: Development of an initial list of uncertainties

Driven by the sources of material captured in Phase 1 an initial list of uncertainties was developed. The process involved collating the types of uncertainties across the specified areas in Phase 1. Furthermore, the initial list of uncertainties for each of the categories is represented in Table 5.4.



Table 5.4 Initial list of uncertainties

Uncertainty category	Uncertainty type
<b>Performance:</b> Measures considered in CfA	Flying hours, Labour availability, Availability of facility (e.g. forklift, stores), Understanding of service scope, Predictability of warranty scope, Reliability of equipment, Relationship with supplier, Operating environment, Third party contractor(s), Joint ventures, Staff objection towards availability type contracts, Customer user skill level, Customer maintainer skill level, Performance against KPI, Skill loss, Incentivisation, Equipment availability, Trainer availability, Affordability, Margin, Rate of human error, Structural changes to the OEM (e.g. merges, partnerships)
<b>Maintainability:</b> Maintaining hardware and software at customer requested level	Complexity of query, Emergent work, Labour effectiveness/efficiency, Capability upgrades, Equipment operating environment, Availability of materials, Safety during maintenance, Customer maintenance behaviour, OEM skill level of personnel for maintenance, Adequacy of the maintenance policy, Effectiveness of maintenance manuals, Influence of technology refresh, Severity of obsolescence, System integration issues, Variability in human performance, Governance transport, Complexity of equipment, Number of engineers
<b>Supportability</b> The means of delivering the maintenance requirements	Ease to find resources (e.g. parts, facilities, tools or labour), Arising rate (e.g. volume), Fleet maturity, Mean time between failure, Platform maturity, No fault found, Request for quotation supplier contracts, Safety in delivering (e.g. logistical) such service, Organisational stability (e.g. bankruptcy, mergers & acquisitions), Capability upgrades, Complexity of the equipment, Administrative activities causing delays, Administrative activities causing delays, Error(s) in storing spare parts (e.g. number keeping), Spares turnaround times, Critical part requirements, Beyond economical repair, Packaging of spare parts, Shelf life of spare parts, Variability in human performance, Rate of tools and facilities usage, Technological developments in service delivery, Mode of failure, Location of maintenance facility, Disposal of defective item (reverse logistics)
<b>Reliability:</b> Hardware and software reliability	Quality of component(s), Quality of system assembly, Volume of queries, Utilisation rate, Design quality of equipment, Skill level of maintainers, Unscheduled failure rate, Awareness of system configuration and handling, Stress and load, Failure rate for the equipment/software, IT Capability, Emergent work, Maintenance performance
<b>Cost estimation:</b> Cost estimation related aspects, e.g. data, process, techniques, and assumptions	Errors in data (e.g. Reliability), Data extrapolation errors, Data omission (e.g. representative, errors), Likelihood of data misinterpretation (e.g. repeatability), Lack of data (e.g. Completeness), Variability in data (e.g. shifts in data values), Accessibility of data (e.g. available, communication), Relevant data (e.g. useful), Errors in cost estimating relationships, Errors in analogy development, Error in selection of escalation factors, Interpretation of output (e.g. Monte Carlo), Overconfidence in contractor capabilities, Overconfidence in savings associated with new ways of doing business, Overconfidence in the learning and rate curve assumptions, Capturing all risks over and above the uncertainty contingency/allowances, Experience of the cost estimation team
<b>Manage business</b> Macro factors e.g. economy, regulation, politics	Commodity and energy prices, Interest rates (e.g. loans), Exchange rates, Inflation, Contractual complexity associated to incentives, Environmental burden (e.g. pollution), Sensitivity deriving from customer funding
<b>Customer Affordability:</b> Areas affecting affordability	Customer ability to spend, Whole life cycle cost, World economic climate, Legislative change, Customer perception on service quality, Supply chain, Requirement changes, Global competition, Performance related measures within the contract, Political climate, Other project specific characteristics
<b>Training:</b> Process of delivering training	Trainee skill level, Availability of trainers, Number of students, Facilities availability, Number of courses to be offered, Affordability, Turnover to staff, Availability of suitable candidates, Length of course

### 5.2.3 Phase 3: Refinement of the initial uncertainty list in the naval domain

Detailed input through a case study in the naval domain enabled to refine the uncertainty list, the scope of each uncertainty and their description. Firstly, a workshop was conducted to make an initial assessment of the list of uncertainties with the particular case study members. During this workshop, the researcher presented the list of uncertainties. As a result of the workshop, it was determined that the list of uncertainties needed to be refined and help with the interpretation of uncertainties needed to be provided (e.g. examples and further explanation). An overview of the attendees at this initial workshop is provided in Table 5.5:

Table 5.5 Overview of attendees at the initial workshop in Phase 3

Organisation	Job role of attendee(s)	Experience (Years)
A	Integrated Logistics Support Manager	18
A	Assistant project manager	22
A	Reliability consultant	26
A	Engineering manager	31

The objective of the second workshop was to refine the list of uncertainties. The workshop lasted for six hours, while an overview of the attendees is given in Table 5.6:

Table 5.6 Overview of attendees at the second workshop in Phase 3

Organisation	Job role of attendee(s)	Experience (Years)
A	Integrated Logistics Support Manager	18
A	Assistant project manager	22

The second workshop began with the determination of the uncertainty categories in light of the initial list of uncertainties and the WBS for the project that the interviewees were involved in. The sample to consider the uncertainties was a WBS for a major naval project within the in-service phase. The main categories of the WBS included:

- Readiness (e.g. at sea within 1 hour) and sustainment (e.g. sustained by supply chain) involving the delivery of mission and decide the shut down time.
- Through life management, which considers aspects such as obsolescence, upgrade, capability management (e.g. more weapons)
- Quality of components, as the transferred responsibility affects operations
- Design quality as a transferred responsibility affects quality of engineering

Through this list the main areas that get influenced were suggested to be including labour, material, planned and unplanned maintenance and spares, whilst also depending on the project training may constitute a major area. Furthermore, at a higher level there are commercial aspects, customer affordability, achieved performance, and estimating capability, which were captured as the major categories of uncertainties.

### Discussion over the initial list of uncertainties

The workshop also covered an assessment of the descriptions for each of the initial set of uncertainties, which have been presented in Table 5.4. The full list of the uncertainties and their descriptions are provided in Appendix E, whilst a sample of the suggested changes is covered in Table 5.7:

Table 5.7 Overview changes suggested to the list uncertainties

Uncertainty Case	Action
“Unscheduled arising”	Typically would not be estimated, which resulted in removing the variable from the list
“Emergent work”	The uncertainty concentrates on the estimation of the extra work that is needed due to arising
“Labour efficiency”	Focus emphasised on labour allocation across tasks
“Transport”	Referred to with respect to the suppliers
“Skill level for maintenance”	Maintenance provision process
“Uncertainty in incentives”	Removed from the uncertainty list as they were suggested to be a given within a contract
“Scope of labour availability”	To include skill loss along with the availability of workforce
“Structural changes to the OEM or the customer”	Removed from the uncertainty list because of the complexity of considering such changes
“Sub-contract”	Removed from the uncertainty list, because these are considered to be transferred to suppliers and the implications are

	contractually bounded
“Customer actual demand”	Specified in terms of changing requirements
“Arising rate” and “failure rate”	Specified to be synonyms and due to its wider recognition the author focused on using the term failure rate
“MTBF”	Replaced as uncertainty originates from the “existing data associated to MTBF”

#### 5.2.4 Phase 4: Further analysis

There were three ambitions when conducting further analysis to the existing list of uncertainties. Firstly, the list of uncertainties were validated by an individual from a major organisation in the defence industry, which the author had no interaction during the course of developing the list of the uncertainties. This aimed to reduce any potential bias that may have originated from the refinement process, which involved one particular organisation. Secondly, a generalisability assessment was conducted with software development organisation in the defence industry, in order to understand whether the list of uncertainties were suitable across the CfA context within the defence industry. Thirdly, in order to understand the specific uncertainties that originate in CfA further analysis was conducted.

The semi structured interviews (over three occasions) to review the list of uncertainties and their descriptions lasted for 6 hours with a reliability engineer from Organisation G with four years of experience in the uncertainty field. The interaction with Organisation G focused on the validation of the developed concepts, framework and tool. Initially the definitions of the uncertainty categories were assessed, and refined as follows:

- Commercial uncertainty: considers factors that affect the contractual agreement, which is driven by certain requirements set by the customer
- Affordability uncertainty: considers factors that affect the ability to predict the customers funding for the given project elements
- Performance uncertainty: considers factors that affect industrial achievement in reaching the performance for the given Project elements
- Training uncertainty: considers factors that affects supplier achievement in reaching customer needs for the delivery of training

- Operation uncertainty: takes a tactical perspective while considering factors that affect industrial achievement in reaching the required level of service and support delivery. It focuses on equipment level activities (e.g. onshore, maintenance) to deliver CfA
- Engineering uncertainty: takes a strategic perspective while considering factors that affect industrial achievement in reaching the required level of service and support requirements (e.g. offshore, obsolescence management) to deliver CfA

The intention of the review was to capture the uncertainties that are included in in a mathematical model. Some of the suggestions made by the respondent concerning the uncertainties and their definitions are provided in Table 5.8.

Table 5.8 Sample changes suggested for the uncertainty types

Uncertainty category	Assessed uncertainty	Action
Commercial	“Customer misuse”	Would get considered as a risk, whilst the uncertainty would involve “customer usage”
	“Work share between partners”	Re-termed to “collaboration effectiveness across suppliers concerning project elements”
	“Environmental burden or impact”	Amount of penalties that are received over time
	“Margin”	Suggested to not influence cost, thus it was removed from the list
Affordability		Include “customer willingness to spend” as an uncertainty
	“Whole life cycle cost”	Changed to “Project cost” due to the lack of life cycle agreements
Performance		No changes were suggested
Training	“Courses to be offered”	Removed because it was suggested to be a certainty rather than uncertainty
Operation	“Skill level of maintenance”	Changed to “maintainer performance”
	“Transport”	Changed to “OEM logistics”, which focuses on the internal supply of materials
	“Delays in supply delivery”	Re-termed to “supply chain logistics”
	“Calibration of facilities”	Re-termed to “calibration of work scope”
	“Uncertainty level of spare parts storage”	Re-termed to “Sufficiency of spare part storage”
Engineering	“Quality of engineering”	Re-termed to “efficiency of engineering effort”
	“Management of risk and opportunities”	Re-termed to “Effectiveness of management of threat and opportunity”

The respondent emphasised that the list of uncertainties were particularly suitable for the early phases of a bid for CfA, where there is a lack of information to make a detailed assessment of the associated uncertainties. Secondly, through an interview with a supportability engineer, whom had over 16 years of experience, the generalisability of the list of uncertainties was questioned. The respondent highlighted that “the list of uncertainties was suitable and represented a comprehensive perspective of uncertainties for the CfA context”.

Thirdly, the detailed list of uncertainties was analysed in order to reflect a concentrated list of uncertainties that is explicitly associated to CfA. It was considered that the major theme of agreeing CfA is associated to the provision of services in a unique manner that focuses on equipment availability. Along these lines the author, used the finalised list of uncertainties and analysed each type of uncertainty in order to classify the list into three categories within the CfA context (1) emergent uncertainties, (2) transformed uncertainties, and (3) those that do not differ from other forms of service based contracts. This classification was validated through questionnaires with participants related to the IPS<sup>2</sup> domain, as explained in Section 5.7. The questionnaire aimed to conceptually assess the coverage and classification of emergent and transformed uncertainties. The responses enabled to improve the concentrated list of uncertainties.

### **5.3 Finalised Uncertainty Considerations for Contracting for Availability**

This section presents the finalised considerations for uncertainty in cost estimation within the context of CfA at the bidding stage. Initially, a framework is presented for uncertainties for the given context. Subsequently, the focus centres on the finalised list of uncertainties, which covers the types of uncertainties and the associated categories.

#### **5.3.1 A framework for uncertainty in Contracting for Availability**

The presented framework was developed based on industrial interaction to conceptualise the understanding within the specified context by illustrating the factors

associated to uncertainty that affect service delivery in an IPS<sup>2</sup>. The framework consists of an explanation of: (1) the drivers of the move to IPS<sup>2</sup>, (2) the focus of service delivery in IPS<sup>2</sup>, while emphasising the significance of the shift in responsibilities, (3) major categories of uncertainties that influence IPS<sup>2</sup> delivery, whilst highlighting that there are unique aspects associated to the delivery of CfA (e.g. emergent and transformed sources). Figure 5.5 represents the uncertainty framework. In order to successfully deliver CfA, the framework gauges the following questions:

- What are the factors that affect the process of agreeing a CfA?
- What are the key capabilities required to deliver CfA?
- What are the key sources of challenges (e.g. uncertainties) in delivering CfA?

The factors that influence the process of agreeing the CfA vary and trigger the formation of uncertainties. Along these lines, through industrial interaction some of the key aspects that emerge were realised to include:

- Shift in the value proposition, which promotes an integrated supply network that interacts to achieve the common goal of operating the equipment
- Left shift in the time at which service requirements are considered means that the supply network needs to conform to given targets much earlier and influence uncertainty and profitability considerations
- Shift in the sources of revenue, which is driven by the delivered performance
- Shift in organisation culture that promotes an emphasis on service
- Enhanced competition due to the higher and stable potential financial gain

It is also observed that the delivery of CfA is driven by the organisational capability in understanding and responding in a preventative or reactive manner to the service requirements. As follows the key areas of emphasis in the availability delivery are associated to the processes/activities that focus on meeting reliability, maintainability and supportability goals. Driven by the shift in responsibilities, improvements in the utilised technology and organisational processes have been experienced that enhance communication. This chapter classifies the categories of uncertainties into commercial, affordability, performance, training, operation and engineering (Erkoyuncu et al., 2010c). Further information about these categories is provided in Section 5.3.2.

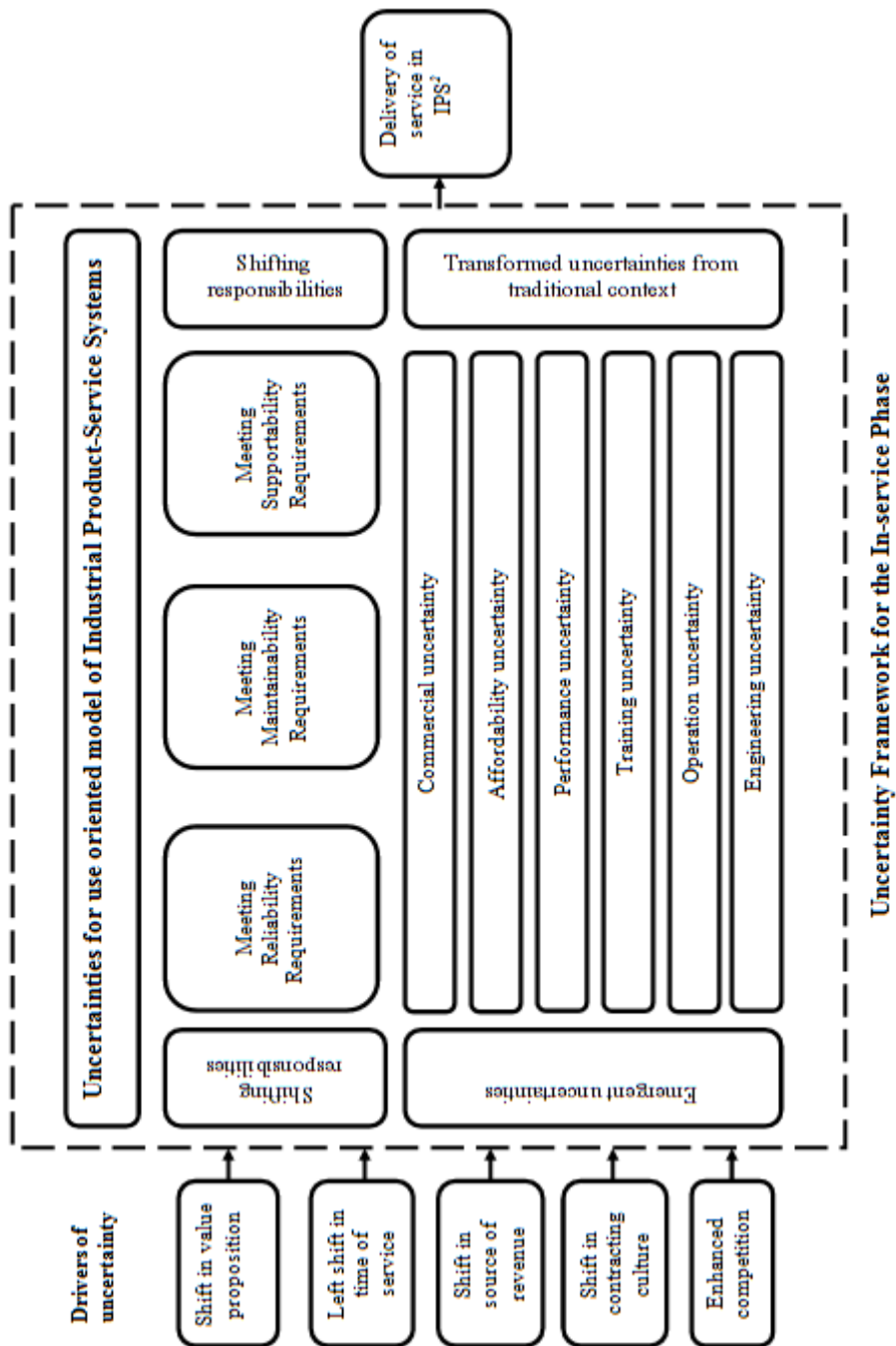


Figure 5.5 Uncertainty framework for Contracting for Availability

### 5.3.2 Finalised list of uncertainties

The finalised list of uncertainties has been developed to represent the typical uncertainty expectations for CfA, which is illustrated in Figure 5.6.



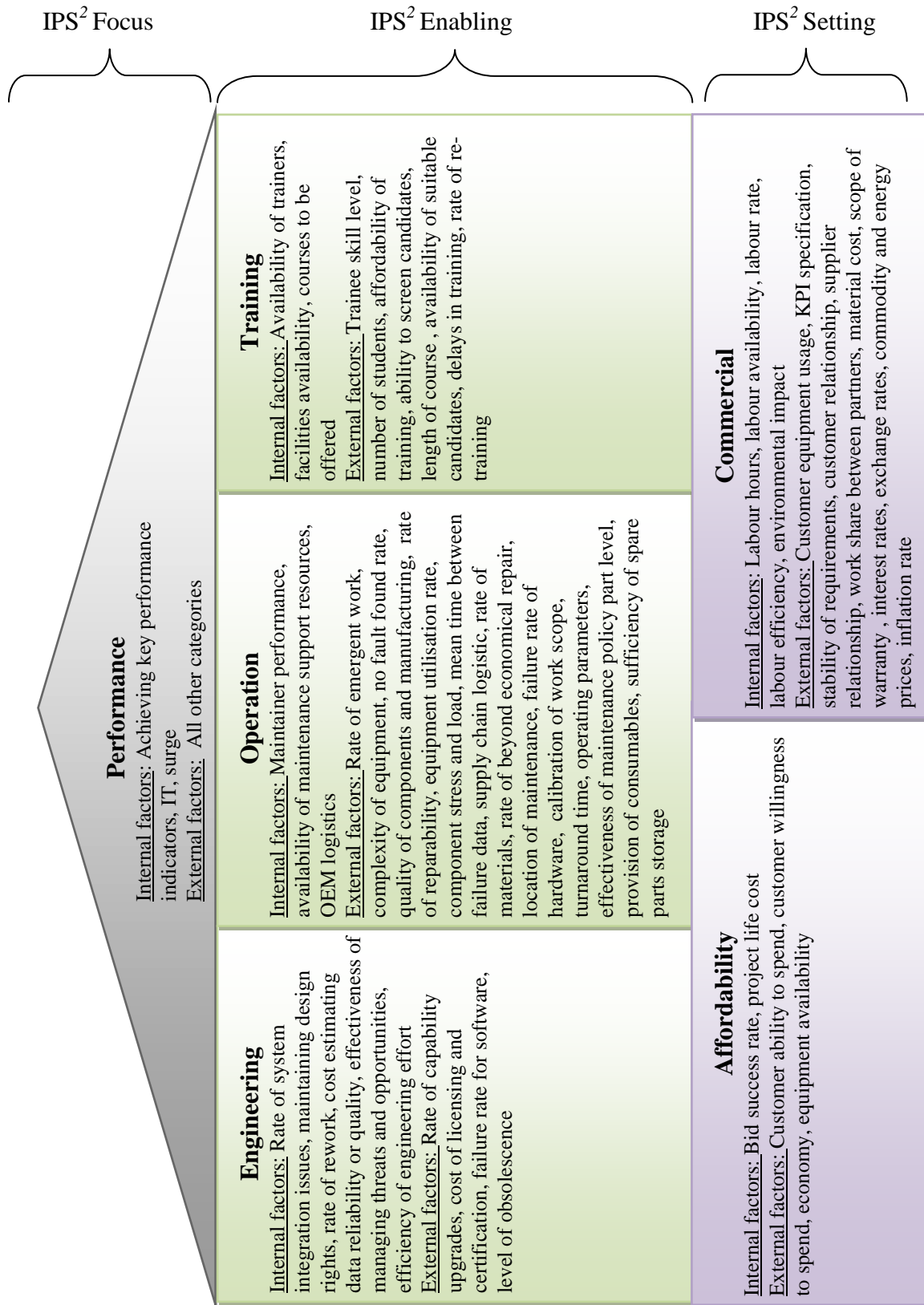


Figure 5.6 Finalised list of uncertainties for Contracting for Availability

The initial set of uncertainty categories represented in Figure 5.3, were refined at the second workshop that is presented in Section 5.3.2. The refinement process took into consideration the established WBS on a naval based project, which is involved in delivering spares, maintenance and training services. During the interview, in order to reduce the bias of relying on a single project, based on the experiences of the participants a view of a typical service project was taken. It was emphasised that it was necessary to spread the uncertainties across the cost estimation process, whilst also getting a view of the customers' ability to pay a given contract. The key elements to consider in CfA were suggested to include labour and material requirements for a planned and/or unplanned maintenance context. In order to achieve these requirements the OEM needs to enhance its capability in managing the service provision by considering the maintenance requirements in terms of labour effort, flow of materials across the supply network, designing services by adequate consideration of equipment architecture and quality of components, IT and knowledge management, planning maintenance and sustainment (e.g. obsolescence and upgrade) and performance against KPIs. Thus, the sources of uncertainties were classified into three sources:

- IPS<sup>2</sup> focus: sets the “performance” goals that influence the sustainability of the contract over the specified time period.
- IPS<sup>2</sup> enabling: elements refer to the capability of the solution provider in achieving the availability level through engineering, operation and training areas
- IPS<sup>2</sup> setting: elements cover the customer requirements within a contract and the ability of the customer to afford the given contract.

Each of the uncertainty categories has a detailed list of uncertainties, which are experienced during bidding. While taking the manufacturers' perspective the following sub-sections explain the uncertainties by classifying them based on internal (e.g. manufacturer processes) and external (e.g. supplier processes) sources.

### **Commercial Uncertainty**

The key uncertainties that are considered during the contracting procedure are reflected within this category. The internal factors are driven by the capabilities of industry, which involves labour hours, labour availability, labour efficiency, and environmental

impact. The external factors involve uncertainties that arise from outside the OEM. The customer may create uncertainty while specifying KPIs, with equipment usage manner, scope of warranty, customer relationship and the stability of requirements. From the supply chain perspective, various uncertainties include material cost (e.g. spares), and the relationship with suppliers. Other areas of uncertainty include interest rates, exchange rates, commodity and energy prices, labour rate and inflation rate.

### **Affordability Uncertainty**

The emphasis is on the customers' ability to fund the project and associated uncertainties are covered in this category. The internal factors include bid success rate that affects the profitability requirements, and the project life cost. On the other hand, the external factors include the customer ability to spend, customer willingness to spend, economy, equipment availability.

### **Performance Uncertainty**

Performance is the main goal of the IPS<sup>2</sup> delivery and it is driven by many factors that concern service delivery (e.g. activities) and it is measured based on KPIs. The internal factors include the ability to achieve KPIs, IT, and surge. In contrast, the external factors involve uncertainties covered in affordability, commercial, training, operations and engineering, which influence the level of performance delivered.

### **Training Uncertainty**

The focus is explicitly on delivering training. Internal uncertainties include the availability of trainers, facilities availability (e.g. computers), and the number of courses that are likely to be offered. The external factors include the trainee skill level, number of students, affordability of training, ability to screen candidates, length of course, availability of suitable candidates, delays in training, and the rate of re-training.

### **Operation Uncertainty**

This category focuses on the uncertainties that arise in the process of actually delivering spares and maintenance. The internal factors relate to the maintainer performance,

availability of maintenance support resources, and OEM logistics. The external factors include equipment originating factors, along with customer and supply chain sources. Equipment originating uncertainties include rate of emergent work (e.g. additional work needed to conduct repair), turnaround time, complexity of equipment (e.g. based on knowledge requirements to maintain), quality of components and manufacturing, and failure rate of hardware. The customer originating uncertainties that affect the IPS<sup>2</sup> include equipment utilisation rate, rate of repairability, operating parameters (e.g. temperature, moisture), component stress and load, calibration of work scope and effectiveness of the maintenance policy part level (e.g. maintainability level). Supply chain originating uncertainty includes supply chain logistic (e.g. degree of logistics as a result of spares/maintenance requirements), location of maintenance (e.g. distance to travel), mean time between failure data (e.g. data uncertainty), no fault found rate (e.g. no need to replace/repair), beyond economical repair (e.g. need for new part), rate of consumables requirements, rate of materials and sufficiency of spare parts storage.

### **Engineering Uncertainty**

Engineering uncertainties refer to the delivery of spares and repair based on the strategic level activities that take place. The internally driven uncertainties include the rate of system integration issues, maintaining design rights, rate of rework, cost estimating data reliability or quality, effectiveness of managing threats and opportunities, and the efficiency of engineering effort. These uncertainties are particularly driven by the existing skill set. For instance, cost related capabilities largely originate from data reliability or quality, and cost estimating data interpretation. The external factors include uncertainties rate of capability upgrades, cost of licensing and certification, failure rate for software, and level of obsolescence.

## **5.4 Emergent Uncertainties in Contracting for Availability**

The emergent uncertainties refer to the specific types of uncertainties, which arise with the agreement of CfA in the defence industry at the bidding stage. In defining the emergent uncertainties the author used the finalised list of uncertainties specified in

Section 5.3.2. Along these lines, the author questioned each type of uncertainty in terms of what could be a new uncertainty in CfA, whilst the criteria included:

- Whether new service features are offered with CfA?
- Whether new aspects associated to the relationships across the supply network are experienced?
- Whether new processes and capabilities are utilised to fulfil the service requirements?

The emergent uncertainties are associated to both the customers' and the manufacturers' activities in the process of co-creation of value. The list includes:

**Equipment availability:** Becomes a key element of the contract as a performance criterion. In the traditional contract this aspect had not been defined as a requirement by the customer. The uncertainty is associated to the level of equipment availability achieved, which is dynamic.

**Payment based on performance:** The uncertainty is associated to achieving the performance requirements particularly with respect equipment availability. In alignment, an associated uncertainty is the way the budget varies over time.

**Human performance:** The focus of this uncertainty is the human performance during the service delivery process. A major element of this uncertainty is the skill level of maintainers, which requires continuous update and also skills obsolescence is a major challenge due to the long time frame.

**End user equipment usage:** The customer influences the equipment availability level with its equipment usage preferences. This uncertainty is associated to the utilisation rate and equipment misuse. The manufacturer needs to take into account this uncertainty in order to deliver availability.

**Change in evolving constraints for support:** Due to the nature of the customers' instant support requirements, the OEM needs to be able to organisationally construct itself. It is an emergent uncertainty due to the nature of the evolving constraints that influence the OEM in meeting the commitment.

**Intangible expectations:** The concept of co-creation of value means that the customer and the manufacturer build close relationships and in essence

intangible expectations such as satisfactory communication and on-time delivery become essential parts of the system.

**Change in capability requirements:** The uncertainty is considered to be new in terms of the change in requirements, driven by the additional responsibilities that the OEM takes to meet the changes in the capability requirements. Though it is also necessary to recognise the boundaries of a contract as well, as significant changes in capability requirements can be considered through re-negotiation.

**Lack of information and knowledge sharing:** Integration between customer and manufacturer activities is required in order to reach the targeted level of co-creation of value. Though, in order to reach this, information and knowledge concerning the service requirements and delivery needs to be shared. Uncertainty is associated to this sharing and it is an emergent uncertainty due to the dependency between the customer and the manufacturer.

**Supplier dependence:** Across the supply chain with the increase in the transfer of responsibility from the customer to the OEM and to suppliers there is an increase in dependency across suppliers. The uncertainty is associated to the performance of each supplier and how this affects the outcome of the system.

**Training for availability:** The manufacturer offers specific training services to maintain the availability level. Such an approach had not been applied in the traditional context and emergent uncertainties in the process of service delivery have emerged with regards to achieving performance goals for training.

## 5.5 Transformed Uncertainties in Contracting for Availability

The transformed uncertainties reflect those that existed in the traditional context and are also present in CfA, though they experience a change due to various reasons. The author reviewed each of the uncertainties specified in Section 5.3.2 from a number of perspectives in order to understand whether a change was experienced in the particular type of uncertainty. The sources of change are driven by the following areas:

- **Responsibility:** The transfer of service activities along the supply network
- **Time:** The decisions made concerning various aspects related to service delivery

- **Information:** The source and flow of information changes across stakeholders
- **Stakeholders' dependency and alliance:** The collaboration across the supply network (co-creation of value across supply network)
- **Capability or knowledge:** Requirements in terms of know-how to fulfil the needs of the new context in service delivery
- **Importance of value:** Change in what the customer considers as added value
- **Source of revenue:** The change in the architecture of generating revenues

Figure 5.7 aims to illustrate these causes of change in uncertainties by taking into account each of these sources and defining their role across the supply network. Co-creation of value forms the central focus of the system across the stakeholders.

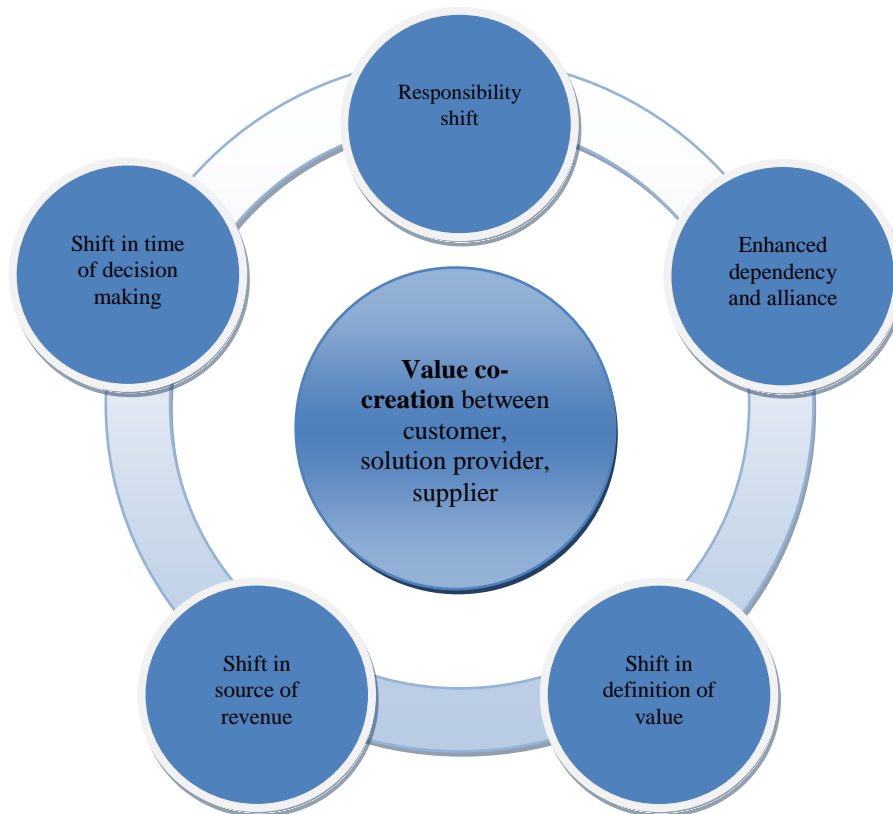


Figure 5.7 Causes of the transformation in uncertainties

The uncertainties that are transformed based on the presented factors include, failure rate for hardware, spare parts storage, rate of capability upgrades, system integration issues, failure rate for software, severity of obsolescence, KPI specification, rate of emergent work, supplier logistics, mean time between failure data, spares requirements,

no fault found rate, operating parameters, turnaround time, rate of materials, rate of beyond economical repair, material cost, and component stress and load.

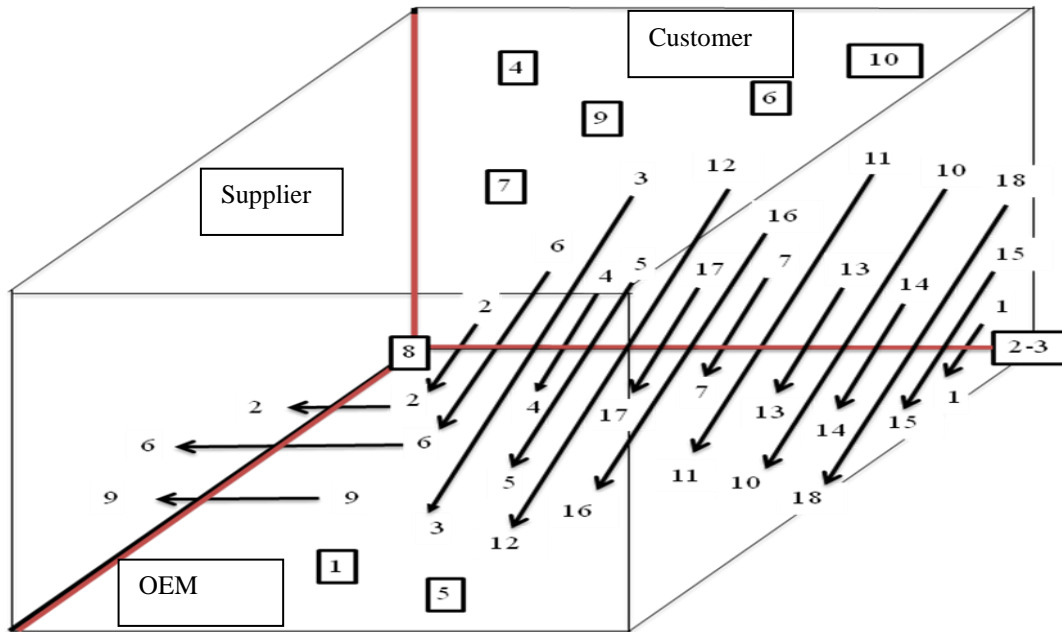
## **5.6 Understanding the Emergent and Transformed Uncertainties across the Supply Network**

This section aims to explain the implications of emergent and transformed uncertainty considerations across the supply network. Figure 5.8 illustrates the emergent and transformed uncertainties by showing the emerging and shifting uncertainties across the customer, OEM and supplier. An emergent uncertainty such as “end user equipment usage” is considered to originate at the customer. Additionally, the responsibility of managing a transformed uncertainty such as “obsolescence” is passed from the customer to the manufacturer, which is largely the case across the complete list of uncertainties. Furthermore, there are a number of uncertainties, which are experienced collaboratively. The uncertainty of “lack of information and knowledge” poses an example for the scenario that the customer, manufacturer and supplier collaboratively face. An uncertainty that both customer and manufacturer faces is the “payment based on performance”. Below further information about some of the key uncertainties is provided through examples. For the emergent context “equipment availability” and for transformed uncertainties “failure rate for hardware” are covered. Detailed explanation of each type of uncertainty is provided in Appendix E, whilst also a detailed explanation of a transformed uncertainty (e.g. failure rate for hardware) is presented.

Equipment availability becomes a new uncertainty for the OEM as such a demand had not been part of the traditional model. This involves transfer of support related processes to the solution provider. Performance driven attitude is a new perspective, which makes the enabling aspects such as service processes less important to the customer as the responsibility of managing processes is transferred across the supply chain at varying degrees. The OEM focuses on understanding these uncertainties at the bidding phase, which is earlier than the traditional context and poses a high degree of uncertainty due to the lack of information about the life cycle expectations. Along these lines, the OEM enhances its communication with the customer in order to gather an in-



depth understanding of the equipment usage and in alignment the evolution of the equipment conditions. Furthermore, due to the performance goal, integration across the supply chain (e.g. storing parts and sharing information) is required. The OEM needs additional capability to track equipment health and to share information with suppliers.



#	Emergent Uncertainties	Transfer of responsibility
#	Transformed uncertainties	
#	<ul style="list-style-type: none"> <li>1. Equipment availability</li> <li>2. Payment based on performance</li> <li>3. Human performance</li> <li>4. End user equipment usage</li> <li>5. Change in evolving constraints for support</li> </ul>	<ul style="list-style-type: none"> <li>6. Intangible expectations</li> <li>7. Change in capability requirement</li> <li>8. Lack of information and knowledge sharing</li> <li>9. Supplier dependence</li> <li>10. Training for availability</li> </ul>
#	<ul style="list-style-type: none"> <li>1. Failure rate for hardware</li> <li>2. Spare parts storage</li> <li>3. Rate of capability updates</li> <li>4. System integration issues</li> <li>5. Failure rate for software</li> <li>6. Severity of obsolescence</li> <li>7. KPI specification</li> <li>8. Rate of emergent work</li> <li>9. Supplier logistics</li> </ul>	<ul style="list-style-type: none"> <li>10. Mean time between failure data</li> <li>11. Spares requirement</li> <li>12. No fault found rate</li> <li>13. Operating parameters</li> <li>14. Turnaround time</li> <li>15. Rate of materials</li> <li>16. Rate of beyond economical repair</li> <li>17. Material cost</li> <li>18. Component stress and load</li> </ul>

Figure 5.8 Emergent and transformed uncertainties across the supply network

Failure rate for hardware is no longer the responsibility of the customer. When preparing the budget for a new project the customer needs to consider the failure rate, in order to communicate the expected cost level. The customer becomes an important source of information for the supply network, and has to manage the flow of

information in order to achieve the performance required. For the OEM failure rate stops being a source of revenue, as the customer pays for the outcome of using the equipment or having the equipment readily available for use when required. As the responsibility moves to the solution provider it becomes essential to have suitable processes to pro-actively fulfil demand. These processes involve planning for failure and delegation across the supply chain to manage impact. The suppliers become more integrated to the supply chain as they are integrated to achieving customer requirements.

## 5.7 Impact of Uncertainty in Contracting for Availability

The different sources of uncertainty including incomplete information, inadequate level or understanding of information, and undifferentiated alternatives (Grote, 2009) may create major impacts on IPS<sup>2</sup> delivery. Furthermore, consideration of uncertainties enables more effective project planning, whilst the impact, typically, on cost, schedule or performance requires attention. Table 5.9 presents the potential impact of the uncertainty categories, shown in Figure 5.6, on various aspects related to CfA delivery. This list is not exhaustive and illustrates some of the potential impacts.

Table 5.9 Impact of uncertainty on CfA

<i>Category</i>	<i>Source</i>	<i>Impact</i>
Commercial	Internal	Low availability level, penalties, inadequate flow of material across supply chain, bad cost estimates
	External	Too ambitious KPIs, high cost from supply chain, inadequate collaboration with partners
Affordability	Internal	Too ambitious cost estimates, price reduction
	External	Downfall of the economy, diminishing budget
Performance	Internal	Unsuccessful in reaching KPIs, penalty
Training	Internal	Inadequate training service, penalty
	External	Low trainee skill level causing longer courses
Operation	Internal	Low equipment availability, penalty
	External	Higher than expected cost, re-negotiation of utilisation rate, penalty to customer
Engineering	Internal	Inefficiency in design which reduces ability to achieve customer needs, inadequate cost estimates
	External	Equipment failure above expectations

Improper planning may cause decisions to be based on distorted foundation-‘propaganda’ and ‘lies’ (Smithson, 1989). This in essence will impact the project

through threats or unrealised opportunities. Thus, appropriate uncertainty management strategy needs to be implemented in order to reduce or prevent uncertainties.

## **5.8 Validation of Emergent and Transformed Uncertainties in Contracting for Availability**

The validation process followed an iterative process, whereby initially the specified list of emergent and transformed uncertainties were validated through semi-structured interviews with two industrials, separately. The first respondent was an Integrated Logistics Support manager with 12 years of experience in the defence industry (Respondent 6). The second respondent was the Vice President, with over 20 years of experience, of a software corporation, which focuses on cost and schedule estimation (Respondent 7). Interaction with each respondent lasted for an hour. The initial validation enabled to refine the list of emergent and transformed uncertainties. For instance, the first industrial expert added the emergent uncertainty of “end user equipment usage”. These changes enabled to finalise the specified uncertainty considerations and led to detailed validation.

For detailed validation the author initially presented the types of emergent and transformed uncertainties to each of the participants, which subsequently led to a questionnaire that focused on assessing the proposed emergent and transformed uncertainties for the CfA context. The questionnaire requested the respondents to score their level of agreement from 1 to 5 for each of the specified uncertainties as emergent and transformed sources within the CfA context. The questionnaire also requested input for additional uncertainties, whilst the complete questionnaire is provided in Appendix A.4.1. During the interaction with participants, it was highlighted that CfA is not standardized and the input for the assessment would need to take into account differences across CfA. Driven by this the presented results were generated with the assumption that the main goal of a CfA is to achieve availability targets and the level of granularity (e.g. system or component) is not differentiated. In total 7 respondents participated in the detailed validation. The pre-mentioned industrials along with five

participants with academic backgrounds in the PSS domain contributed to the validation. Further information about the respondents is provided in Table 5.10, where experience refers to the associated research field.

Table 5.10 Overview of the respondents of validation

	<b>Job role of attendee(s)</b>	<b>Research field</b>	<b>Experience (Years)</b>
<b>Respondent 1</b>	Professor	Life Cycle Engineering	25
<b>Respondent 2</b>	PhD researcher	PSS design process	4
<b>Respondent 3</b>	Senior Research Fellow	Service operations	22
<b>Respondent 4</b>	Research Fellow	Integrated Vehicle Health Monitoring – Service delivery	6
<b>Respondent 5</b>	EngD researcher	Cost uncertainty modelling for manufacturing	5
<b>Respondent 6</b>	Integrated Logistics Support Manager	Cost estimation	12
<b>Respondent 7</b>	Vice President – software development	Developing tools for cost estimation	20

The presented results in Table 5.11 aim to illustrate the representativeness of the differentiated emergent and transformed uncertainties for CfA based on input from 7 respondents. The uncertainties that were agreed to be highly emergent with CfA included “equipment availability”, “payment based on performance”, “end user equipment usage”, and “supplier dependence”. These uncertainties reflect the fact that CfA promotes inter-dependencies, which were not present in the traditional context. Respondent 5 highlighted that in order to achieve “equipment availability” the customer focuses on the delivered performance and the OEM requires enhanced processes and integration with suppliers. Furthermore, “intangible expectations”, “training for availability” and “change in capability requirements” received the lowest scores of representativeness of emergent uncertainties. Respondent 3 highlighted that “change in capability requirements” was new only in terms of the change in the type of requirement. The respondent with the in-depth experience in service operations highlighted that this particular uncertainty is driven by the processes that are required to meet the required changes in capability. The respondent highlighted the importance of narrowing the description of the uncertainty to the given context. The scoping issue came across as a major theme across respondents for this uncertainty. For “intangible

expectations”, Respondent 2 indicated that customers frequently change their mind about future expectations, though driven by the long term relationship the impact on the interaction is affected differently. Along these lines, Respondent 4 emphasised the enhanced importance of sustaining positive customer perception through enhanced interactions along the supply network.

Table 5.11 Validation: agreement level for the emergent uncertainties

<b>Emergent uncertainties</b>	<b>Respondent 1</b>	<b>Respondent 2</b>	<b>Respondent 3</b>	<b>Respondent 4</b>	<b>Respondent 5</b>	<b>Respondent 6</b>	<b>Respondent 7</b>	<b>Agreement level</b>
<b>Equipment availability</b>	5	5	5	5	5	5	5	100%
<b>Payment based on performance</b>	5	5	5	5	5	5	5	100%
<b>Human performance</b>	5	5	3	4	3	5	4	80%
<b>End user equipment usage</b>	5	5	5	5	5	5	5	100%
<b>Change in evolving constraints for support</b>	5	4	5	3	4	4	3	60%
<b>Intangible expectations</b>	5	4	3	3	3	5	4	80%
<b>Change in capability requirements</b>	5	3	2	4	3	4	3	60%
<b>Lack of information and knowledge sharing</b>	5	4	4	5	3	5	5	100%
<b>Supplier dependence</b>	5	5	5	5	5	5	5	100%
<b>Training for availability</b>	5	4	3	3	4	4	4	80%
<b>Meaning of scores:</b>								
<b>1: Lowly perceived as a potential for emergent uncertainty</b>								
<b>5: Highly perceived as a potential for emergent uncertainty</b>								

Concerning the transformed uncertainties all respondents highlighted that the provided list of uncertainties and the factors causing the shift in uncertainties were reflective of

the uncertainty changes that are experienced with CfA. Based on the scores that were provided the most relevant transformed uncertainties were defined to be “failure rate for hardware” and “operating parameters”, where both of the uncertainties are transformed due to the shift in responsibilities from the customer to the manufacturer. Other factors that highly influenced the uncertainty changes include “stakeholders’ dependency” and “alliance and information flow”. “Severity of obsolescence” and “turnaround time” were also other uncertainties which scored highly with their relevance as transformed uncertainties within the CfA context. The second industrial expert highlighted that “the provided set of uncertainties are highly comprehensive, which are relevant and influential in managing projects and recognising such issues early on can assist in achieving targets in CfA”.

## **5.9 Summary**

In Section 5.1, an overall framework, which the thesis is structured to, is presented by using the findings from literature review and elicited industrial challenges. The framework is classified into three phases including (1) uncertainty management (see chapter 5 and 6), (2) Three-point estimating (see chapter 7), and (3) dynamic cost estimation (see chapter 8).

In Section 5.2, the methodology for structuring the list of uncertainties was presented in order to reflect the iterative steps that were followed within this process. The author presented four steps, which included (1) Phase 1: Familiarisation of uncertainty types, (2) Phase 2: Development of an initial uncertainty list, (3) Phase 3: Refinement of the uncertainty list in the naval domain, and (4) Further analysis. The interaction across with industry, which in totalled seven organisations for this part of the research, is presented as appropriately for each of the phases. Additionally, the role of literature was emphasised to be in guiding with the industry interaction.

In Section 5.3, the final list of uncertainties is presented including the categories of commercial, affordability, performance, training, operation and engineering. For each of these categories a detailed set of uncertainties are presented, whilst classifying the

sources into internal (e.g. OEM originating) and external (e.g. outside OEM control) causes. This section also presents results from further analysis into the unique uncertainties that are experienced in CfA. Along these lines, uncertainties are classified into emergent and transformed sources.

In Section 5.4, focuses on the emergent uncertainties in CfA. Emergent refers to the uncertainties that are explicitly new with CfA. This section also presents how this set of uncertainty list was developed. Subsequently, the emergent uncertainties are presented. In Section 5.5, the transformed uncertainties in CfA are presented. Transformed refers to the uncertainties, which have evolved from the traditional mode due to various factors associated to the adoption of CfA. This section initially provides the sources of these factors that trigger a change in the uncertainties (e.g. shift in responsibilities). Subsequently, the list of transformed uncertainties is presented.

In Section 5.6, in order to enhance the understanding of the emergent and transformed uncertainties the implications along the supply network is covered. This involved allocation of the full list of the specified uncertainties across the supply network. Additionally, the section provides examples for specific uncertainties as to how they are experienced within CfA. In Section 5.7, a brief overview of the potential impact of uncertainty in CfA is illustrated while considering each of the defined categories of uncertainty. The impact is classified into the internal and emergent sources as presented in Section 5.3. In Section 5.8 the validation of the emergent and transformed uncertainties is presented. Through an iterative process initially, the considered list of uncertainties were refined through semi-structured interviews. Subsequently, the level of agreement over the uncertainty considerations is presented, where results through a questionnaire that was participated by 7 respondents is discussed.

The following chapter presents the cost uncertainty management framework that has been built and implemented in a software prototype.





## 6 COST UNCERTAINTY MANAGEMENT

The focus of this chapter is on cost uncertainty management at the bidding stage of Contracting for Availability (CfA). Driven by time constraints (e.g. tight timescales during the bidding phase), industrial collaborators in common indicated that there is insufficient time to analyse uncertainties sufficiently in provision of support during the bidding process. Furthermore, to be able to agree CfA it is necessary to have a common understanding between the customer and the supplier of the uncertainties. This is a particularly challenging aspect which requires a synergy in approaches to consider uncertainties. This may be achieved by means of a common framework utilised to capture uncertainties at the bidding stage. This chapter offers an alternative approach to managing uncertainties and continues the debate for a prescriptive framework to aid project managers in developing a valid foundation for engaging with uncertainties. The framework is embedded in a software prototype, which has been developed in MS Excel. Furthermore, the tool has been called: Uncertainty Tool for Assessment and Simulation of Cost (U-TASC). Initially the need for uncertainty management as opposed to risk management is presented, which sets the focus of this chapter. Section 6.1 highlights the main differences between risk and uncertainty management. Section 6.2 presents the process of developing the bid cost uncertainty management framework. The framework which has been classified in six phases is explained in Section 6.3. Finally, the initial validation that was undertaken is outlined in Section 6.4.

The main reason behind the cost estimation challenge relates to uncertainties that undermine the ability to forecast. For example, in transportation infrastructure projects, estimates are on average between 20 and 45% inaccurate (Flyvberg, 2006). It is worth recognising that given inherent uncertainty of many programmes (Meyer et al., 2002), having trouble forecasting is not something new (Turner & Cochrane, 1993). The move towards CfA changes the sources of uncertainties for industry (Erkoyuncu et al., 2009a). It firstly may originate from providing system level support, where traditionally provision of service(s) was more concentrated and performance requirements did not have a bounding influence. Secondly, support requirements need to be captured much earlier, whilst time pressure creates additional uncertainties as detailed design of

offerings can not be made. Because of the increasing degree of complexity and dynamism, the potential impact of inaccurate forecasts becomes more significant. Forecasting inaccuracies are suggested by most studies (e.g. Morris & Hough, 1987) to be caused by technical errors. The concept of technical error refers to unreliable or inaccurate data, the absence of data or the use of imperfect forecasting techniques. These factors are particularly influential in CfA, which span over the equipment's service life cycle, lasting 30-40 years. Furthermore, rigorous approaches to manage the uncertainty experienced in CfA are necessary. Existing literature has considered uncertainty management as part of risk management as covered in Section 2.6. Though, in risk management the systematic approach to identify, assess and respond to risk has received some criticism (e.g. Whittaker, 1999).

Driven by this criticism and the highlighted challenges, this chapter presents a framework that is embedded in a software tool that facilitates bidding teams to manage uncertainty, where the applied context is cost estimation. The uncertainties that emerge at the bidding stage in the delivery of services including maintenance, spares and training are focused on due to their wide application across the defence industry. The framework considers a distinction between uncertainties and risks, and specifically focuses on uncertainty. Thus, risk is defined as the resultant effect of uncertainty (Lefley, 1997). The tool has been designed to be used by cost estimators, project managers, risk specialists, support managers, and reliability engineers involved in the bidding stage. The user needs at bidding stage are considered to be with respect to identifying, prioritising and devising response measures for cost-uncertainties. The tool is flexible in terms of the granularity of application (e.g. work breakdown structure, system, component), and aims to support in building a complete bid proposal with respect to cost-uncertainty considerations. Furthermore, it is assumed that better operational knowledge of planning quality requires better management of uncertainty.

## **6.1 Uncertainty Management – The Missing Link**

Traditional deterministic risk management as practiced in a variety of industries provide among others the benefits of reassuring stakeholders and supporting the effective use of

resources (e.g. Akintoye & MacLead, 1997). Yet, the benefits are in vain if the decisions are based on data that is inherently wrong:

“The techniques of risk estimation are largely quantitatively based and make claims to scientific objectivity, which are undermined on several fronts. There are question marks about the extent to which event and reliability data can itself be relied on for accuracy. In the absence of adequate data, the assignment of probabilities is a subjective process dependent on the assigner’s own bias.”  
(Frosdick, 1997, p. 176)

Most risk management process standards assume a ‘perfect’ knowledge (Jaeger et al., 2001). Consequently, questions about the validity of the input data into risk management procedures are not raised. Uncertainty management requires an extension to answering the questions of ‘What needs to go through a quality check?’. Establishing planning quality as one of the primary pillars for ‘good’ decision making is important.

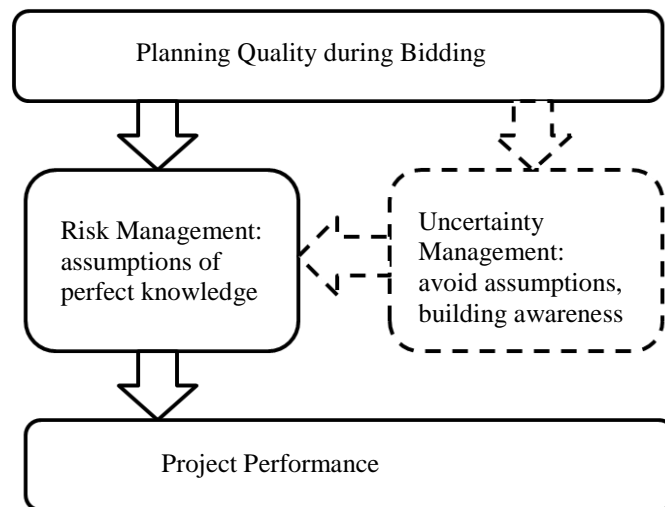


Figure 6.1 The missing link: Uncertainty management

Figure 6.1, illustrates that uncertainty management avoids building assumptions into decision making, which is commonly the case in risk management. By integrating uncertainty management into planning, early on, it is possible to ask questions that do not get considered in a traditional assessment for a project. Furthermore, these questions enable to capture both opportunities and threats, which is a broader view than risk management. It is envisaged that uncertainty management enables to enhance planning

quality, and risk management contributes to increased project performance through learning. Uncertainty management is considered to be the missing link in achieving increased project performance. This chapter considers project performance from a cost dimension. Driven by this aspect the main research questions for this chapter include:

- How to conduct uncertainty identification and assessment systematically?
- What are the suitable response measures for cost-uncertainties in CfA?
- How can uncertainty management be implemented systematically?

## 6.2 Detailed Methodology for Developing the Cost Uncertainty Management Framework

The presented study combines theoretical and practical research in an applied manner in order to propose a framework to solve an industrial problem of managing cost uncertainties in CfA.

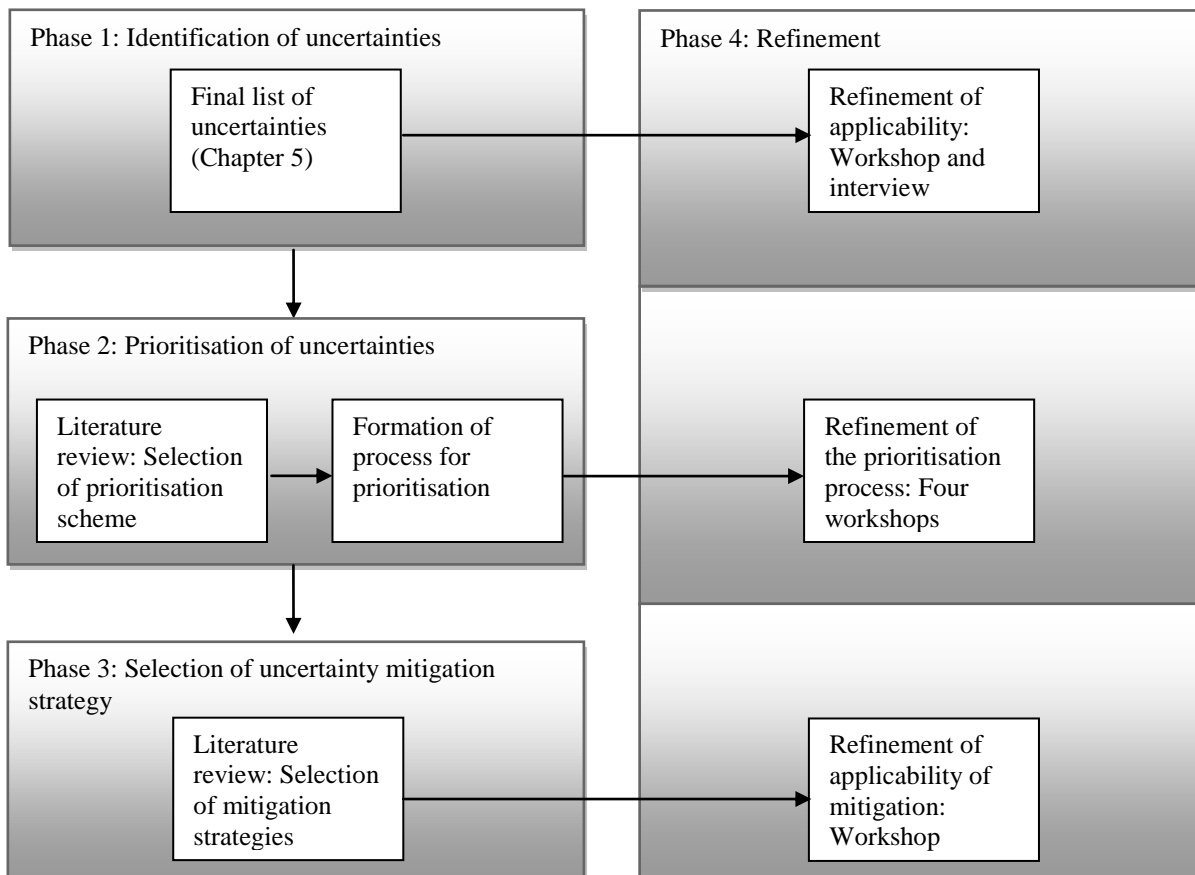


Figure 6.2 Overview of the methodology for developing the bid cost uncertainty management framework

A procedure was followed to define the elements of the bid cost uncertainty management framework. Following literature review (Section 2.6), it was determined that three phases would be incorporated into the framework including: (1) identification of uncertainties, (2) prioritisation and classification of uncertainties, and (3) mitigation of uncertainties. Phase 4 focuses on refining the considerations for the pre-defined phases. Figure 6.2 represents an overview of the methodology followed to develop the cost uncertainty management framework, which has been classified into three phases based on the features of the framework. In the following subsections a detailed explanation of the activities within each of these phases is provided.

### **6.2.1 Phase 1: Identification of uncertainties**

The finalised list of uncertainties that were covered in Chapter 5 is an input into this phase. Furthermore, industrial experts were queried about the applicability of the identification process within U-TASC. In the workshop presented in Table 5.5, it was highlighted that in some cases due to the lack of available information it may not be possible to make an assessment of an uncertainty level. In order to capture this variability in the ability to assess, the respondents suggested including tick boxes. Also, in the interview presented in Section 5.2.4 (as part of the first further analysis), it was suggested to include a comparison of those uncertainties that are relevant through tick boxes, which resulted in adjustments in U-TASC.

### **6.2.2 Phase 2: Prioritisation of uncertainties**

During this phase, literature was reviewed to identify an approach for assessing uncertainty. The Numeral, Unit, Spread, Assessment and Pedigree (NUSAP) matrix approach was adopted for assessing data uncertainty. NUSAP, as proposed by Van der Sluijs et al., (2005), aims to provide an analysis and diagnosis of uncertainty. It, originally had been developed to support with policy considerations for science. When applied in the full sense it captures both quantitative and qualitative dimensions of uncertainty and enables to visualise the results in a standardised and self-explanatory way. The NUSAP acronym is composed five qualifiers that cover a range of aspects that

are associated to understanding uncertainties. Furthermore, this enables flexibility in acquiring information from subject matter experts. NUSAP enables to concisely and clearly convey the quantity or degree of uncertainty. An overview of the acronyms:

- Numeral refers to an ordinary number that represents the uncertainty quantity
- Unit refers to conventional data such as the date at which the unit is evaluated
- Spread focuses on “random error” of experiments of the “variance” of statistics. Methods to address spread can be statistical data analysis, sensitivity analysis or Monte Carlo analysis, which would typically utilise expert knowledge
- Assessment involves qualitative judgments about the information
- Pedigree is concerned with an evaluation of the production process of information and indicates different aspects of the knowledge used. Pedigree involves a set of criteria to assess the different aspects, through qualitative expert judgment. In order to minimise arbitrariness and subjectivity in measuring strength a pedigree matrix is used to code qualitative expert judgments for each criterion into a discrete numeral scale with linguistic descriptions of each level on the scale. Furthermore, in order to qualify a range of different information, it is possible to construct different pedigree matrices using different pedigree criteria. In order to produce a metric for parameter strength the pedigree scores can be aggregated by dividing the sum of the scores of the pedigree criteria by sum of the maximum attainable scores.

Some of the key benefits of the approach include (Van der Sluijs et al., 2005): (1) NUSAP enables to identify the different sorts of uncertainty in quantitative information and promotes display of results in a standard and self-explanatory way. Furthermore, as a result a clear and transparent assessment of uncertainties is achieved; (2) NUSAP enables an enhanced appreciation of the issue of quality of information, whilst promoting enhancements by identifying the sources of the challenges; (3) NUSAP enables to focus efforts to reduce the influence of critical uncertainty elements; and (4) NUSAP enables flexibility at different levels of comprehensiveness, which may involve structured in-depth group discussions for each pedigree criterion. On the other hand, the major weaknesses include (Van der Sluijs et al., 2005): (1) The NUSAP approach currently does not have a quality assurance mechanism in its applications, whilst

additionally there are no settled guidelines for good practice; (2) The scoring process involves a certain degree of subjectivity, which requires design of unambiguous pedigree matrices and the involvement of multiple experts in the scoring process, where the selection of experts may cause bias.

### **6.2.3 Phase 3: Selection of uncertainty mitigation strategy**

Driven by the results from uncertainty prioritisation, a suitable uncertainty management strategy is proposed. In literature two approaches exist with regards to uncertainty management; coping and minimizing uncertainties (Grote, 2009). Firstly, coping with uncertainties considers the external environment, where the management needs to protect the organisation from external uncertainties. Minimizing uncertainty relates to the internal system that can be controlled through appropriate processes that reduce any possibility of errors. The presented framework offers a process to choose management strategies.

### **6.2.4 Phase 4: Refinement**

The refinement process involved an iterative process concerning each of the features related to the cost uncertainty management process adopted in U-TASC. Within this process six workshops were conducted and additionally a semi-structured interview was carried out. The initial workshop, which was attended by seven participants, involved a review of the initial version of U-TASC by four of the collaborating organisations (A, C, D, and G). An overview of the participants is provided in Table 6. 1. The workshop firstly involved a presentation by the author to illustrate the key features of U-TASC, while also demonstrating the use of the tool. At this phase of the research the tool specifically focused on the identification of uncertainties. Subsequently, a questionnaire was distributed to capture initial feedback about various aspects such as benefits, usability and relevance to business. The questionnaire is presented in Appendix A. Among the seven respondents six of which emphasised the potential benefit of the tool for the defence industry in effectively identifying uncertainties at the bidding stage, as represented in Figure 6.3.

Table 6.1 Overview of participants at the initial workshop

Organisation	Job role of attendee(s)	Experience (Years)
A	Engineering manager	31
A	Systems engineer	25
C	Program manager	25
D	Through life analysis manager	33
D	Project manager	25
D	Early cost forecaster	25
G	Life cycle cost analyst	3

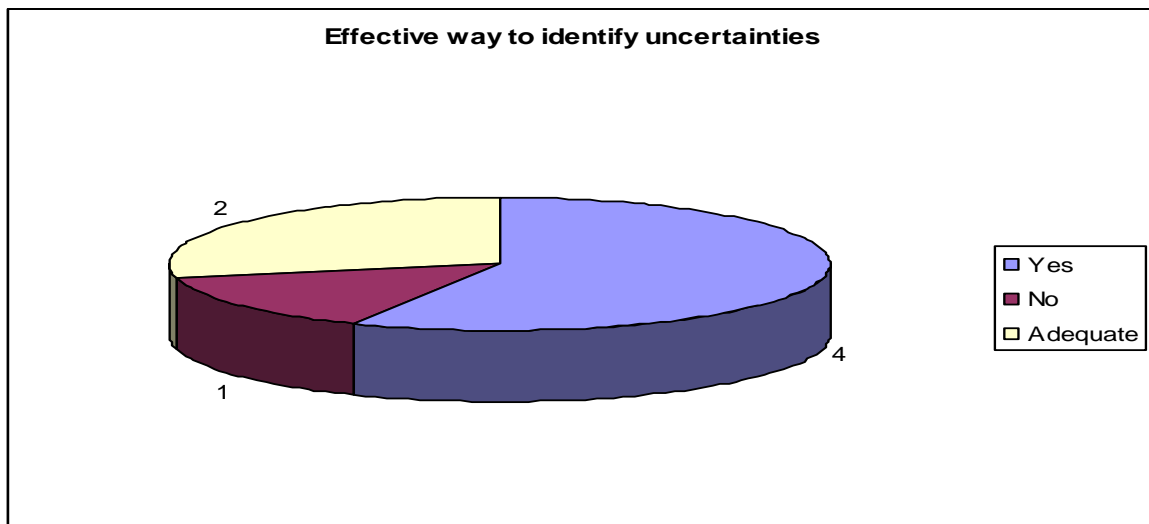


Figure 6.3 Effectiveness of the process of uncertainty identification

At this phase of the research the tool was considered to be suitable for use in (1) informing design reviews/phase reviews, (2) supporting to focus effort, (3) supporting in agreeing the price type. Furthermore, the respondents were requested to illustrate the strengths and weaknesses of the tool, which is covered in Table 6.2.



Table 6.2 List of strengths and weaknesses identified for the initial version of U-TASC

Strengths	Weakness
<ul style="list-style-type: none"> <li>• Range of uncertainties</li> <li>• Good coverage of project issues</li> <li>• Good user interface</li> <li>• Focus on uncertainty</li> <li>• Hands on usage</li> <li>• Graphics speak for own words at the bidding stage</li> <li>• Simple to use</li> <li>• Exhibits some useful concepts and ideas</li> <li>• Good process for projects to follow at each stage of CADMID</li> <li>• Logical build-up</li> <li>• Familiar spreadsheet method</li> </ul>	<ul style="list-style-type: none"> <li>• Rating scheme</li> <li>• Range of domains</li> <li>• Subjective (in terms of data input)</li> <li>• Lack of /limited detailed coverage of specific issues (i.e. supply chain)</li> <li>• At a low level of maturity – probably not yet ready to be deployed in company</li> <li>• Needs to cover all aspects – capability through to disposal and beyond</li> <li>• Metrics lacking</li> </ul>

It was suggested that the tool could facilitate to reduce uncertainty. Also it could potentially provide a view of the bidder to the customer to focus the questions related to the bid. The workshop also enabled to realise that the selected services (including spares, maintenance and training) were overall considered to be sufficient. Additionally, the link between services and uncertainties was commonly acknowledged to be suitable. Based on the workshop a range of improvements were suggested to the tool, including:

- More consistency with the definitions of the uncertainties and examples would help to further clarify the questions
- Uncertainty queries need to be concise
- The procedure for grading uncertainties (e.g. scores) needs explanation
- Guidelines should be set out to guide with the ownership of uncertainty
- Description of how the tool may be used in setting up the budget
- Need to establish a common understanding across users of the tool in order to reduce the subjectivity involved with the responses

A brief overview of the attendees at the second workshop is provided in Table 5.1. It is also important to recognise that the nature of uncertainties varies for each business case. The typical process to manage uncertainty begins with the identification of uncertainty, after passing the assessment and evaluation stages, various risk mitigation approaches are realised. In association the list of assumptions are developed and finally the cost/time impact is established. The flow of these activities is illustrated in Figure 6.4.

In this process, some of the key areas that create challenges were suggested to include unknown usage rates, transfer of knowledge in failure rates and repair times.

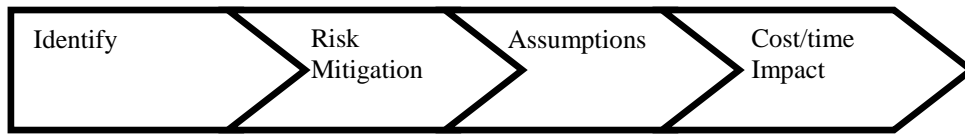


Figure 6.4 Uncertainty management process

The third workshop enabled to further clarify the suitable features that the tool could include. An overview of the attendees is provided in Table 5.4. Some of the key areas of feedback concerning U-TASC included:

- Provides value by assessing the expected uncertainty given the level of maturity
- Applicable as a secondary back up model for validation at the early bid phase
- The list of uncertainties needed to be updated
- Mitigation strategies for uncertainties should be added

The fourth workshop was conducted as a WebEx meeting. The aim of the workshop was to elicit feedback concerning the latest version of the tool, whilst it lasted for two hours. Initially U-TASC was demonstrated to the participants, subsequently feedback was requested. An overview of the attendees is provided in Table 6.3.

Table 6.3 Overview of attendees at the fourth workshop

Organisation	Job role of attendee(s)	Experience (Years)
A	Engineering manager	31
A	Integrated support manager	18
A	Principal Reliability Specialist	20
A	Assistant project manager	22
A	Supportability engineer	12
A	Risk specialist	24

At this workshop it was suggested that the tool offered a good basis to conduct uncertainty management. Though, an explicit process to mitigate uncertainties was suggested for further development (e.g. reliability assessments were suggested to offer a

good practice to reduce uncertainty). As a result of this feedback a tick box approach was followed for the user to select those strategies that are suitable to mitigate prioritised uncertainties. Some of the other key comments that were received within this workshop included:

- Need to distinguish between the terms availability and capability and the focus within the tool in terms of these terms
- Need to establish the reasons behind the evolvement of uncertainty
- Define different levels of granularity for the uncertainties
- Set a differentiation between line replaceable unit (LRU), system and subsystem
- Make the differences between the uncertainty scores more apparent
- Add weighting for the importance of the uncertainties
- Provide a severity report for each type of uncertainty

At the fifth workshop an initial validation of the U-TASC was performed, whilst the participants commented on the features associated to cost uncertainty management and modelling. The workshop was conducted through WebEx, whilst the meeting lasted for three hours. An overview of the participants is provided in Table 6.4.

Table 6.4 Overview of participants at the fifth workshop

Organisation	Job role of attendee(s)	Experience (Years)
A	Program manager	16
A	Modelling and simulation expert	21
A	Business & Solutions modelling for combat systems (land)	12
A	Program support- Finance Function	24
A	Business & Solutions modelling – Risk expert	33
A	Business and solutions modelling – Process and guidance	14

The meeting began with a demonstration of U-TASC, and subsequently questions were raised by participants. During the session it was highlighted that self assessment tools need consistency across projects. Furthermore, such tools need honest input, in order to

make the use of the tool worthwhile. This is particularly influential with areas such as uncertainty weighting.

During the sixth workshop the focus was on adjusting the definitions of the scores and the terms of the metrics that have been specified for the NUSAP matrix in literature. Information regarding the attendees is provided in Table 5.5. The adjustment was proposed as a measure to enhance clarity of the metrics and the meaning of each score particularly driven by the used terminologies in the defence industry. The metrics considered in the traditional NUSAP matrix included empirical, methodological rigour and validation. Briefly, these refer to data availability, maturity of applied processes and validation of achieved outcomes, respectively. The definitions of the scores for each of these metrics are provided in Table 6.5.

Table 6.5 Traditional terminology in the NUSAP matrix

Score	Empirical	Methodological rigour	Validation
9	Large sample direct measurements or controlled experiments are carried out	Best available practice in well established discipline	Compared with independent measurements of the same variable over long domain
7	Historical/field data and small sample direct measurements	Reliable method common within established discipline, best available practice in immature discipline	Compared with independent measurements of closely related variable over shorter period
5	Modelled/derived data; indirect approximate	Acceptable method but limited consensus on reliability	Measurements not independent, proxy variable, limited domain
3	Educated guesses, indirect approximate rule of thumb estimate	Preliminary methods unknown reliability	Weak and very indirect validation
1	Crude speculation	No discernible rigour	No validation performed

Finally, a semi-structured interview was conducted with a supportability engineer at Organisation H, which was conducted through WebEx and lasted for two hours. Organisation H is involved in providing advice within the global aerospace, defence and security markets. The respondent had over 20 years of experience in the particular field of uncertainty. During this interview, initially the tool was presented, subsequently feedback was captured. It was suggested that within this particular organisation uncertainty is considered in terms of multiple layers, which was considered to be in alignment with the considerations in U-TASC. The layers were referred to as outputs (e.g. availability), cost drivers (e.g. large sources of cost), leavers (e.g. aspects that can

change the cost drivers), and mechanism (e.g. measures to take). As a combination of these layers it was suggested that the outputs can be managed. It was suggested that the uncertainty level in a work breakdown structure would be influenced by the toughness of the required operation. The respondent highlighted the key benefits of the tool as:

- Ability to drive down prioritised uncertainties
- Ability to support a proactive approach based on selected mitigation strategies
- Ability to enhance project management

### **6.3 Bid Cost Uncertainty Management Framework**

The framework follows a systematic approach to identify, prioritise, and manage uncertainties within the cost context for the bidding process. The framework is composed of seven stages, which is illustrated in Figure 6.5. Firstly, initial bid preparation takes place where assessments take into account the scope of the project by specifying a rough work breakdown structure. In alignment, initial considerations regarding cost, price, investment in relation to labour required, competition, and the probability of winning a project is shaped during this process. This leads to the bidding process where a number of reviews are undertaken prior to the negotiation phase (Stage 6: Revise Bid) with the customer. In this process aspects such as risk, uncertainty, cost against request, and price is assessed in detail with the constraint of available information. The focus of this chapter is on uncertainty and explicit attention is paid to it in Stages between 2 and 5 in the Bid Uncertainty Management Framework. In Stage 2 the uncertainty identification covers a list of uncertainties that can potentially affect the project through the cost drivers. The third stage focuses on prioritising the uncertainties by considering the level of uncertainty and its relevance to the project. The Stage 4, based on the prioritisation process classifies uncertainties into high, medium and low level uncertainties. In this stage an uncertainty score is calculated and used. The Stage 5, based on the classified uncertainties defines various strategies to respond to uncertainties. Growth in confidence concerning the uncertainty considerations enables to revise the bid and reach a final bid, which is satisfactory for both the customer and the solution provider. In the following sub-headings explanation of each of the uncertainty aspects is presented. Moreover, in order to gather further understanding of

how the framework is embedded in the MS Excel Software prototype the reader is referred to the User Manual for U-TASC, which is provided in Appendix F.

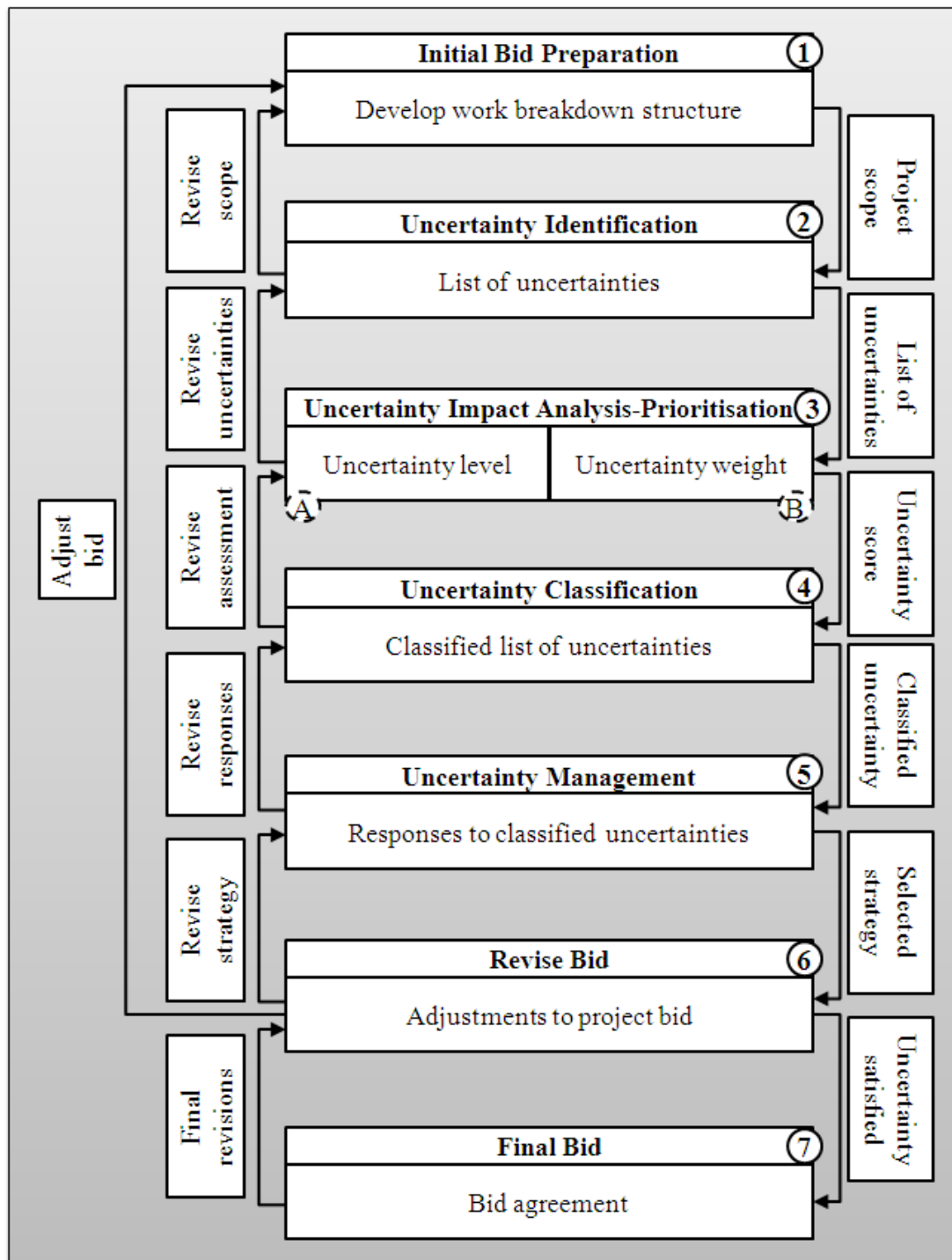


Figure 6.5 Bid uncertainty management framework

### **6.3.1 Uncertainty identification**

In the initial section the user is guided to identify the relevant uncertainties, where the framework aims to provide a systematic approach to identify uncertainties. The user is also requested to determine whether there is sufficient information that is available to make an assessment of the specific uncertainty.

Uncertainty identification is the first step in the uncertainty management process. There are a number of ways to identify the types of uncertainties including semi-structured interviews, brainstorming techniques, the nominal group technique, the Delphi technique, identification tools (e.g. systems dynamic models), identification aids (e.g. checklists), UML diagrams, SWOT (strengths, weaknesses, opportunities, threats) analysis (Ward and Chapman, 2003). Furthermore, the identification of uncertainty is typically driven by expert judgment and experience (Maytorena et al., 2007), where application of the Delphi technique has been a common route to capture a common view across a team when identifying the specific uncertainties. This also enables to reduce the level of subjectivity involved in identifying uncertainties. The framework poses a number of questions (list of uncertainties) that aim to capture the many sources of uncertainties that arise during bidding. The list of uncertainties has been developed by considering a typical work breakdown structure in the defence industry as discussed in Chapter 5. The list of uncertainties is categorised into commercial, affordability, performance, training, operations and engineering areas, which the list has been referred to as CAPTOE (Erkoyuncu et al., 2010c). A detailed description of these areas is provided under Section 5.2.4.

In total 70 uncertainty types are covered and each has been classified in to the qualitative and quantitative categories, which has been illustrated in Table 6.6. The qualitative category implies that the type of uncertainty requires a subjective consideration during the assessment. A quantitative measure specifies that the uncertainty consideration can be based on statistical data. The full list can be considered to assist in defining an appropriate risk register or an uncertainty checklist. Although, the study was conducted specifically within the defence industry, due to the level of available information at the bidding stage concepts are fairly generic and for uncertainty

identification it can be used across other industries. As opposed to Table 6.5, the list of uncertainties can also be classified in to positive and negative uncertainties. Positive uncertainties refer to the uncertainties that have a positive influence on the project and negative uncertainty refers to the contrary case. An example for the positive case is when the trainee skill level exceeds the expectations and as a result cost expectations exceed actual costs. An example for the negative case is when the uncertainty of the equipment utilisation rate is under estimated and as a result the requirements for spares and maintenance are above expectations.

Table 6.6 Types of uncertainties covered

<b>Uncertainty Category</b>	<b>Qualitative uncertainty</b>	<b>Quantitative uncertainty</b>
<b>Commercial</b>	KPI specification, environmental impact, work share between partners, level of relationship with supplier, level of relationship with customer, stability of customer requirements	rate of labour availability, labour efficiency, predictability of warranty scope, customer equipment usage, material cost, commodity and energy prices, exchange rates, interest rates, inflation rate , labour hours, labour rate
<b>Affordability</b>	customer ability to spend, customer willingness to spend	bid success rate, project life costs, economy, equipment availability level
<b>Performance</b>		performance against key performance indicators, rate of surge, IT efficiency
<b>Training</b>	trainee skill level, ability to screen candidates for training	availability of trainers, number of students, facilities availability, number of courses to be offered, level of affordability for training, availability of suitable candidates for training, length of course, delays in training, rate of re-training
<b>Operation</b>	maintainer performance, effectiveness of the maintenance policy	complexity of equipment, quality of component(s), quality of manufacturing, mean time between failure data, equipment utilisation rate, rate of emergent work, equipment operating parameters, component stress and load, OEM logistics, rate of reparability, no fault found rate, supply chain logistics, location of maintenance, calibration of work scope, availability of maintenance support resources, rate of material, turnaround time, beyond economical repair, provision of consumables, failure rate for hardware, sufficiency of spare parts storage
<b>Engineering</b>	maintaining design rights, effectiveness of managing threats and opportunities, cost estimating data reliability and quality	rate of capability upgrades, rate of system integration issues, rate of rework, efficiency of engineering effort, failure rate for software, level of obsolescence, cost of licensing and certification



When analysing the types of uncertainties that have been defined suitable for availability contracts there are two aspects which stand out: (1) emergent uncertainties, (2) transformed uncertainties, which were illustrated in Sections 5.4 and Section 5.5.

### 6.3.2 Uncertainty impact analysis

The uncertainty impact analysis refers to the prioritisation process. The impact analysis derives the “Uncertainty Score”, which reflects a numerical measure of the influence of each uncertainty to the given project. This score is calculated by multiplying “Uncertainty level” and “Uncertainty weight”. Figure 6.6 demonstrates the associations between the specified concepts with respect to the frameworks for cost uncertainty management and cost uncertainty modelling (as described in Chapter 7). For the cost uncertainty management framework the user initially needs to identify the relevant uncertainties, which follows with the definition of the “Uncertainty level” and the “Uncertainty weight”, respectively.

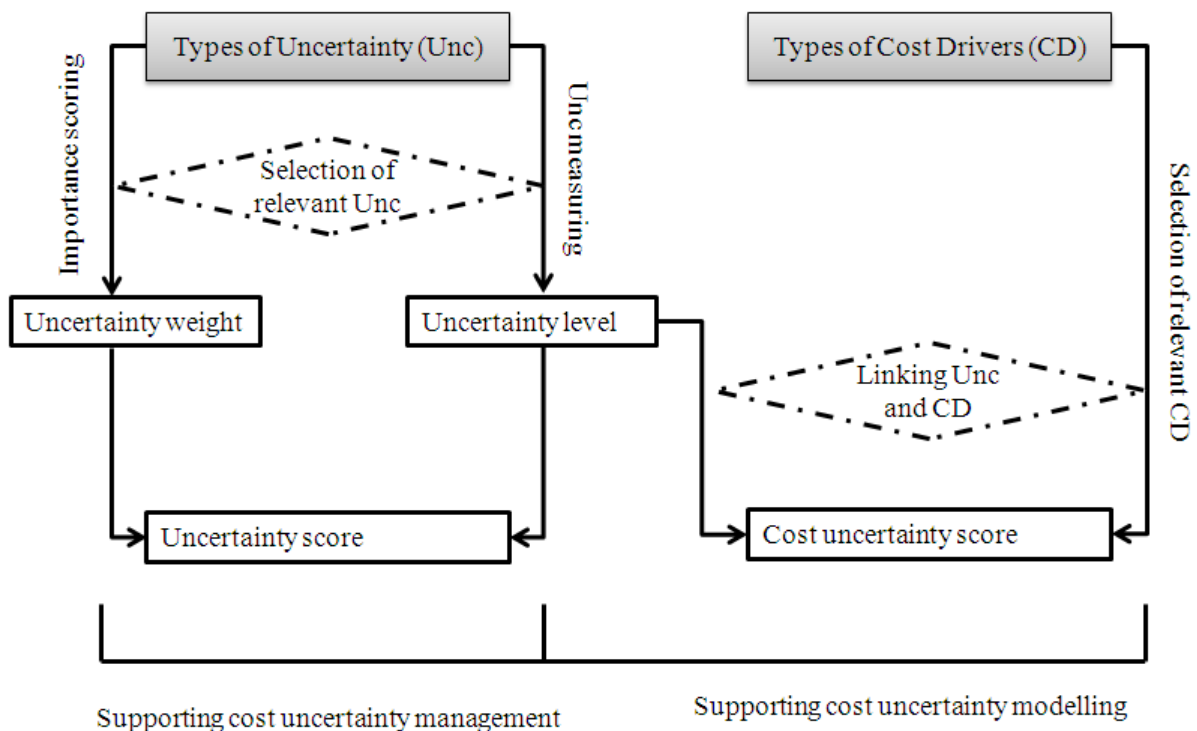


Figure 6.6 Uncertainty concepts for the cost uncertainty and management frameworks

## Uncertainty level

The types of uncertainties listed in Table 6.6 are assessed through the NUSAP matrix approach in order to define an uncertainty level. This offers a systematic structure to elicit expert knowledge and additionally it enables to communicate the uncertainties. The assessment aims to capture the level of uncertainty for each relevant type of uncertainty. To be able to apply this approach an expert needs to implement four steps (Van der Sluijs et al., 2005). Firstly, an elicitor needs to be aware of the subject matter to interview an expert, and the expert needs to have full access to relevant material (e.g. cost data). Secondly, through the interview a structure of the uncertainty related to the project needs to be put in place. This involves, defining the variables, identifying the possible range of outcomes, disaggregating types of uncertainty if necessary, and selecting an appropriate measurement scale. This is followed with the expert thinking process, which considers relevant knowledge related to the uncertain variable. This is largely driven by the available data (e.g. experience). The final step involves encoding that focuses on arriving at a quantitative description of the subjective probability distribution in order to capture the experts beliefs about an uncertain variable.

The NUSAP matrix approach is capable of combining qualitative analysis (numeral, unit, spread) and the systematic multi-criteria evaluation of a given knowledge base (pedigree) (Van der Sluijs et al., 2005; Durugbo et al., 2010). Pedigree is expressed by means of a set of pedigree criteria to assess these different types of uncertainties. Although, assessment of the pedigree criteria necessitates subjective input, explicit definition of each score enables to reduce subjectivity as a standard level of understanding of concepts and scores are established (Erkoyuncu et al., 2009b). The pedigree criteria covered in this chapter are basis of estimate, rigor in assessment and level of validation, as explained below:

- **Basis of estimate:** Typically refers to the degree to which direct observations are used to estimate the variable. The focus of this measure is the level of data that is available to be able to make a cost estimate
- **Rigor in assessment:** In this case, it refers specifically to the methods used to collect, improve, and analyze the data that is used to make cost estimation

- Level of validation: This metric refers to the degree to which efforts have been made to cross-check the data against independent sources.

Table 6.7 Pedigree Matrix: Scoring of uncertainties

Score	Basis of estimate	Rigor in assessment	Level of validation
1	Best possible data, large sample, use of historical field data, validated tools and independently verified data	Best practice in well established discipline	Best available, independent validation within domain, full coverage of models and processes
3	Small sample of historical data, parametric estimates, some experience in the area, internally verified data	Sufficiently experienced and benchmarked internal processes with consensus on results	Internally validated with sufficient coverage of models, processes and verified data. Limited independent validation
5	Incomplete data, small sample, educated guesses, indirect approximate rule of thumb estimate	Limited experience of applied process with lack of consensus on results	Limited internal validation, no independent validation,
7	No experience in the area	No established assessment processes	No validation

Of the many qualitative measures of data quality that are available, the study focused on these three metrics due to their suitability to the given context. For all these criteria Table 6.7 provides the definitions for each of the scores in the Pedigree Matrix.

### Uncertainty weight

The uncertainty weight refers to the level of relevance of a particular uncertainty in terms of its significance in affecting the cost dimension of a project. The weights are represented as a percentage score that is calculated using the analytic hierarchy process (AHP). The project can define their uncertainty weight (relative importance/relevance of the uncertainties to the project as seen at the bidding stage) using pairwise comparisons. The application of AHP aims to support decision making with multiple conflicting and subjective criteria, whilst it is a highly mature technique that has been applied in a wide range of areas. The approach derives ratio scales of relative magnitudes of a set of elements by making paired comparisons (Saaty, 2006). In the framework decision making with AHP is based on ranking uncertainties in terms of relative ratio scales (Ishizaka and Labib, 2009). The framework adopts the scale of absolute values to make the comparisons. Within each of the described categories of

uncertainties the classified types are used for comparison purposes. Furthermore, it is assumed that each uncertainty category contributes to the variation in cost at an equal level. AHP is based on human ability to use information and experience to estimate relative magnitudes through paired comparisons (Saaty, 2006). As a result ratio scales for each element is constructed on a variety of dimensions, while representing the system in smaller constituent parts by using a hierarchic or network structure, which enables a systematic procedure. As a result of applying AHP, simple pairwise comparison judgments are transformed into the priorities in the hierarchy.

Whilst in the traditional sense the AHP is applied to compare across elements in a hierarchical sense with a number of layers, in U-TASC a single hierarchy is considered and for each cost driver the comparison is made against the total cost estimate. The comparison process between the cost drivers using scores between 1 and 9 follows the AHP principles. The user decides the values based on a discussion within a small group involving a Focus Group (to define the relevant cost drivers) and then a simple Delphi (a form of controlled debate) to define the scores. A definition of each of the scores used in the pairwise comparison is provided below:

1. Minimally contributing
2. Minimally to moderately contributing
3. Moderately contributing
4. Moderately to strongly contributing
5. Strongly contributing
6. Strongly to very strongly contributing
7. Very strongly contributing
8. Very to extremely strongly contributing
9. Extremely contributing

The recorded judgments and priorities are represented on a matrix, also known as positive reciprocal matrix. The numbers contained in the matrix show the intensity of dominance of the criterion in the column heading over the criterion in the row heading. The numbers which are symmetric with respect to the diagonal are inverses of one

another (e.g. if one criterion is defined 7 times important than the other, then the reciprocal is 1/7 times important). Table 6.8 demonstrates a complete matrix, with a sample response from an industrial interaction where the focus is on a naval radar project and the input is provided by a supportability engineer with an experience of 12 years. The table focuses on the “Affordability” associated uncertainties experienced in the project, and it is identified that as a source of uncertainty “Project life costs” and “Equipment availability” have a higher influence over the project. Further information about the results about this project is provided in Section 9.3.

Table 6.8 Sample pairwise comparison

	Customer ability to spend	Customer willingness to spend	Bid success rate	Project life costs	Economy	Equipment availability
Customer ability to spend	1.00	5.00	5.00	5.00	1.00	5.00
Customer willingness to spend	1/5	1.00	1.00	5.00	1/3	1.00
Bid success rate	1/5	1.00	1.00	5.00	1/3	1.00
Project life costs	1/5	1/5	1/5	1.00	1/3	1/3
Economy	1.00	3.00	3.00	3.00	1.00	5.00
Equipment availability	1/5	1.00	1.00	3.00	1/5	1.00
Total	2.80	11.20	11.20	22.00	3.20	13.33

A major benefit of utilising AHP relates to the possibility to evaluate quantitative as well as qualitative criteria and alternatives based on the same preference scale of nine levels. These scores are used to make a comparison between the uncertainties. The comparison of the alternatives  $A_1$  and  $A_2$  is achieved through an algorithm as illustrated in Figure 6.7. The algorithm takes an input for each of the specified uncertainties (a defined score between 1 and 9), which illustrates the contribution of that particular uncertainty to the overall uncertainty level. This input is subsequently used for comparison purposes, where the difference between the input values is translated into a multiplier, which is calculated as follows:

- If the input for the uncertainty of interest is lower than the uncertainty compared to, then the multiplier receives a value of  $1/x$ , where  $x$  is determined by the degree of the difference and may receive a value of 3, 5, 7, and 9.
- If the input for the uncertainty of interest is equal to the uncertainty compared to, then the multiplier receives a score of 1.
- If the input for the uncertainty of interest is higher than the uncertainty compared to, then the multiplier receives a value of  $y$ , where  $y$  is determined by the degree of the difference and may receive a value of 3, 5, 7, and 9.

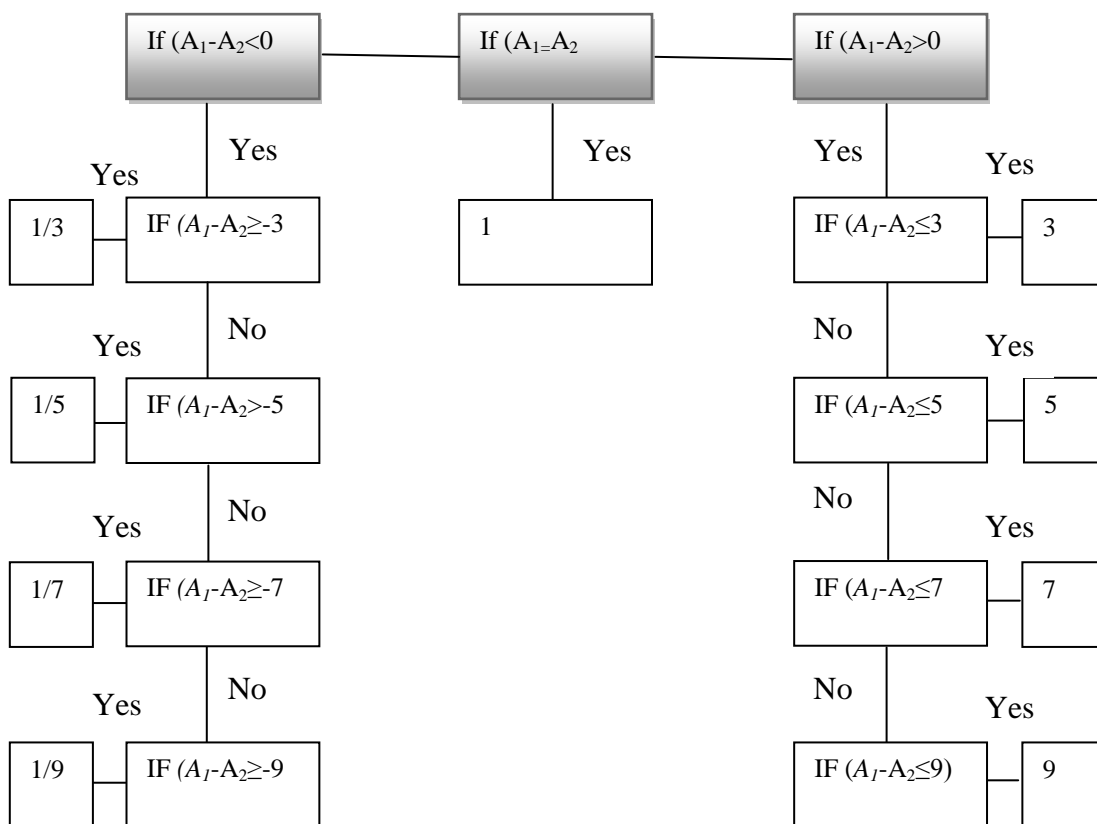


Figure 6.7 Algorithm used to fill the matrix in Analytic Hierarchy Process

The application of AHP leads to the logical consequence of the input judgements, while the generated percentage contribution is used to allocate the total uncertainty into the respective types of uncertainties.

### **6.3.3 Uncertainty classification**

This phase enables to classify uncertainties into high, medium and low level of uncertainty using a traffic light system for services including maintenance, spares, and training. The procedure follows for the relevant set of uncertainties for each of these services. The classification is based on the calculated uncertainty score. This is a multiplication of the average of the three criteria (used in determining the uncertainty level) with the percentage relevance level (uncertainty weight) that is calculated through AHP. The classification enables to focus on uncertainties that need attention. The uncertainty classification follows the following reasoning:

- The uncertainty is deemed red (high uncertainty) if the uncertainty score is greater than five
- The type of uncertainty is orange (medium uncertainty) if the uncertainty score is between three and five (including five)
- The type of uncertainty is green (low uncertainty) if the uncertainty score is lower than or equal to three

### **6.3.4 Uncertainty mitigation**

The framework classifies the uncertainty management strategies into three domains: reliability, maintainability, and supportability. The focus has been on these three measures due to their coverage of key aspects that relate to industrial service delivery processes. Reliability involves the ability of a system and its parts to perform its intended function (mission) for a specified period of time under stated conditions without failure, degradation or demand on the support system (Kececioglu, 1991). Maintainability involves a measure that reflects how easy, accurate, effective, efficient and safe the maintenance actions related to the product can be performed (Kececioglu, 1995). Supportability is a measure of how easy, cost effective, and safe it is to support the product (Jones, 2006).

Table 6.9 Examples of uncertainty management strategies

	Uncertainty Management Strategies
Reliability	<ol style="list-style-type: none"> <li>(1) Implement an integrated reliability engineering and product assurance program in purchasing, quality control, inspection, etc.</li> <li>(2) Obtain the required data and prepare reliability bathtub curves, which define the failure rate for that part or equipment is plotted versus its age</li> <li>(3) Study the types of failures experienced by parts, components, products and systems to minimise failures</li> </ol>
Maintainability	<ol style="list-style-type: none"> <li>(1) Incorporate the correct maintainability specifications into all of the previous company activities that come in contact with the product from its birth to its death</li> <li>(2) Determine the optimum maintainability that should be designed into equipment so that its life cycle cost is the minimum</li> <li>(3) Obtain the required times-to-failure and success-and-failure data and prepare reliability bathtub curves where the failure rate of the equipment plotted versus its age</li> </ol>
Supportability	<ol style="list-style-type: none"> <li>(1) Enhance communication across a large network of interlinked entities including suppliers, manufacturers and distributors across multiple organisations across the globe</li> <li>(2) Manage the conflicting objectives of these members</li> <li>(3) Improve resilience across a supply network</li> </ol>

An illustration of the uncertainty management strategies that the framework suggests are represented in Table 6.9, while the total number of strategies reaches fifty seven. This list has been developed based on the guidelines that have been provided in Kececioglu (1991), Kececioglu (1995) and Jones (2006) to manage reliability, maintainability and supportability. Overall, a management strategy is implemented with the aim of preventing or reducing the influence of uncertainty and its potential impact. Furthermore, the selection process of the uncertainty strategy can also assist in defining the interaction across the supply chain (Trkman and Cormack, 2009). As opposed to risk mitigation, the focus of uncertainty mitigation relates to enhancing the clarity of aspects and it requires the previous sections emphasised in the framework to be put in place.

#### 6.4 Iterative Development and Initial Validation

The validation reflects results from the qualitative based semi-structured interviews that were conducted via WebEx and face to face to understand aspect such as usability, generalisability, benefits and areas to improve within U-TASC. During these validations cost uncertainty management and modelling approaches were queried due to the integrated approach and the results are separated across Section 6.5 and Section 7.4.



Within this section in total five validation sessions were undertaken, whilst a similar format was adopted for each of the interviews. This initially involved a presentation of the tool and subsequently gathering feedback, while each session lasted for two hours.

The first validation was with an Integrated Logistics Support Manager with 12 years of experience from Organisation A. The tool was indicated to be a useful tool, which enabled to reduce the subjectivity involved in the uncertainty considerations. The tool was suggested to show the source of the outputs, while giving reasons, and the rational. Logic was suggested to be right and suitable for the bidding context, while the outputs were highlighted to be in a format that could be used. The tool was suggested to be generalisable, though a lack of consideration of schedule was indicated. From the cost uncertainty management perspective the key benefit was referred to be the ability to take subjective views of uncertainty and to formalise the choices to the higher management in an auditable manner. Furthermore, tool usability was suggested to be high due to the use of MS Excel as the platform. On the other hand, a limitation was suggested to be the need to use the tool frequently to fully understand the features of the tool and lack of consideration of schedule. Results were suggested to be well reasoned arguments and should be dependable due to the repeatability aspect within MS Excel.

The second validation was attended by three participants as indicated in Table 6.10. The respondents in common highlighted that the tool was robust. The advantage of the tool was suggested to be the transparency and the integrated nature of the tool. U-TASC was suggested to be used in as short as one day. Furthermore, the respondents in common agreed that the suggested list of uncertainty mitigation strategies were suitable and comprehensive for the purpose of supporting the bidding process.

Table 6.10 Overview of attendees at the second validation

Organisation	Job role of attendee(s)	Experience (Years)
A	Integrated Logistics Support Manager	18
A	Assistant project manager	22
A	Engineering manager	31

A number of suggestions were made involving verification, which got incorporated into the tool. Some of the suggestions included:

- Insufficient data should not be considered as it dilutes the uncertainty score
- Include the score of “0” uncertainty, which was achieved by adding the tick box for uncertainty relevance
- Labour cost needs to be split into labour hours and labour rates
- Develop an overall score of uncertainty as a project maturity indicator

Table 6.11 Overview of attendees at the third workshop

Organisation	Job role of attendee(s)	Experience (Years)
A	Principal reliability specialist	20
A	Cost modelling lead	30

The third validation was participated by two subject matter experts, as detailed in Table 6.11. The respondent particularly highlighted that the tool would be supporting the process of contracting from various aspects such as in defining the potential scope of work, and the interaction between customer, OEM, and suppliers. The respondents suggested the scoring on the NUSAP matrix should include all values between one and seven (rather than neglecting the even values) in order to provide flexibility when it is hard to select a value.

The fourth validation was conducted with a supportability engineer with 12 years of experience in uncertainty analysis. The respondent highlighted that MS Excel based applicability was suggested to be very useful in the bidding process in understanding the uncertainties within the contract. The systematic approach was suggested to be very beneficial to quantify the uncertainty

The fifth validation was conducted with a project manager with 20 years of experience. The respondent highlighted that U-TASC only considers corrective maintenance and predictive maintenance is not considered. It was highlighted that the tool was very useful for the bidding stage because, (1) a suitable level of granularity is taken in to account in association to the lack of time and information that experienced during

bidding, (2) flexibility to use across the bidding phase. The benefits of the tool were suggested to firstly include applying rigour to an area that is subject to subjective views. Secondly, the tool provides a more consistent view which could give confidence to the bidding team. Furthermore, as a result of the tool the bidding team understands the customer (e.g. senior management understands the contract requirements). As a limitation it was suggested that with too difficult/complicated assessment approaches, data inputs might unlikely be meaningful. The tool was suggested to offer useful outputs that could support the bidding process with relevant guidance.

## **6.5 Summary**

The chapter presents the cost uncertainty management side of the Uncertainty Tool for Assessment and Simulation of Cost. Initially a link between cost estimation and cost uncertainty management is presented by emphasising that a systematic approach is required to assist during the bidding stage to identify, assess and respond to uncertainties. It is highlighted that the considered uncertainties are limited to the delivery of maintenance, spares and training.

Section 6.2 focuses on emphasising that uncertainty management rather than risk management is the missing link in forecasting the future due to the ability to assess the validity of existing data and assumptions. It is suggested that by rigorous application of uncertainty management project performance can be enhanced.

Section 6.3 highlights the process that was followed to elicit information that was required to develop the bid cost uncertainty management framework. The section presents the steps that were taken across four phases associated to the framework: (1) Identification of uncertainties, (2) Prioritisation of uncertainties, (3) Selection of uncertainty mitigation strategy and (4) refinement, which is associated to each of the previous phases.

Section 6.4 presents the developed bid cost uncertainty management framework. Initially, the respondent needs to identify uncertainties based on the suggested list of

uncertainties (including 70 types). This leads to the prioritisation of uncertainty through the NUSAP matrix (to define the uncertainty level) and the AHP (to define the level of uncertainty weight). The identification and prioritisation through a defined uncertainty score enables to classify uncertainty and to subsequently define mitigation measures. It is emphasised that by applying the framework the bid can be revised to account for the influences of uncertainties. This refers to the specification of how uncertainties can impact the performance of the project in terms of cost and establishing uncertainties that need detailed control.

Section 6.5 presents the initial validation that has been undertaken. This involved five sets of semi-structured interviews conducted through WebEx and face to face. As explained in the section, the results of the interviews enabled to make adjustments in the tool from a number of perspectives including: features, usability, and reliability of results. Additionally, the benefits and limitations of the tool were captured.

The following chapter diverts the focus towards the cost uncertainty modelling side of U-TASC by focusing on the methodology adopted to develop the associated framework and the components of the framework.

## 7 UNCERTAINTY BASED COST ESTIMATING

In this chapter application of the Uncertainty Tool for Assessment and Simulation of Cost (U-TASC) to integrate uncertainty to cost estimation during bidding in Contracting for Availability (CfA) within the defence industry is presented. The tool consists of five key areas developed in MS Excel. Firstly, a pre-defined set of uncertainties are provided to identify and assess relevant uncertainties. Secondly, the variation in the provided set of service cost drivers is defined by considering the specific uncertainties that affect each cost driver. Thirdly, a range is specified for the cost uncertainty level using the Cost Estimate Classification System presented in the Association of the Advancement of Cost Engineering (AACE) recommended practice. In the fourth key area, the range suggestions are used to transform a single point estimate into three. Fifthly, Monte Carlo simulation is conducted to generate triangular, uniform and beta distributions. The research benefitted from interaction with four major organisations through semi-structured interviews, workshops and case studies, whilst validation enabled to make refinements in the framework. Section 7.1 focuses on introducing the cost uncertainty modelling domain. The methodology followed to develop the cost uncertainty modelling framework is presented in Section 7.2. The features of U-TASC are presented in Section 7.3 and the initial validation is covered in Section 7.4.

The integration of uncertainty to cost estimation follows a step by step procedure (NATO, 2009). In this process initially all cost drivers affected by uncertainties need to be identified. In parallel a single point estimate needs to be calculated in order to add the influence of uncertainty on this value, which is typically represented through a probability distribution devised for each cost driver. For this purpose it is necessary to select the type of distribution (e.g. commonly normal, log-normal, and triangular) to apply. Subsequently it is necessary to estimate the distribution's parameters such as maximum, minimum and most-likely values, which refer to a Three-point estimate. These values reflect the possible outcomes, which yield numerical values that can be used in quantitative risk analysis to support decision making. Setting these values involves a degree of subjectivity as it relies on expert opinion; however it is commonly

acknowledged that defining a cost range enables to capture the world more realistically compared to a single point estimate (Curran, 1989). Definitions for the minimum, most likely and maximum cost estimates are defined as follows (MoD, 2007a):

- Minimum – Reflects the optimistic scenario where the cost outcomes are most in favour of the estimator.
- Most Likely – Represents the cost level which is right more often than any other (i.e. the mode, in statistical language).
- Maximum – Covers the pessimistic view of cost outcomes, where the worst scenario is assumed, but excluding the very unexpected (e.g. "Acts of God")

In CfA the customer predominantly aims to transfer responsibility, in other words risk and uncertainty, to the manufacturer. The transition to CfA has shifted the sources of perceived customer value, while the service content has increased in the provision. Cost estimation has emerged as a major challenge at the bidding phase due to the uncertainty that arises from the dynamic behaviour experienced in service delivery (e.g. changing usage conditions and equipment health) and the manipulation of customer requirements. The degree of uncertainty is associated to the length of the contract which can last for over 30 years. In order to deal with the cost uncertainty modelling challenge a number of areas can be considered, including:

- Firstly, as the nature of the in-service phase has drastically changed for the solution provider when delivering CfA, there is a need for an effective mechanism to identify uncertainties. The challenge is coupled with the need to understand differences between projects, when establishing guidelines or checklists. The issue is caused by a lack of established types of uncertainties.
- Secondly, prioritisation of uncertainties is a challenging task, due to the lack of standardised processes (e.g. metrics) in comparing cost uncertainties. This means among uncertainties that are considered their influence over potential costs may not easily be captured. Also, a systematic approach would enable to reduce the influence of optimism arising from engineers.

- Thirdly, a means to visualise uncertainties is necessary because of the lack of understanding of the boundaries of a cost estimate not only across organisations but also across internal departments.
- Fourthly, there is a need to consider the uncertainty in input variables when developing Three-point estimates. A systematic and rigorous approach needs to be put in place in order to be able to justify the defined confidence in an estimate as this determines the level of uncertainty. Furthermore, as the uncertainty grows, the confidence in estimates decreases and the price typically increases. As a result the bid may become unaffordable for the customer.
- Fifthly, since in the bidding stage there is substantial time pressure, it would be beneficial to reduce the impact of the be-spoke nature of projects on adjusting processes by utilising a generic model through a tool that provides a standardised methodology to integrate uncertainty to cost estimation. Furthermore, the cost-benefit of the analysis must be justifiable in terms of time spent and accuracy of a cost estimate.

Three-point estimating has already commonly been applied across industry. Though, in order to handle the subjectivity involved in developing Three-point estimates this chapter presents a systematic framework to predict uncertainty based cost. For further information about the application of the systematic framework in U-TASC, the reader is guided to Appendix F, where the User Manual is provided.

## **7.1 Detailed Methodology for Developing the Cost Uncertainty**

### **Modelling Framework**

The shift into CfA is promoting the need for more rigorous assessments of life cycle costs, because of the life cycle view of equipment usage and better understanding of the service phase is a critical aspect. The key questions that U-TASC has aimed to address for cost uncertainty modelling include:

- How can the incorporation of the influence of uncertainty be enhanced systematically in cost estimation?
- How can uncertainties that explicitly arise in CfA be identified systematically?

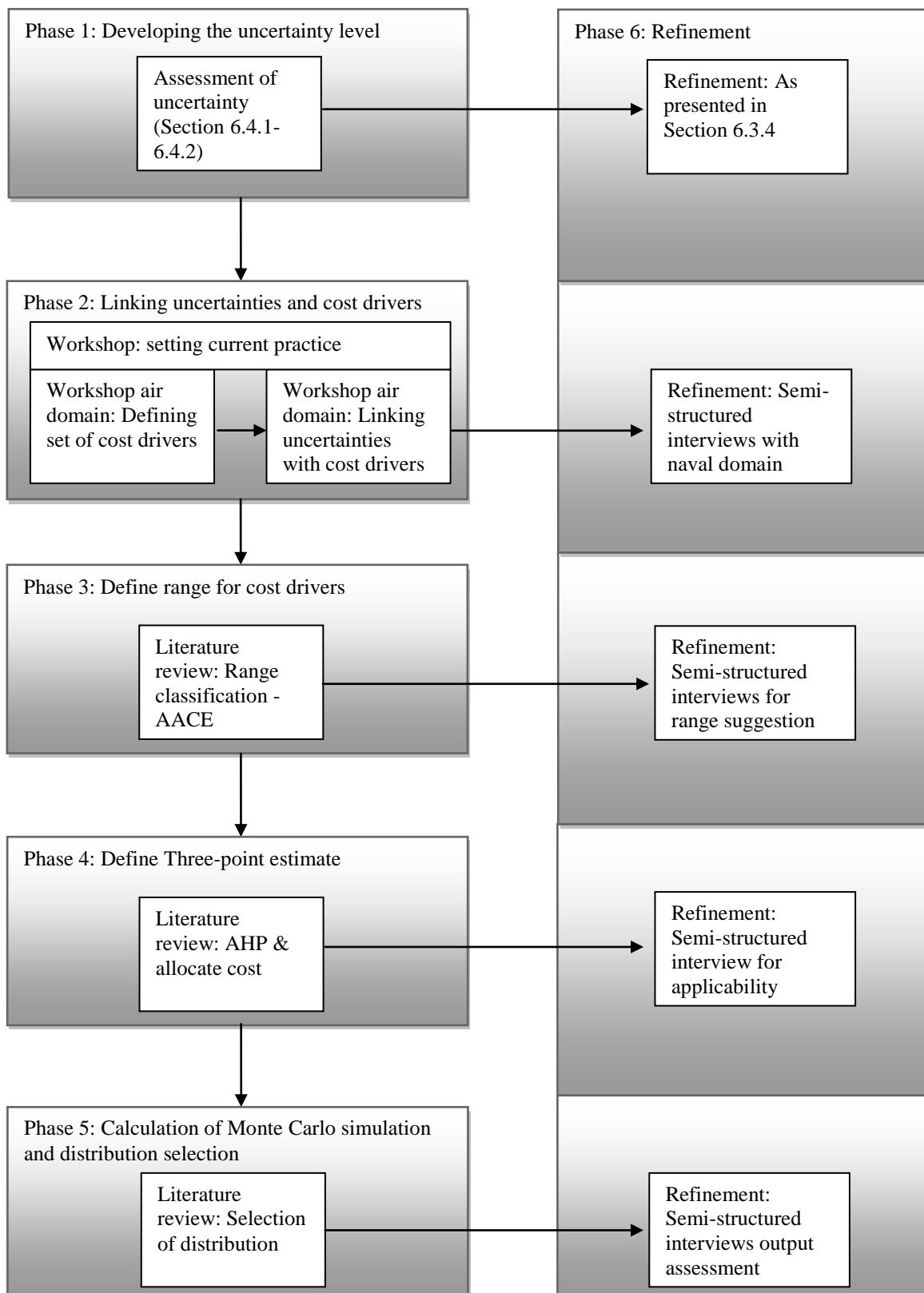


Figure 7.1 Methodology for developing the bid cost uncertainty modelling framework



In Figure 7.1 the research development is presented based on the key features of the cost uncertainty modelling framework. There are five key areas associated to the bid cost uncertainty modelling framework, whilst refinement is added to represent the adjustments that were made for each of these key areas including:

- Developing the uncertainty level
- Linking uncertainties and cost drivers
- Defining the range for cost drivers
- Defining the Three-point estimate
- Monte Carlo simulation and distribution selection

### **7.1.1 Uncertainty level**

The concepts of uncertainty identification and determination of the “Uncertainty level” are interlinked between the cost uncertainty management and modelling frameworks. The described approach in Section 6.4.1 and Section 6.4.2 (only the “Uncertainty level” side) applies to this Chapter as well.

### **7.1.2 Linking uncertainties and cost drivers**

Linking uncertainties and cost drivers refers to determination of a standard set of associations between uncertainties and cost drivers, which enables to understand the sources of uncertainty within cost drivers. For this purpose the final list of uncertainties presented in Section 5.3 has been applied. An extension within this chapter is with regards to determining a list of cost drivers that is comprehensive for the CfA context and in setting standard associations between the cost drivers and uncertainties. Within this process three workshops were undertaken, as follows.

The first workshop relevant to this section aimed to establish an understanding of the current practice for cost uncertainty modelling. The workshop enabled to establish a suitable methodology for the cost uncertainty modelling framework. An overview of the first workshop in terms of attendees and objectives is provided in Table 5.3. The typical structure of cost uncertainty modelling at Organisation A was explained, including three

steps: (1) cost driver identification through the work breakdown structure, (2) linking uncertainties and cost drivers through Monte Carlo simulation, (3) development of the Three-point estimate, which enables to understand the impact on cost. An illustration of these steps is presented in Figure 7.2.

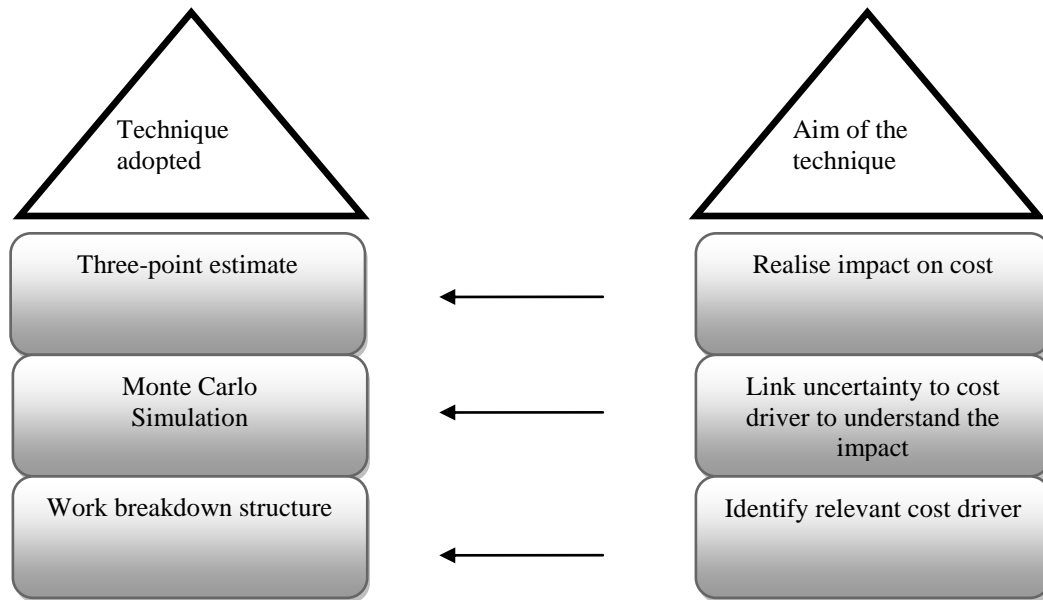


Figure 7.2 Process of uncertainty based cost estimation at Organisation A

At the workshop also the uncertainty modelling approach at Organisation D was presented.

1. Before the bidding stage Organisation D conducts an assessment, called the initial gate assessment, to find the suitable contract, where the decision is based on the in-house capability and the level of support required from industry
2. Integrated Project Team (IPT) produces a cost model for spares and in-service availability
3. Through a driver analysis the key drivers for cost estimation are linked into uncertainty issues which may include aspects such as the availability of material, labour and stock
4. Code uncertainties by identifying the major issues
5. Look at Master Data Assumptions List (MDAL) and IPT assumptions and the logic behind estimates. This enables to classify the main areas of cost, including areas such as the availability of equipment
6. Understand the impact on cost typically through Monte Carlo simulation

At the second workshop, which lasted for four hours and was attended by 9 participants, the discussions focused on establishing quantifiable cost drivers that depict a comprehensive picture of CfA. This particular workshop also aimed to determine those cost drivers that require additional attention due to the level of uncertainty. The interaction with the particular participants was spread across two workshops. Furthermore, the workshops were organised in collaboration with Dr. Partha Datta, who was a Research Fellow at Cranfield University, working on the S4T project with the particular participants whom focused on the air domain. The interaction with this particular organisation was aimed to enhance the generalisability of the authors' research, whom had concentrated on the naval domain. One of the objectives of the interaction with these participants was to assess the authors' cost uncertainty considerations, which were developed in the naval domain, regarding the identified uncertainties, the application of the NUSAP matrix, and the specified initial links between uncertainties and cost drivers. During this process, Dr. Partha Datta focused on developing relationships between uncertainties and value drivers, which include aspects related to revenue in addition to costs. On the other hand, the author explicitly worked on building links between uncertainties and cost drivers. As mentioned the respondents came from the air domain with varying degrees of experience in CfA, whilst an overview of the attendees is provided in Table 7.1.

Table 7.1 Attendees of the cost driver determination workshop

<b>Organisation</b>	<b>Job role of attendee(s)</b>	<b>Experience (Years)</b>
A	Business and solutions modelling lead	34
A	Business and solutions modelling expert	36
A	Integrated Logistics Support manager	26
A	Project manager	21
A	Business and solutions modelling expert	24
A	Supportability engineer	18
A	Business & Solutions Modelling Integration Project Manager	22
A	Systems engineer	14
A	Reliability consultant	23

During this workshop the major sources of costs were categorised, whilst also specifying the components/cost drivers associated to each of these cost categories. The top level generic list of cost categories was considered to include “supply chain”, “engineering”, “maintenance”, “performance”, “business management” and “training”. Table 7.2 highlights the considered cost drivers for each of the cost categories:

Table 7.2 Overview of the initial cost categories and cost drivers

Cost category	Cost drivers	
<b>Supply chain</b>	<ul style="list-style-type: none"> <li>• Stock level</li> <li>• Mean time between failure</li> <li>• Arising rate</li> <li>• Turnaround time</li> <li>• Lead time</li> </ul>	<ul style="list-style-type: none"> <li>• Ordering a new kit</li> <li>• Provision requirements</li> <li>• Repair cost</li> <li>• Demand satisfaction rate</li> <li>• Obsolescence</li> <li>• Transportation cost</li> </ul>
<b>Engineering</b>	<ul style="list-style-type: none"> <li>• Rate of change</li> <li>• Query volume</li> <li>• Engineering mistakes</li> <li>• Complexity of equipment (e.g. volume of query)</li> <li>• Level of publication</li> </ul>	<ul style="list-style-type: none"> <li>• Query response time (e.g. value driver-right first time)</li> <li>• Cost of labour</li> <li>• IT infrastructure causes uncertainty in forecasting because of its influence on data availability</li> </ul>
<b>Maintenance</b>	<ul style="list-style-type: none"> <li>• Platform MPAL (e.g. how many times to maintain)</li> <li>• Emergent work</li> <li>• Maintenance elapse time (e.g. how many days?)</li> <li>• Schedule</li> <li>• Labour efficiency</li> <li>• Labour cost</li> </ul>	<ul style="list-style-type: none"> <li>• Availability of labour</li> <li>• Availability policy (e.g. when to maintain?)</li> <li>• Physical capacity for maintenance</li> <li>• Government furnished asset (e.g. labour provided by customer)</li> <li>• Cost of simulating performance (e.g. through WITNESS)</li> </ul>
<b>Training</b>	<ul style="list-style-type: none"> <li>• Number of courses</li> <li>• Pass rate</li> <li>• Length of each course</li> <li>• Concurrency of courses (e.g. customer demand)</li> <li>• Course load factor</li> </ul>	<ul style="list-style-type: none"> <li>• People at a certain skill level</li> <li>• Number of people</li> <li>• Training facilities</li> <li>• Skill gap</li> </ul>
<b>Manage business</b>	<ul style="list-style-type: none"> <li>• Exchange rate</li> <li>• Incentivising mechanism</li> <li>• Managing risk and opportunity (including the retirement of risk and considering opportunity)</li> <li>• Integration delivery</li> </ul>	<ul style="list-style-type: none"> <li>• Safety (e.g. reputation)</li> <li>• Carbon values (e.g. expected to be influential in the future)</li> <li>• Overhead rate (e.g. across sites)</li> <li>• Trade union protection (e.g. pension)</li> </ul>
<b>Performance</b>	<ul style="list-style-type: none"> <li>• Customer demand usage</li> <li>• Customer actual usage</li> <li>• Unit cost per flying hour</li> </ul>	<ul style="list-style-type: none"> <li>• Maintenance event per flying hour</li> <li>• Training pass rate</li> <li>• Revenue rate</li> </ul>

Each cost category follows its own dynamics driven by the associated cost drivers. For instance, in the case of “Training” the cost drivers fluctuate driven by the ambitions of the customer, which may be driven by aspects such as reducing the number of people in the system, enhancing operational efficiency, reducing query volume, and cost per trained people. Furthermore, the performance criteria for the delivery of “Training” may include elements such as revenue generation of trained personnel, availability, customer demand (e.g. varying with fixed or firm price type arrangement), customer usage, unit cost per unit demand achieved, and KPI performance (e.g. spares, number of aircraft available, technical query response, number of courses and pass rate).

### Comparison across cost categories

One of the outcomes of the second workshop was a comparison of the cost categories, including engineering, supply chain and maintenance. Figure 7.3 highlights that approximately 60% of the costs arise from the supply chain. Furthermore, 20-25% of the costs are driven by maintenance activities and around 10-15% of the costs arise from engineering activities. In contrast, maintenance activities constitute approximately 65% of the sources of costs, as they influence the supply chain and engineering activities. Thus, maintenance activities along with the supply chain require additional recognition of uncertainty in cost estimation.

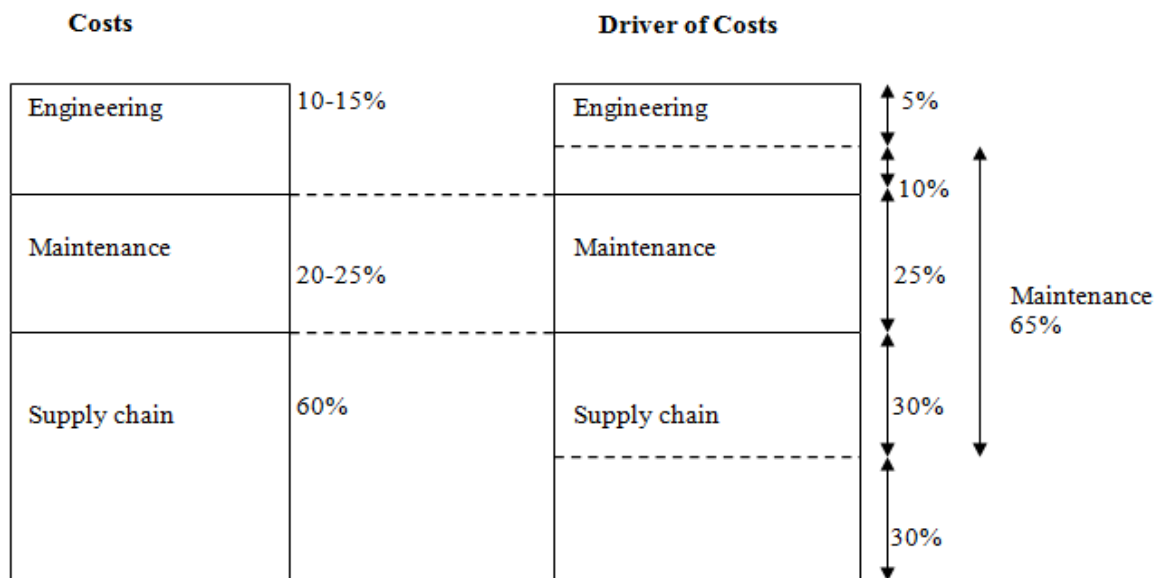


Figure 7.3 Cost impact across the major cost categories

This workshop also aimed to determine the key cost drivers that faced the largest amount of uncertainty. For this purpose the NUSAP matrix was applied for each of the cost drivers within each of the cost categories. The respondents in common agreed that the scheme to assess the level of uncertainty was suitable for the defence context. In the case of the “Supply chain” cost category, results that were gathered at the workshop for a typical air domain project to compare the uncertainty level in the cost drivers is presented in Table 7.3. ‘MTBF’, ‘Turnaround time’, and ‘Repair cost’ emerged as the cost drivers with the highest amount of uncertainty, as represented in the Pedigree score.

Table 7.3 Example for rate of uncertainty in “Supply chain” cost drivers

Supply chain	Basis of estimate	Rigour assessment in	Level of Validation	Pedigree Score
Stock Level	3	2	1	0.5
MTBF	4	4	3	0.92
Arising Rate	2	2	3	0.58
Turnaround time	3	3	3	0.75
Lead Time	1	1	1	0.25
Repair Cost	3	3	3	0.75
Ordering new kit (Purchase Cost)	1	2	2	0.42
Demand satisfaction rate	1	3	3	0.58
Obsolescence	1	1	1	0.25
Transportation cost	3	2	2	0.58
Provision Requirements	2	3	2	0.58

For each of the cost categories apart from ‘supply chain’ a brief overview of the cost drivers with the highest uncertainty is listed below:

- Maintenance: Platform Maintenance Policy, facilities capacity, and labour effectiveness
- Engineering: query volume and query response time
- Training: training facilities and number of students
- Manage business: exchange rates, overhead costs, and labour cost
- Performance: customer actual usage, customer demand usage

Table 7.4 Overview of cost drivers across case studies

Cost category	Cost drivers	
<b>Project 1</b>	<ul style="list-style-type: none"> <li>• Flying hour</li> <li>• MPOL contracted</li> <li>• Maintainability contracted</li> <li>• Arising rate</li> <li>• Average unit spares cost</li> <li>• Debtor/creditor days</li> </ul>	<ul style="list-style-type: none"> <li>• Average unit repair cost</li> <li>• Labour efficiency</li> <li>• Performance contracted</li> <li>• Tax</li> <li>• Inflation</li> <li>• Weighted average cost of capital (WACC)</li> </ul>
<b>Project 2</b>	<ul style="list-style-type: none"> <li>• Component reliability (arisings per 100 flying hours)</li> <li>• Flying hours</li> <li>• Unit purchase cost (£ per flying hours)</li> <li>• Purchase lead time (to send parts)</li> </ul>	<ul style="list-style-type: none"> <li>• Repair turnaround time</li> <li>• Transaction cost (filling sheet)</li> <li>• Backstop time</li> <li>• Stock out cost</li> </ul>
<b>Project 3</b>	<ul style="list-style-type: none"> <li>• Supply total cost</li> <li>• Risk pot</li> <li>• Engineering non-direct maintenance</li> <li>• Repair cost</li> </ul>	<ul style="list-style-type: none"> <li>• Cost of incentives</li> <li>• Maintenance cost</li> <li>• Supply quantity cost</li> <li>• Engineering support cost</li> <li>• Spares cost</li> </ul>
<b>Project 4</b>	<ul style="list-style-type: none"> <li>• Consumables</li> <li>• Purchase (beyond economical repair, spares rework)</li> </ul>	<ul style="list-style-type: none"> <li>• Repairs (no fault found rate)</li> </ul>
<b>Project 5</b>	<ul style="list-style-type: none"> <li>• Repair cost</li> <li>• Packaging cost</li> <li>• Transport cost</li> <li>• Repair cost</li> </ul>	<ul style="list-style-type: none"> <li>• No Fault Found cost</li> <li>• Beyond Economical Repair cost</li> <li>• LRU Cost</li> </ul>

The author also benefitted from provided documents from Organisation A, which listed the major cost drivers for five projects in CfA. The documents consisted of cost breakdown structures, and cost models. An overview of the projects is provided below, whilst Table 7.4 lists the main areas of the cost drivers:

- Project 1: availability of aircrafts for frontline operations. The project aims to provide day-to-day flightline maintenance and will combine this with a structured and cost effective approach to upgrade work under the Capability Development and Sustainment Service to maintain the aircraft's warfighting effectiveness through its service life.
- Project 2: the capability to meet the wide range of maintenance and technical support requirements for aircraft. The range of services offered includes fleet and supply chain management, forward and depth maintenance, and technical support. The project also offers availability of spares.

- Project 3: arrangements for forward and depth maintenance agreed with the customer, involving additional responsibilities for fleet maintenance and maintenance policy and incentivised performance based on aircraft availability. The contract has been agreed to continue to the aircraft's out of service date.
- Project 4: frontline service for a naval ship self-defence missile system that entered service over thirty years ago. The contract concentrates on providing availability to missile systems naval ships, which requires maintenance throughout the duration of the contract.
- Project 5: spares/repairs/replacements for a set of systems, whilst providing a view of performance within the naval domain. The support contract is currently in the process of agreement, and is at a relatively immature state compared to the pre-defined projects.

A follow on workshop was organised, where the respondents were initially asked to further concentrate the list of cost drivers. Subsequently, a direct association between the cost drivers and the finalised list of uncertainties presented in Chapter 5 were gauged. The workshop lasted for four hours and was attended by seven participants. As a result 19 cost drivers were determined, which are listed in Section 7.3.2. An overview of the respondents is provided in Table 7.5.

Table 7.5 Attendees of the cost driver and uncertainty linkage workshop

Organisation	Job role of attendee(s)	Experience (Years)
A	Business and solutions modelling lead	34
A	Business and solutions modelling expert	36
A	Project manager	21
A	Business and solutions modelling expert	24
A	Supportability engineer	18
A	Business & Solutions Modelling Integration Project Manager	22
A	Reliability consultant	23



The associations between the cost drivers and uncertainties were gathered through provided Fishbone diagrams which were filled by the respondents. The adoption of this approach for collecting data was considered suitable because of the ability of the technique to illustrate associations between different variables. The following section lists a generic list of uncertainties for each cost driver in each cost category, while focusing on the key areas including supply chain, maintenance and engineering.

The main cost drivers considered in the ‘supply chain’ category are ‘arising rate’, ‘MTBF’, ‘purchase cost’ and ‘repair cost’. Furthermore, in the case of MTBF the uncertainties that cause variation in cost are considered to be ‘fleet maturity’, ‘mode of failure’, ‘equipment operating environment’ and ‘quality of item’. Uncertainties associated to the cost drivers ‘arising rate’, ‘repair cost’ and ‘purchase cost’ are represented in Figure 7.4.

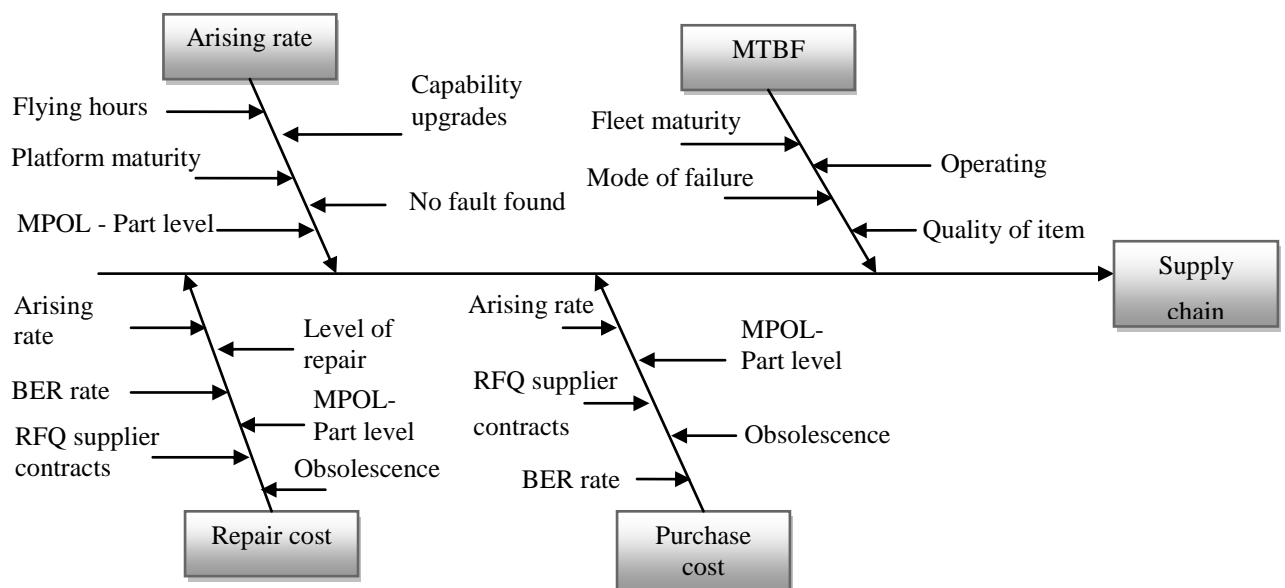


Figure 7.4 Linking cost drivers in the ‘Supply chain’ category with uncertainties

The main cost drivers considered in the ‘engineering’ category are ‘query response time’, ‘query volume’ and ‘quality of response’. In terms of the uncertainties related to the cost driver named ‘query response time’ the participants highlighted aspects such as ‘number of engineers’, ‘volume of queries’, ‘IT capability’, ‘efficiency of engineers’

and ‘complexity of a given query’. Furthermore, the uncertainties for query volume and quality of response are represented in Figure 7.5.

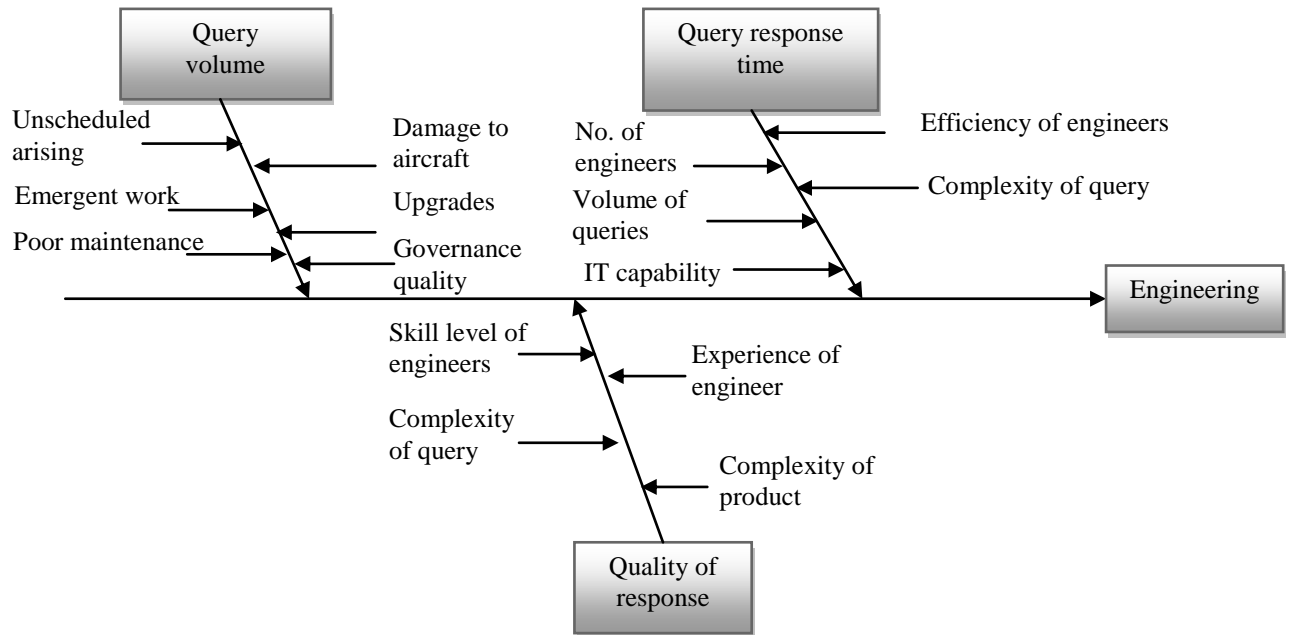


Figure 7.5 Linking cost drivers in the ‘Engineering’ category with uncertainties

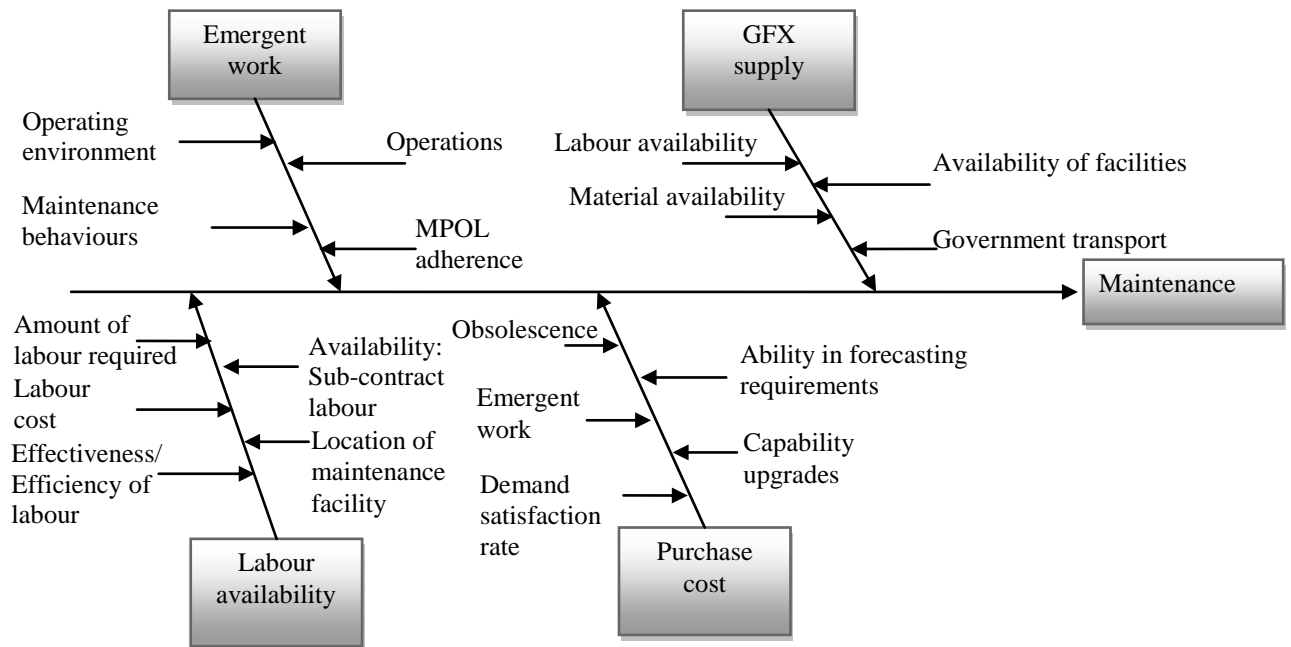


Figure 7.6 Linking cost drivers in the ‘Maintenance’ category with uncertainties

The main cost drivers considered for maintenance are ‘emergent work’, ‘GFX supply’, ‘labour availability’ and ‘purchase cost’. The uncertainties in emergent work have been considered to be ‘operating environment’, ‘maintenance behaviours’, ‘operations’ and ‘MPOL adherence’. Figure 7.6 represents the elements considered for ‘maintenance’.

As a result of the analysis for linking cost drivers and uncertainties the author observed that a number of uncertainties get to affect more than one cost driver. Table 7.6 illustrates a number of examples for this case. For instance, as an uncertainty ‘emergent work’ influences the cost drivers ‘query volume’ and ‘material availability’.

Table 7.6 Uncertainties influencing many cost drivers

Uncertainty	Cost driver 1	Cost driver 2	Cost driver 3
<b>Emergent work</b>	Query volume	Material availability	
<b>Query volume</b>	Query response time	Purchase cost	Repair cost
<b>Complexity of query</b>	Query response time	Quality of response	
<b>Aircraft operating Environment</b>	MTBF	Emergent work	Customer demand usage
<b>Flying hours</b>	Arising rate	Customer demand usage	
<b>MPOL</b>	Arising rate	Emergent work	Repair cost
<b>Request for quotation</b>	Repair cost	Purchase cost	
<b>Obsolescence</b>	Repair cost	Material cost	Purchase cost
<b>Operating Environment</b>	Emergent work	Customer demand usage	MTBF
<b>Affordability</b>	No. of students for training	Customer actual Usage	Customer demand usage
<b>Capability upgrades</b>	Query volume	Arising rate	Material availability

### 7.1.3 Defining the range for cost drivers

U-TASC suggests ranges for cost drivers by applying AACE International’s Recommended Practice for cost estimate classification (AACE, 1997; AACE, 2005). The document outlines the level of scope definition that is recommended for each class of estimate through five classes. Additionally, the typical contingency and accuracy range “bands”, which refer to the range of ranges, for process industry projects is

provided. The file represents a consensus across industry experts and has been considered to be reasonable across the industry collaborators of the research. The cost estimates are considered to be engineering, procurement and construction work explicitly. The process industry projects refer to the manufacturing and production of chemicals, petrochemicals, and hydrocarbon processing. The common characteristic among these industries (for the purpose of estimate classification) is their reliance on process flow diagrams and piping and instrument diagrams as primary scope defining documents. The delivery of service as in the CfA context also requires a similar form of structuring, which is why the approach was considered to be suitable.

The five estimate classes are presented in Table 7.7 in relation to the specified primary and secondary characteristics. The estimate class is determined by the level of project definition, which is considered to be a primary characteristic. The secondary characteristics (e.g. typical purpose of estimate) are likely to be correlated with the level of project definition. The five estimate classes have been defined to be generally applicable across the process industries, through flexibility built into the tool.

On the one extreme Class 5 estimates are generally prepared based on very limited information, which results in wide accuracy ranges (AACE, 1997). It may apply to the context when there is limited amount of time and with little effort expended. The context refers to 0% to 2% project definition, which refers to percent of engineering and design completion. Within this context the query may be with regards to strategic business planning purposes (e.g. initial viability assessment and resource needs). The expected accuracy range which feeds into U-TASC vary between -20% to -50% on the low side and +30% to +100% on the high side depending on the technological complexity of the project, availability of information and the inclusion of an appropriate contingency determination. The author applied the extreme cases for the high and low sides due to the complexity associated to the delivery of CfA. On the other extreme, Class 1 estimates refer to a level of project definition between 50% and 100%, which means that potentially all engineering and design documentation, project execution and commissioning of the project is virtually complete (AACE, 1997). The highest degree of deterministic estimating may be suitable for this context, whereby it is possible to

prepare estimates with great detail. The typical accuracy ranges vary between -3% and -10% on the low side and +3% to +15% on the high side (AACE, 1997). These estimates require the highest amount of effort to develop. For Class 1, similar to Class 5 the author applied the extreme cases for the specified ranges.

Table 7.7 Range suggestions through AACE (AACE, 1997)

	Primary characteristic	Secondary characteristic			
ESTIMATE CLASS	Level of Project Definition: (Expressed as % of complete definition)	End Usage Typical: purpose of estimate	Methodology: Typical estimating method	Expected Accuracy Range: Typical variation in low and high ranges [a]	Preparation effort: Typical degrees of effort relative to least cost index of 1 [b]
<b>Class 5</b>	0% to 2%	Concept screening	Capacity Factored, Parametric Models, Judgment or Analogy	L: -20% to -50% H: +30% to +100%	1
<b>Class 4</b>	1% to 15%	Study or Feasibility	Equipment Factored or Parametric Models	L: -15% to -30% H: +20% to 50%	2 to 4
<b>Class 3</b>	10% to 40%	Budget, Authorisation, or Control	Semi-Detailed Unit Costs with Assembly Level Line Items	L: -10% to -20% H: +10% to +30%	3 to 10
<b>Class 2</b>	30% to 70%	Control or Bid/Tender	Detailed Unit Cost with Forced Detailed Take-Off	L: -5% to -15% H: +5% to +20%	4 to 20
<b>Class 1</b>	50% to 100%	Check Estimate or Bid/Tender	Detailed Unit Cost with Detailed Take-Off	L: -3% to -10% H: +3% to 15%	5 to 100

Notes: [a] The state of process technology and availability of applicable reference cost data affect the range markedly. The +/- value represents typical percentage variation of actual costs from the cost estimate after application of contingency (typically at a 50% level of confidence) for given scope.

[b] If the range index value of "1" represents 0.005% of project costs, then an index value of 100 represents 0.5%. Estimate preparation effort is highly dependent upon the size of the project and the quality of estimating data and tools.

There is a lack of research that has focused on defining such ranges. Figure 7.7 illustrates a comparison across various classifications for cost estimates that have been proposed, including the ANSI Standard, AACE Pre-1972, Association of Cost Engineers, Norwegian Project Management Association, and the American Society of Professional Estimators. The figure also explains the basis for the classifications. Apart

from AACE (1997) only the ANSI standard and ACostE have specified suitable ranges, whilst the most detailed classification is provided in AACE (1997).

AACE Classification	ANSI Standard Z94.0	AACE Pre-1972	Association of Cost Engineers (ACostE)	Norwegian Project Management Association (NFP)	American Society of Professional Estimators (ASPE)
Class 5	Order of Magnitude Estimate -30/+50	Order of Magnitude Estimate	Order of Magnitude Estimate Class IV -30/+30	Concession Estimate	Level 1
Class 4				Budget Estimate -15/+30	
	Feasibility Estimate				
Class 3	Preliminary Estimate	Study Estimate Class III -20/+20	Authorisation Estimate	Level 2	
Class 2			Definitive Estimate -5/+15	Definitive Estimate	Current Control Estimate
Class 1	Detailed Estimate	Definitive Estimate Class I -5/+5			
					Level 6

Figure 7.7 Comparison of literature for range suggestions (AACE, 1997)

### 7.1.4 Defining the Three-point estimate

In order to define the Three-point estimate U-TASC applies the suggested ranges as explained in Section 7.2.3. The Three-point estimate is calculated for each cost driver, where flexibility is built in to the tool in terms of specifying the level of cost estimate whether at the cost driver or system level. For the case of the system level the AHP is applied, in order to understand the percent contribution of each cost driver, where expert opinion is used to define the significance of each cost driver. This in turn is used to allocate the single cost estimate representing the system level into each of the cost drivers. Further information about the reasons for selecting the AHP approach is explained in Section 6.3.2.

### 7.1.5 Monte Carlo simulation

The application of Monte Carlo simulation in U-TASC was considered to be suitable because of it being the common practice across the defence industry. Distributions and ranges are one area where Monte Carlo methods typically offer much information to the expert. Although the author could have used an independent software tool to conduct the Monte Carlo simulation (e.g. @risk), this application is embedded within MS Excel in order to have a complete tool which is capable of providing the required outputs.

### 7.1.6 Validation involving refinement

The refinement process followed an iterative process, which enabled to make enhancements to the bid cost uncertainty framework. During this process information was elicited through workshops as well as a semi-structured interview and also feedback through e-mails was received about provided documents (e.g. updating reports). Each of the aspects presented across Section 7.2 were put under consideration. The initial workshop was attended by three participants, which was conducted through WebEx and lasted for one hour. The session began with a presentation of U-TASC leading to feedback about the features and applicability of the tool. An overview of the attendees is presented in Table 7.8.

Table 7.8 Overview of attendees at the initial refinement workshop

Organisation	Job role of attendee(s)	Experience (Years)
G	Life cycle engineering lead	26
G	Reliability engineer	4
G	Integrated Logistic Support manager	6

The respondents highlighted that application of the tool at the Line Replaceable Unit (LRU) level would be too tedious and it would be necessary to consider costs at the system level. Various applicability related suggestions include: (1) adding a sheet for scoring the weights of the cost drivers, (2) adding a sheet to increase flexibility when adding new cost drivers, and (3) to develop an interdependency matrix between the

uncertainties and cost drivers. Furthermore, the respondents also provided a set of suggestions to enhance the features of the tool, as set out below:

- The evolution of uncertainty can be gauged by having a further assessment of the level of maturity in light of the expectation over the future
- Capturing optimistic estimating by being able to compare across uncertainty considerations that had been stored at different stages of the bidding and also comparing with considerations in other projects
- Need to support with defining the suitable level of granularity by considering the LRU, system, integrated system, and to bring these together
- Realising the concept of maturity growth across years
- Use across phases during the bidding process
- Definitions of uncertainty needs to be tailored across projects
- Develop a matrix profile for different platforms and illustrate differences
- Tool learns as each time a new project is brought in it results in learning
- Three-point estimates for each risk-confidence limit gives traceability of the uncertainty and offer simulation at a lower level
- Draw links between uncertainties and guide people with the uncertainties

A follow-on semi-structured interview, lasting one hour, was conducted with a reliability engineer from Organisation G with four years of experience in the uncertainty field. The respondent made a number of suggestions to the framework, which enabled to support with enhancing the outputs or features of the tool. The respondent indicated that given the availability of the minimum, maximum and most likely cost figures only the triangular, PERT/Beta and uniform distributions would be possible to compute within U-TASC. Furthermore, it was suggested that PERT/beta distribution has the minimum emphasis on outliers and applies more emphasis on the maximum. On the other hand, the uniform distribution was suggested to have the most emphasis on outliers. The triangular distribution was referred to have a decreasing emphasis on outliers compared to uniform distribution as it has more emphasis on the most likely figure. The respondent also highlighted that the tool assumes independence between the uncertainties. Some of the applicability related suggestions include:

- Store input data, which enables to understand changes in project characteristics



- Restrict from further input if single point estimate is required at the system level
- Automate the calculation of the percentile values for each of the distributions

The second workshop enabled to further clarify the suitability of the tool to the defence industry. An overview of the attendees is provided in Table 5.6. It was highlighted that a major feature of the tool was to support in determining the Three-point estimates. Furthermore, the tool was suggested to be used as a secondary model for validation at the early bid phase, whilst also supporting the communication with the customer.

At the third workshop it was mentioned that a link between the level of maturity and the spread of each type of distribution for all uncertainties would be useful. In response to this comment the author added the calculation of a maturity score based on the input, whilst concentrating on the significance of the cost drivers and the uncertainty level. An overview of the attendees is provided in Table 6.3. The respondents were particularly interested in the proposed systematic approach that can be adopted across their organisation in a standard manner.

At the fourth workshop, which an overview of the participants is highlighted in Table 6.4, a number of comments concerning applicability of U-TASC were made. It was highlighted that the AACE matrix provides a measure of estimate accuracy and the assumption in the tool is that the uncertainty level in relation to the cost driver is a determinant of the estimate accuracy. The respondents also suggested that the tool should provide suggestions with regards to selecting the suitable probability distribution. U-TASC was referred to be capable of guiding people across the life cycle. It was also suggested that it would be beneficial to define the influence of each uncertainty on the overall project.

At the fifth workshop, an overview of the participants is highlighted in Table 6.11, gathered a number of comments about U-TASC. The respondents highlighted that the tool offered benefits in supporting the modelling. Some of the comments included:

- Cost drivers were suggested to have a “technical” focus and would need to add the “political” and “commercial” sides as well (e.g. 5-6 high level cost drivers)

- The maximum and minimum values calculated can be the confidence levels for the considered distributions

The established cost drivers that were based on the air domain were subsequently validated with input from the naval domain in order to understand the generalisability of the concepts. During this process the author e-mailed the list of cost drivers to the participants of Organisation A. An Integrated Logistics Support manager and an assistant manager (Supportability engineer) with an experience of 18 and 22 years respectively indicated that “If some general terms were used (i.e. platform instead of aircraft) the document could be very generic and applicable across the business”. Additionally, a number of comments were made concerning the associations between uncertainties and cost drivers. In the case of the maintenance cost category (a response to Figure 7.7) it was suggested that:

“For Naval, the maintenance is split between what the ships staff can do and what they need the dockyard to do and then what they need specialist “supplier” support to do. So this gives an uncertainty over the split of ships staff, dockyard and supplier scope. This split is related to training and the availability of tools and test equipment to perform the maintenance as well. I don’t know if it fits under this part but we also provide consumable items (e.g. oil, fuses, lamps, and adhesives) so there is a need to show this – and this is also influenced by utilisation.”

A reliability engineer with six years of experience at Organisation G also suggested that the list of cost drivers were comprehensive and applicable across the defence industry.

## **7.2 Bid Cost Uncertainty Modelling Framework**

U-TASC follows a systematic approach to identify and prioritise uncertainty, to turn single point estimates into three and to conduct simulation, which focuses on supporting bidding teams. The framework is composed of six stages, which is demonstrated in Figure 7.8. Firstly, initial bid preparation takes place where assessments take into account the scope of the project by specifying a rough work breakdown structure. In

alignment, initial considerations regarding cost, price, investment in relation to labour required, competition, and the probability of winning a project is shaped during this process. This leads to the bidding process where a number of reviews are undertaken prior to the negotiation phase (Stage 6: Revise and Finalise Bid) with the customer. In this process aspects such as risk, uncertainty, cost against request, and price is assessed in detail with the constraint of available information.

The focus of this Chapter is on modelling of cost uncertainty and explicit attention is paid to it in the Stages between 2 and 5 in the Bid Cost Uncertainty Modelling Framework. In Stage 2 initially the uncertainty identification (Stage 2a: Uncertainty identification) is covered, whereby a list of uncertainties that can potentially affect the project through the cost drivers are provided. Within Stage 2 the level of uncertainty is assessed (Stage 2b: Uncertainty level), and an uncertainty level for each uncertainty type is calculated using a scoring mechanism following the Numeral, Unit, Spread, Assessment and Pedigree Matrix (NUSAP Matrix). In Stage 3 an association between uncertainties and cost drivers is established, which enables to realise the major sources of uncertainty in cost drivers. The calculated uncertainty levels are aggregated and the average of the associated uncertainty levels for each cost driver is calculated to represent the cost uncertainty score. In Stage 4, the cost uncertainty score and AACE (1997) guidelines are used to initially define a minimum and maximum range (as a percentage) for the potential variability in cost (Stage 4a: Define range for cost drivers). Subsequently, the percentage values are used to calculate the Three-point estimates (minimum, most likely and maximum cost estimate) (Stage 4b: Define three point estimates). Though, U-TASC requires the input of a single point estimate for either the system or each relevant cost driver. The Three-point estimates are used in Monte Carlo Simulation to generate triangular, uniform and PERT/beta distribution in Stage 5. Subsequently, adjustments are made to the estimates based on the negotiation procedure between the customer and the solution provider, where the process continues until the bid is finalised. The uncertainty focused stages are presented in the following sub-headings.

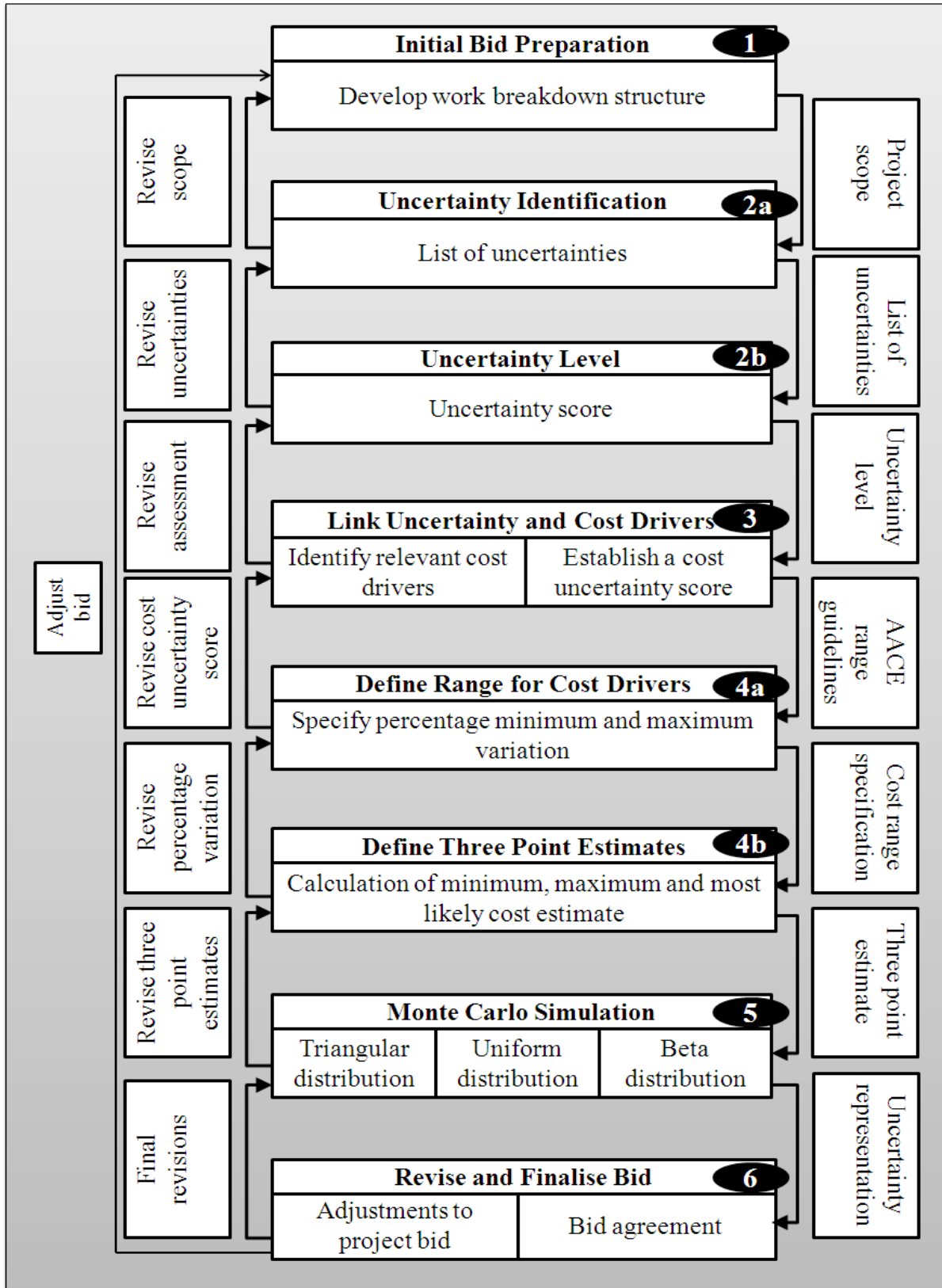


Figure 7.8 Bid cost uncertainty modelling framework

### **7.2.1 Uncertainty level**

The uncertainty level is calculated by combining the “Uncertainty identification” and “Uncertainty impact analysis – uncertainty level”. These procedures are explained in Section 6.4.1 and Section 6.4.2 (only “Uncertainty level”) respectively. The uncertainty level as calculated from the NUSAP matrix enables to gather an understanding of the degree of uncertainty experienced in a type of uncertainty.

### **7.2.2 Linking uncertainty and cost drivers: Cost uncertainty score**

Within this stage U-TASC defines a cost range for the cost drivers by applying two steps. Firstly, a list of cost drivers is provided for the user to select from based on the relevance to the project. Secondly, a link between specific uncertainties and cost drivers is established in order to calculate a cost-uncertainty score, which represents the level of uncertainty in a cost driver. For this purpose the uncertainty level that had been calculated for each uncertainty type is used and the linkages refer to specific associations between particular uncertainties and cost drivers. The average value is normalised by dividing this with the number of uncertainty variables that affect the cost driver, which represents the cost uncertainty score. Figure 7.9 illustrates the process of calculating the cost uncertainty score.

A total of 19 cost drivers have been considered in U-TASC. The process of capturing this refined list that was developed in the air domain and validated in the naval is explained in Section 7.1.2 and Section 7.1.6, respectively. The finalised list of the cost drivers includes:

Failure rate, turnaround time, line replaceable unit (LRU cost), transport cost, packaging cost, repair cost, demand rate (spares), storage, emergent work, GFX Supply, material availability, labour availability, customer demand usage (e.g. fleet time and harbour), customer actual usage (e.g. fleet time), no fault found (NFF) cost, beyond economical repair (BER) cost, number of students, number of trainers, facilities for training

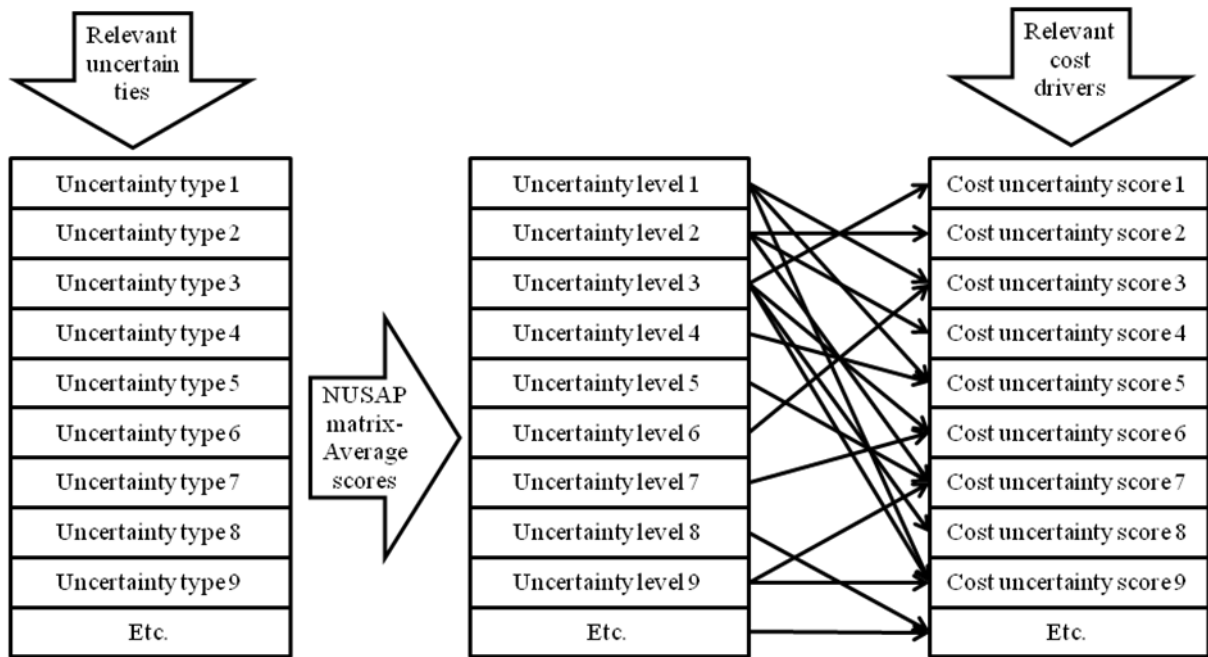


Figure 7.9 Process of calculating the cost uncertainty score

Each of the 19 cost drivers is associated to 70 uncertainties in different ways depending on the possibility of an uncertainty affecting a particular cost driver. The associations were developed based on the workshop and validations represented in Section 7.1.2 and Section 7.1.6, respectively. An example for the association between the cost driver of “failure rate” and the associated sources of uncertainty is considered to include:

- Uncertainty in the ‘level of relationship with the customer’
- Uncertainty in the ‘rate of surge’
- Uncertainty in the ‘quality of components’
- Uncertainty in ‘equipment utilisation rate’
- Uncertainty in the ‘operating parameters’
- Uncertainty in the ‘failure rate of hardware’
- Uncertainty in the ‘rate of capability upgrades’
- Uncertainty in the ‘rate of system integration issues’
- Uncertainty in the ‘failure rate for software’
- Uncertainty in ‘customer equipment usage’

The cost uncertainty score can reach the maximum value of 1, and this value supports the process of defining a range for the cost drivers.

### 7.2.3 Turning a single point estimate into three

#### Defining the range for cost drivers

U-TASC adopts guidelines provided by AACE (1997) to specify appropriate ranges based on the cost uncertainty score. Table 7.9 presents the range specifications based on the cost uncertainty score. For the classification of the cost uncertainties, the tool adopts the considerations for the degree of project definition as explained in Section 7.2.3. This characteristic is based upon percent complete of project definition or engineering. U-TASC considers the level of project definition from the perspective of uncertainty, which is represented through the cost uncertainty score.

Table 7.9 Range specification based on the cost uncertainty score

Estimate class	Level of project definition	Methodology	Lower uncertainty value	Upper uncertainty value	Range-Minimum (%)	Range-Maximum (%)
Class 1	50% to 100%	Deterministic	0	0.3	-10	15
Class 2	30% to 70%	Primarily deterministic	0.3	0.5	-15	20
Class 3	10% to 40%	Mixed but primarily stochastic	0.5	0.7	-20	30
Class 4	1% to 15 %	Primarily stochastic	0.7	0.9	-30	50
Class 5	0% to 2%	Stochastic or judgment	0.9	1	-50	100

The level of project definition is considered across 5 classes as explained in Section 7.2.3. This arbitrary “countdown” approach considers that estimating is a process whereby successive estimates are prepared until a final estimate closes the process.

#### Defining the Three-point estimate

This phase combines information including the minimum and maximum range suggestions, with actual cost considerations. U-TASC requires the cost estimate to be

generated from an alternative source and treats it as an input. In order to provide flexibility, two levels of granularity are defined where initially it is assumed that due to the lack of project maturity cost estimates for each cost driver has not yet been calculated. For this scenario principles from the AHP are applied in order to define the percentage significance of each cost driver over the total cost. This in turn, gets used to allocate the total cost estimate at the project or system/subsystem level that is inputted based on calculations from an alternative source. At the second level of granularity the user inputs the cost estimate for each of the cost drivers, which enables to calculate the maximum and minimum cost figures using the range suggestions. The approach adopted to assess the uncertainty weights is explained in Section 6.4.2 (Uncertainty weight). The significance assessment of cost drivers also follows the same approach.

#### **7.2.4 Monte Carlo Simulation**

U-TASC conducts the Monte Carlo simulation through in built algorithms in MS Excel, which yield cumulative probability distributions, including uniform, triangular and PERT-Beta. The cumulative probability distribution refers to the probability that a real valued random variable  $x$  with a defined probability distribution will fall below or equal to  $x$ . The types of distributions offered in U-TASC, were selected driven by the available input, including minimum, maximum and most likely (or mode) cost estimates. These values enable to define the nature and characteristics of the entire distribution. For each distribution 2000 simulation runs is applied. The amount of runs was determined based on industrial interaction, and this figure was considered to be sufficient for a detailed representation of uncertainty. Furthermore, the PERCENTILE function in MS Excel was used to capture the cost level for the desired level of confidence. A percentile refers to the value of a variable below which a certain percent of observations fall.

##### **Triangular distribution**

Triangular distribution has a lower limit, mode and an upper limit, which is a continuous probability distribution. In simulation in order to generate a cumulative



probability a random number between 0 and 1 is necessary in order to include a random variate. As the formula for the triangular distribution has reference to the random number generation, RAND(), more than once, therefore, the random number is computed externally because for each run the same random number needs to be considered in the formula. The formula would use the IF() function to determine which side corresponds to the random number generated. The structure of the IF function is:

=IF(expression, what is returned if true, what is returned if false)

The IF() function is used to determine which side corresponds to the random number generated. For the triangular distribution, the formula firstly examines the side of the distribution to the random number and then evaluates the appropriate formula.

x=random number;

y=left sided range; z=right sided range; i=range

m=minimum cost estimate for a cost driver;

n=maximum cost estimate for a cost driver

=IF(x<y,  
m+SQRT(x\*y\*i),  
n-SQRT((1-x)\*z\*i))

### **Uniform distribution**

The uniform distribution uses the minimum and maximum cost estimates. A random variable is used to select between these two estimates. The uniform distribution is computed using the algorithm provided below:

x=minimum cost estimate for a cost driver;

y=maximum cost estimate for a cost driver;

z=random value

=x + z\*(x-y)

## **PERT/Beta distribution**

The PERT distribution can be constructed when the minimum, most likely, and maximum cost estimates are available. The provided values may result in a close fit with the normal or lognormal distribution. This distribution is considered to be an alternative to the triangular distribution. Some differences exist between the two distributions. For instance, the standard deviation of a PERT distribution is less sensitive to the estimate of the extremes. Furthermore, PERT distribution has an emphasis on the maximum value and has minimum emphasis on the outliers. On the other hand, the uniform distribution puts the most emphasis on the outliers. The triangular distribution puts a lesser amount of emphasis on the outliers, where the emphasis is on the most likely value. The calculation of PERT requires the percentile value, Shape A, Shape B, minimum and maximum cost estimates, which are all used in the BETAINV function in MS Excel.

### **7.2.5 Future uncertainty expectation**

U-TASC also enables to visualise the change in uncertainty over time by asking the subject matter expert the future expectation of the degree of uncertainty. The input is a percentage reflection of how the cost uncertainty score is expected to change given various time frames including ‘up to 1 year’, ‘between 1 and 2 years’, ‘between 2 and 5 years’, and ‘over 5 years’. The suggested percentage change is used to revise the cost uncertainty score, which subsequently similar to Section 7.3.4 the suitable range from the AACE (1997) guidelines is realised. With the calculated minimum and maximum cost values, this feature of U-TASC applies the Monte Carlo simulation to represent the variation in cost over time.

## **7.3 Iterative Development and Initial Validation**

As explained in Section 6.5 a number of initial validation sessions were conducted with subject matter experts across industrial collaborators. In common it was observed that

the respondents highlighted that the ability to turn a single point estimate into three in a justifiable manner offers opportunities across the supply network.

For this Chapter an additional validation session was organised with Organisation D, which enabled to assess aspects related to the framework such as generalisability, usability, benefits, limitation, logical considerations and reliability of outputs. Two participants from Organisation D participated in the validation, which involved a semi-structured interview that the respondents were asked to score between 1-10 and to comment on in a questionnaire to illustrate the suitability of the framework and U-TASC. The questionnaire is provided in Appendix A. An overview of the respondents is provided in Table 7.10.

Table 7.10 Overview of respondents participating at initial validation

Organisation	Job role of attendee(s)	Experience (Years)
D	Through life analysis expert (Assurance)	25
D	Integrated logistic support manager	18

The respondents indicated that the applied cost uncertainty modelling framework was logical (receiving a score of 8 out of 10) and that it improved current considerations. Furthermore, it was mentioned that the tool was suitable for the bidding stage, particularly the early stages. Concerning applicability of U-TASC across various stages of the bidding process the respondents highlighted that the tool would be suitable. This was further clarified, as the framework was mentioned to be highly generalisable.

The application of U-TASC was suggested to be potentially used by prime's and leading suppliers, where departments involved in cost estimating were referred to take responsibility of using the tool and in conducting regular maintenance. The key benefit of the framework was referred in relation to the support that is offered with reflecting the influence of uncertainty on estimates. Furthermore, the three point estimates were suggested to be useful in guiding with the selection of the mitigation approach. The interlinked approach taken between cost uncertainty modelling and management were suggested to be beneficial from this perspective.

Concerning the usability of the software prototype the respondents emphasised the ease of use driven by the application of MS Excel, whilst mapping between features was suggested to be a weakness. Furthermore, the considered terminologies were considered to be clear and sufficient guidance was suggested to be provided in the tool. In terms of assessing the framework, whilst the responses are presented in Table 7.11:

Table 7.11 Overview of responses from the initial validation

Topic	Score – Out of 10	Comment
List of uncertainties	8	The respondents were not able to suggest any additions to the list. Though, in order to get the full score it was suggested that organisations, driven by the specific requirements of contracts, may need to incorporate additional uncertainties.
Uncertainty level calculation through NUSAP	9	It was emphasised that the standardisation of measuring uncertainty and storing the justifications would enable consistency in uncertainty considerations at an organisational level. Furthermore, it was suggested that training the users to score uncertainties would further enhance the applicability.
List of cost drivers	9	It was recognised that within a service context the terminology and scope of cost drivers can drastically vary driven by project needs and personal considerations. Though, the list was specified to depict a common and comprehensive perspective of costs.
Associations between the uncertainties and cost drivers	7	It was mentioned that the sources of uncertainty in cost drivers was less direct and many sources with varying degrees of influence could affect the costs. Whilst the specified relationships were considered to be reasonable, the respondents mentioned that when adding new cost drivers the users of the tool would need to specify relationships, which would need to be documented. Furthermore, it was highlighted that standard associations had not been specified in this organisation, though benefits were suggested in managing uncertainties.
Suitable ranges through AACE (1997)	9	Whilst the respondents agreed with the suggested ranges, it was indicated that it offered a standardised measure to classify the influence of uncertainties into different range groups. Furthermore, it was suggested that the approach would also facilitate recognition of the changes in the degree of uncertainty over time.
Using AHP for significance analysis	9	The provided definitions for the scores were highlighted to be sufficient in guiding the respondents to specify the significance of uncertainties and cost drivers. Though, training was suggested to be needed to fully acknowledge the scoring mechanism, along with further transparency in the derived results.
Process of turning a single point estimate into three	9	The respondents were particularly satisfied with the transparent approach in reaching the three point estimates. This was suggested to enable an iterative process during bidding by enhancing communication with the customer. Though, it was suggested that it would be beneficial to promote collaboration across experts to fill the tool.
Outputs from Monte Carlo simulation	9	The outputs were suggested to follow the current practice. The respondents highlighted that commonly guidance in interpreting the results from Monte Carlo simulation was needed and the systematic process provided in the tool offered better understanding of outputs.

## 7.4 Summary

In Section 7.1 the reader was presented with an overview of cost estimation and the role of uncertainty. It was indicated that Three-point estimating was a commonly followed approach to recognise the influence of uncertainty on cost. Furthermore, a number of challenges associated to their development were highlighted, where it was emphasised that subjectivity was involved in defining ranges and required systematic approaches to recognise the degree of uncertainty influence.

In Section 7.2 the author presented the methodology of developing the bid cost uncertainty modelling framework. The author presents six phases that were involved during this process: (1) Phase 1: Developing the uncertainty level, (2) Phase 2: Linking uncertainties and cost drivers, (3) Phase 3: Define range for cost drivers, (4) Phase 4: Define Three-point estimate, (5) Phase 5: Calculation of Monte Carlo simulation and distribution selection, and (6) Phase 6: Refinement. For each of these phases the conducted workshops, semi-structured interviews and the gathered results are presented.

In Section 7.3 the actual bid cost uncertainty modelling framework is presented, whilst covering a step by step procedure including: (1) developing the uncertainty level, (2) linking uncertainties and cost drivers, (3) defining the range for cost drivers, (4) defining the Three-point estimates and (5) Monte Carlo simulation. The author for each of these aspects explains the steps required to achieve outcomes.

Section 7.4 presents the initial validation outcomes whilst focusing on results from interaction with two participants from Organisation D. The interaction was achieved through a semi-structured interview, where the respondents provided feedback about the framework through a questionnaire. Information concerning the framework was gauged from a number of dimensions including: generalisability, benefits, limitations, usability, and the reliability of the results. The respondents indicated that the framework was comprehensive with its approach across the key features of the framework.

In the following Chapter the author presents an application of agent based modelling to cost estimation through a developed model that focuses on the impact of incentives and the influence of dynamic uncertainty within the CfA context.

## **8 DYNAMIC UNCERTAINTY BASED COST ESTIMATING**

This chapter aims to contribute to the decision making in integrating dynamic uncertainty to service cost estimation by providing a novel approach through agent based modelling (ABM) for the early stage of bidding for Contracting for Availability (CfA). The chapter presents the ABM architecture describing the agents that represent the customer, industry and suppliers, which captures responsibilities in areas including failure, repair, spares supply and availability management. Furthermore, internal and external rules are defined to capture the interaction between the cost drivers. The major outcome relates to the robust “what-if” scenarios of the dynamic interplay among the many cost uncertain elements. The approach is a unique addition to the cost estimation literature by enabling to capture dynamic patterns and effects which have cost impacts during the service delivery. The remainder of the chapter has been organised as follows. The chapter initially presents the context of CfA in relation to the need for advanced techniques that can capture the dynamic nature of services and their impact on cost. Section 8.1 explains the adopted methodology in light of the developed model. The architecture of the agent based model is presented in Section 8.2, where a link is also formed with U-TASC. The validation through expert judgment and a pilot case study is presented in Section 8.3. The validation results reflect the increased understanding and precision in decision making for costs within a major company in the defence industry.

Whilst there are many types of services that are offered including health check, obsolescence management, defect response, performance assessment, provision of spares and repairs is the most widely offered service within the defence industry, which sets the context to this chapter. Uncertainty is considered in association to service requirements early on during the bidding stage where limited information and knowledge exists. Some of the main areas that influence the service cost estimation includes equipment usage rate, failure rates, repair turnaround time, beyond economical repair, no fault found, obsolescence rate and labour efficiency as well as financial measures such as exchange and inflation/deflation rate. Considering that industry

traditionally was not responsible for most of these engineering tasks, capturing the dynamism of these uncertainties has created challenges. Furthermore, the dynamism refers to the evolutionary characteristics of uncertainties that influence costs. The factors causing the evolution may include the equipment life cycle and equipment usage conditions. The adoption of CfA, due to heavy financial responsibilities incurred by the OEMs and growing contractual complexities, has increased the importance of visualising maintenance costs under various scenarios in deciding the incentivisation scheme to follow. In CfA incentives may be devised in various forms including (Caldwell and Zheng, 2009):

- Contractual incentive mechanisms: e.g. revenues sharing contracts
- Relational incentive mechanisms: e.g. repeat business, reputation effects, information exchange and knowledge sharing
- Fixed price: cost-plus contract and performance-based contracting
- Performance and cost-sharing incentives change over time

Across the approaches, particularly Target Price Performance Incentive (TPPI) has received much interest due to its focus on giving a price sufficiently stable at contract signature to allow internal approvals. Furthermore, it builds flexibility as the price may change with varying equipment usage levels. The approach also provides a financial motivation and simple share-out mechanism across partners, which has been considered to be beneficial. Given that CfAs are typically agreed based on incentive mechanisms, it is necessary to realise their cost implications early on at the bidding stage. The challenge is driven by two aspects. Firstly, there is dynamism associated to cost, which is driven by a number of uncertainties that trigger the variability over time. An example involves the number of failure events, which are not static over time (e.g. 10 events) and face a different range (likelihood of occurrence) over time (e.g. -10/+25%). Secondly, the behaviour of the supply chain affects whole life cycle cost, particularly due to the activities that takes in operationing and supporting the equipment. For instance, if the actual cost of the spares supplier is below the 3% profit level it triggers the risk sharing mechanism to allocate the excess costs across the solution provider and supplier over time. Thus, there is a need for improved estimating techniques that can take account of the increased range and scale of uncertainties that is typically experienced in CfA.



This chapter contributes by applying ABM to reflect the dynamism in maintenance costs across the supply network in a novel manner early on in the bidding stage of CfA. The model considers a Target Price Performance Incentive (TPPI) mechanism to demonstrate the relationship between the customer and the OEM. This incentive approach considers a fixed-price incentive contract, which typically specify a target cost, profit, a price ceiling (but not a profit ceiling or floor), and a profit adjustment formula. In order to negotiate these elements it is necessary to be able to visualise cost estimates at the outset. Furthermore, the relationship between the OEM and suppliers is considered to vary across different risk sharing options. The following section presents the detailed methodology followed to develop the agent based model.

## **8.1 Detailed methodology of developing the agent based model and initial observations**

This chapter advances the cost estimation literature by integrating a systematic approach across uncertainty identification, assessment, range definition and simulation for maintenance cost estimation specifically for the early stages of bidding. Using agent based modelling for this purpose sets a novel approach, due to its limited use in the cost estimation literature. The methodology for this chapter consists of four key steps, including (1) literature review, (2) industrial interaction, (3) framework development and (4) validation. Figure 8.1 illustrates the activities that took place in each step.

A number of advantages of adopting the ABM approach have been recognised from literature review including (1) enhanced realism, where agents can be made directly comparable to machines, organisations, or people, which enable easier understanding of the problem at hand in an empirical manner; (2) includes heterogeneity by avoiding a homogeneous approach in aggregating different agents' behaviour into average variables. For instance, the customer, OEM, spares and resource suppliers follow a different set of activities and aim to achieve different targets; (3) includes bounded rationality, which is driven by taking the degree of available information as a boundary that influences decision making; (4) promotes scalability and flexibility, whereby agents and systems can be developed separately and in several stages until the query of interest

is fulfilled. Furthermore, there is flexibility in this process when adding new agents, particularly of similar type. On the other hand, a disadvantage can include the required level of detail that may become too burdensome with relatively high costs in both time and effort compared to equation based models (Swaminathan et al., 1998). Furthermore, the large size of data input (Bonabeau, 2002) can in some cases cause difficulties in understanding whether the produced results have a programming error or useful information. The model tends to be developed for a particular context and any application in other areas may not be possible (Swaminathan et al., 1998). The ABM approach investigates the characteristics of phenomena at the lowest possible level of granularity, where the behaviour of each of the participants across the supply network may change over time, which may promote the model to be updated on a regular basis. The update may require the rules, states, and other types of data to change in order to adjust to the modelled reality. An additional area of challenge is associated to the need for knowledge of programming languages.

The second phase involved the development of the research protocol through industry. The ABM development was an extension to the presented work in Chapter 6 and 7. The extension refers to providing an additional option to the user (from the OEM perspective) of U-TASC in terms of taking a step forward to understand the cost implications of the interaction across the supply network. This requires further information relating to the contractual arrangements (e.g. cost per equipment flying hours). U-TASC feeds into the ABM with the selection of the cost drivers, the cost estimates, and the calculated range specifications. Additionally, the application of ABM aims to reflect an approach to capture the dynamism in cost within the service context. The outputs from ABM are particularly developed to get an understanding of the cost implications of various contractual options. The application of ABM is not considered to be a rival to the typical approach of Monte Carlo simulation, but a complement in order to get a better perspective of cost at the early stages of bidding.

The interaction with industry concerning the ABM development centred on five key areas, including (1) formation of contract scope and contents, (2) defining rules that guide the interaction between the agents, (3) determination of the beneficial outputs, (4)

development of assumptions, and (5) specification of key uncertainties to be included in the agent based model. Furthermore, the presented findings in Chapter 6 and 7 particularly supported with the first, third and fifth areas of interest. In order to capture the specified information in the other areas four interviews were conducted.

The initial meeting was conducted with participants from Organisation D, as illustrated in Table 8.1, whom both had a high degree of experience in contracting. The aim of the meeting was to establish the process of contracting in order to understand the interaction across the supply network and the way in which a TPPI gets considered.

Table 8.1 Participants of the initial meeting

Participants	Meeting Duration (Hours)	Job role of attendee(s)	Experience (Years)
Organisation D	3	Through life analysis expert (assurance)	25
		Contracting manager	16

The respondents highlighted that the differences in CfA from traditional contracts centre on co-operation and partnering. For instance, the customer’s staff may work at the OEM’s facilities, which refers to Government Furnished Assets (GFX labour). During this meeting the differences across the contracting approaches were presented as:

- Target price: monitors how much money is spent, where actions are taken when below or above a target
- Firm price: the price does not change over the course of the contract
- Fixed price: has a firm element, but majority can change driven by variations in indices (e.g. titanium price)

It was mentioned that a target cost enables to distribute the incentive fee and the penalty level between the customer and the OEM, which is typically arranged between these two parties. In a particular project it was highlighted that the program had developed a risk management function in order to manage the target cost incentive. The success in delivering services was highlighted to be associated to the selected KPIs. It was suggested that the contracting process is driven by agreeing KPIs in an affordable and

profitable manner, whilst uncertainty prevails in the interaction. For an example project the following KPIs were suggested to be highly relevant:

- Availability of platform
- Spares for form fit and function
- Query answering, which is the only metric that requires qualitative information

The customer starts the information flow by providing an indication about the required level of equipment usage (e.g. flying hours) for the following year. This then is transformed in to fixed and variable costs (e.g. spares and labour requirements). From this point onwards continuous trade-off analysis between performance, cost and risk or uncertainty is made in order to bid for the most beneficial contract, which enables to develop long term relationships.

The second meeting was conducted with a project manager at Organisation A, whom had over 25 years of experience in contracting across the naval and air domains. The respondent was selected due to his high involvement across the contracting process in various aspects including cost estimation, setting contractual clauses, and affordability assessments. The meeting lasted for an hour, where the focus was on determining the major areas that are considered in CfA. It was suggested that in CfA the incentive could be applied to either performance/output or cost. In terms of performance a direct link with payments was suggested, which causes a variation in income for the OEM. Furthermore, the key measure of performance was suggested to be the degree of availability. The major challenge in delivering CfA was suggested with regards to the alignment across the supply chain, where variation in customer budget has knock-on effects. It was suggested that in order to avoid the divide of losers and winners in CfA, better understanding of how risk and uncertainty gets shared is required.

An overview of attendees at the third meeting is presented in Table 6.10. At the workshop, application of ABM to the context of CfA was queried. The respondents were selected due to their high degree of experience in the cost estimation processes particularly in the service context. It was highlighted that the agent based model should be developed based on the projects' business model. Furthermore, the need for generic

performance measure was emphasised. A perspective for the application of ABM was suggested in terms of scaling the nominal performance (e.g. availability level) with a view to understanding the earned value or schedule adherence. The respondents highlighted that ABM would be particularly beneficial in understanding the interaction across the supply network. The key aspects that trigger the interaction were suggested to include: incentive mechanism, failure rate, GFX labour, storage capacity, spares and resource requirements. Along these lines the base usage was suggested to consider the influence of both planned and random failure events. The benefit of the model was considered to be in the calculation of the initial total cost, where a view on the implications across the supply chain can be visualised.

The fourth meeting was conducted with a reliability engineer from Organisation G with four years of experience in the uncertainty field. The respondent was selected due to his high experience in modelling uncertainty using different approaches including ABM. The focus of the interview was on defining the suitable variables and assumptions. Some of the key results of the interview included:

- A multiplier could be considered for the number of spares occurrence for a given time duration in order to compare the actual and the expected level of failures
- The cost drivers that are selected in U-TASC can be allocated into three cost buckets including resource, spares and other (e.g. training) in order to differentiate the sources of cost
- Failure rate should be the main source of uncertainty in the model, which should be reflected through a three point figure
- Capture the variation in failure rate over time (e.g. 10 failure over a year), whilst managing these variations through a timer in the model
- Associate the failures with costs in order to consider an average cost level for a part of a system
- Have two sources of variation (1) per event variation (e.g. number of events), (2) failure (event) variation (e.g. distribution of event over time). The dynamic cost estimation process presented in this chapter is based on these premises
- The agent based model can be used at the early preliminary stage in order to visualise the interaction across the supply chain

- Store results from AnyLogic in an array in visual basic in order to make further analysis with increased availability of data

In light of the presented interactions with industry a number of assumptions have been developed in order to limit the scope of the model. To begin with the model is developed with the assumption of peace state and war scenarios are not considered. This assumption is a typical consideration in CfA, though measures tend to be built in order to have the flexibility in case a war scenario arises. The other assumptions include:

- The customer and solution provider have TPPI arrangement: this sets the context of the model, where information related to the TPPI arrangement (e.g. number of flying hours) is required as an input
- No cannibalisation: due to the focus on a particular equipment or system the practice of removing parts or subsystems necessary for repair from other similar devices is not considered
- The spare consumption rate is assumed to be stochastic and expressed as a probability distribution attaining values from 1 onwards: This sets the means of the variability, which is an input from U-TASC
- A certain amount of technical investment is necessary to reduce spare costs for both the supplier and the solution provider. The technical investment is used as a means to build communication between the OEM and the spares supplier

The third phase focused on framework development of the agent based model, whilst bearing in mind the outputs from U-TASC. During this process the scope of the simulation was decided and the rules and assumptions for the agent based model were developed. This process involved three subject matter experts in the naval domain. The rules and assumptions were defined to represent interaction between the considered agents, while focusing on the key sources of uncertainties and cost drivers. The model was constructed using AnyLogic, a Java based multi-paradigm software. The reason for selecting AnyLogic is driven by the multi-paradigm environment, which can combine various simulation approaches including system dynamics, discrete event and ABM. Furthermore, the software package provides a suitable means to visualise the changes in costs across the defined agents. Furthermore, it supports limitless extensibility including

custom java code, external libraries, and external data sources and it has widely been applied across industry.

The final phase of the methodology involved validation. Through initial validation the model was updated. Additionally, expert opinion from four participants of the research and a pilot case study was conducted to gather feedback about the model. The model used in the case study was validated in stages. Initially, the rules and assumptions were validated with three subject matter experts (participants of three different projects in the naval domain) whom on average had over 20 years of experience in maintenance cost estimation. Expert opinion was also used to define the benefits, weaknesses and potential areas to use the model. An initial validation with participants from Organisation A was attended by a Principle Reliability Specialist with 20 years of experience and the Cost Modelling Lead who had over 30 years of experience. It was highlighted that in the naval side availability refers to the platform/equipment at specific time and it was emphasised that in the model the focus was at the equipment level. Some of the feedback that was received included:

- Add input variables to reduce the input directly in AnyLogic. Furthermore, collate the input in the MS Excel file that bridges U-TASC and AnyLogic
- In the OEM agent for the cost plots need to write the axis

Driven by the literature review and the industrial interaction the following challenges were identified, which led to the development of the model, which cocentrates on the specific case of CfA:

- Understanding the influence of uncertainties on cost drivers on an individual and collaborative basis
- Representing the variation of cost over time
- Developing sound contracts which enables to compare different cost options and relationships across the supply network
- Understand cost of CfA by considering how cost varies with different performance levels and how this can be used during bidding
- Better understanding of service delivery by considering the interaction across the service supply chain. Some of the issues associated to the supply chain

include: sustainability of the supplier, cost effectiveness, timely and quality provision of service, and the dynamic nature of the service supply chain.

## **8.2 Dynamic Uncertainty Based Service Cost Estimation Framework**

The agent based model aims to visualise the interaction across the supply network with respect to cost implications at the bidding stage of CfA in the defence industry. The supply network is considered to be composed of the customer, solution provider/OEM, and suppliers including resource and spare. Among the suppliers an emphasis is laid on the spares supplier, due to its significant contribution to the OEM in meeting the required equipment availability level. The relationship between the customer and OEM is governed by the TPPI incentive mechanism, and the relationship between the OEM and the spares supplier is driven by the risk sharing mechanism. These relationships were specified due to their wide application across agreements of CfA. The model also builds an approach to recognise the dynamism that the OEM faces with the spares and resource requirements that are associated to failures. This feature aims to represent the implications of the dynamic nature of service requirements. The dynamic nature of services has commonly been documented across the literature as discussed in Chapter 2. Furthermore, this aspect was often highlighted as a challenge influencing cost estimation during industrial interaction as explained in Chapter 4. The dynamism considered in the model refers to the evolution of the uncertainty associated to the number of failure events that take place over time, and the variation in the likelihood of these events materialising. Thus, the model concentrates on three aspects, which are associated to the relationships between the agents:

- The implications of the agreed incentive mechanism between the customer and OEM
- The dynamism in the uncertainty associated to failure rate that the OEM faces. As an implication of this, through the risk sharing mechanism the costs incurred by the spares supplier shifts. Through the incentive mechanism the customer gets affected
- OEM and spares supplier interaction through a risk sharing mechanism, given the uncertainty in the spares requirements. Along these lines, various scenarios



are considered: (1) solution provider owns uncertainty, (2) spares supplier owns uncertainty, (3) solution provider and spares supplier share uncertainty

As an outcome of the model the evolution of maintenance costs for various time scales including the life cycle of equipment, a specific mid-term, or for the short term can be represented. However, the minimum time scale of the model is a year. Furthermore, orders can be raised sequentially at different points of time. The granularity of the model is considered to be the system or subsystem level due to the limited amount of information that is available at the early stages of a bid.

### **8.2.1 Architecture of the agent based model**

Information is initially generated by the customer agent concerning the equipment usage level and the price that varies based on equipment usage. The customer provides this key information to the OEM. Subsequently, based on the dynamic failure rate, the OEM sends messages to the spares supplier to source the amount that is above its given spares and resource capacity. In parallel, the actual and expected cost calculations for the OEM are made. The information that the OEM receives from the customer feeds into deciding the incentive level through the gain/pain level. This consideration is based on the difference between the actual cost and price that the customer pays for the equipment usage level. On the other hand, the OEM is able to choose a form or risk sharing with the spares supplier and variation in associated costs can be observed. Furthermore, capturing such information can assist in building relationships between the OEM and the spares supplier. Figure 8.1 represents the agents and the main aspects that trigger interactions between agents. Each agent has many parameters and variables, which serve the purpose of defining associated characteristics and what-if scenarios can be performed by adjusting them.

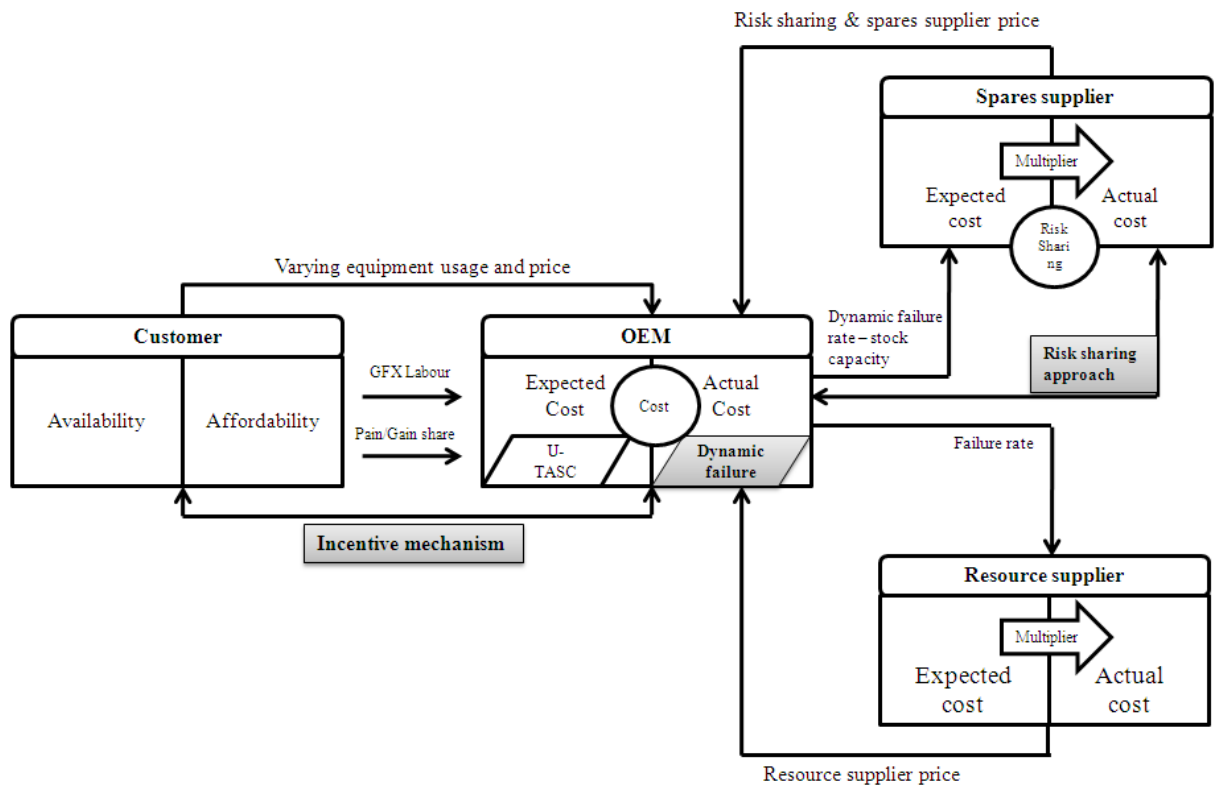


Figure 8.1 Relationships in the agent based model

The following subsections outline the considerations for each of the presented agents and the interactions between the agents.

### Customer agent

The customer agent aims to achieve an equipment usage level as specified in a CfA. Accordingly, as an input a pre-defined level of price is used for the equipment usage level. The model assumes that the equipment usage level will comply within a given boundary. So the customer agent requires input regarding the price that it will pay for the various levels of equipment usage (e.g. for 30,000 hours of flying=£30,000, and 32,000 hours=£32,000). The variation in the usage level is achieved through a random number generator between these ranges. In order to capture these variations variables such as ‘price or actual cost to customer’, ‘total usage required’, and ‘total actual usage’ are considered to be inputs to the model. An additional variable that is an input is “GFX labour”, which aims to calculate the labour contribution of the customer during the CfA delivery. This constitutes the additional cost to the customer agent and is deducted from

the value generated. The final input for the customer agent is the pain/gain share level that gets considered in the contract. This is driven by the profitability of the OEM and, it can derive savings or additional costs for the customer.

The second set of variables considered in the customer agent includes outcomes experienced from the received service in a contract. The variables include “affordability”, “availability” and the “value” that is attained. The variable “value” enables to measure the performance of the supply chain. This takes into account the savings through the pain/gain mechanism, price that take into account the escalation (e.g. 5%) and the “GFX Labour” provided. Thus, it represents a net benefit to the customer. The “availability” variable is a representative at the equipment level, whilst a comparison between the actual and targeted level of equipment usage is considered. The “affordability” variable is calculated based on a comparison between the price paid to the OEM and the actual cost to the OEM. The calculation that is performed for affordability in AnyLogic is represented below, whilst an overview of the codes used in the model are provided in Appendix G:

```
Affordability=Price-ActualCostOEM;  
  
if (Affordability>0) {  
    PercAffordability= 1;  
} else {  
    PercAffordability = Price / ActualCostOEM;  
}
```

Figure 8.2 represents the variables in the customer agent, whilst also showing the interactions between these variables. The variables are classified into: input, output, and source of variability. The variability (e.g. demand) can affect input variables (e.g. equipment usage required). Furthermore, within the customer agent the outputs are with regards to customer value, affordability and equipment availability. For instance, in the case of customer value, the calculation is based on the difference between actual customer cost and the expected cost, whilst the pain/gain share might also have an influence. The software package enables to select suitable variables and to assign relationships between these variables in a flexible manner.

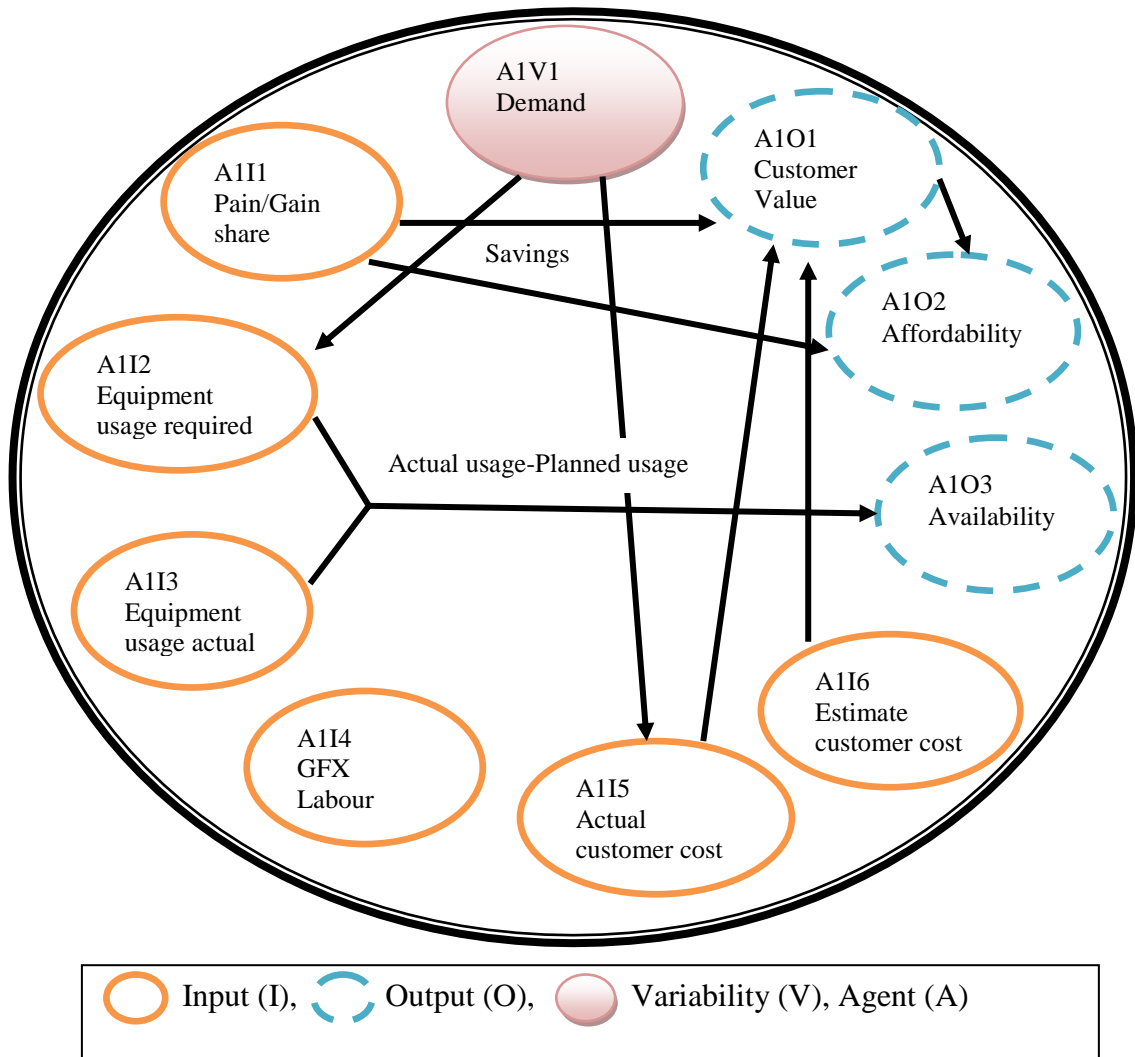


Figure 8.2 Overview of the interaction between the variables within the customer

### Interaction between the customer and OEM agents

In the interaction between the customer and the OEM, the incentive mechanism plays a critical role in determining the actual cost estimate for support, which is considered to compose of resource costs, spares costs and other costs. The incentive mechanism is achieved through the arrangement of TPPI between the solution provider and the customer. This involves consideration of variable costs (e.g. spares inclusive repairs) subject to 50:50 gain and pain share while keeping aside a certain level of savings. The threshold for the gain and pain share levels is 10% and 3% profit for the OEM. This is calculated based on the difference between actual cost and payment or price for variable

costs which are adjusted annually based on changes to contract assumptions. Annual adjustment can also compare baseline cost/risk against actual cost/risk spend to calculate implications of the specified pain/gain share. The structure of the TPPI is shown in Figure 8.3. It is worth recognising that the considered concepts are based on the air domain; however the principles apply to other domains as well. Within the TPPI, a differentiation between variable costs and fixed costs is considered, as different measures are taken between stochastic and fixed costs in the pain and gain share mechanism (e.g. any cost increase with fixed costs is the responsibility of the OEM).

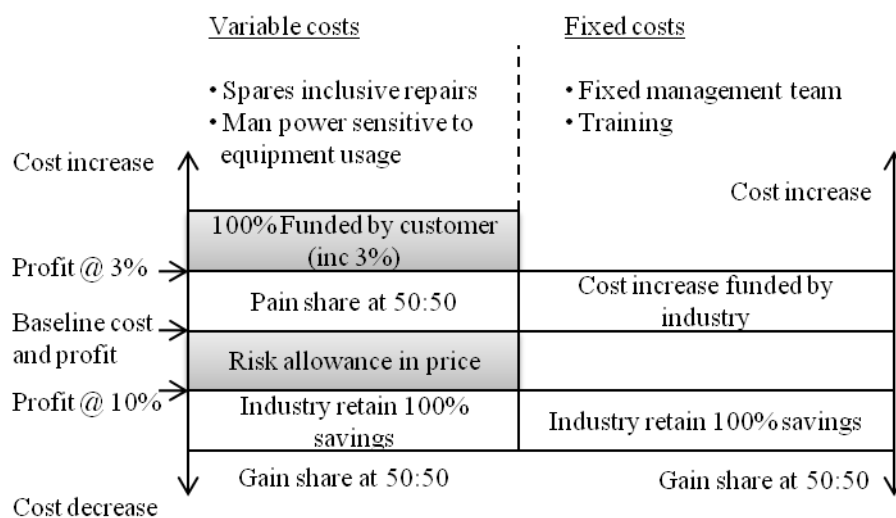


Figure 8.3 Adopted Target Price Performance Incentive mechanism (Erkoyuncu et al. 2010d)

Along these lines, the model assumes that initially a price is set for pre-defined equipment usage (e.g. flying hours) levels. The price and payment for variable costs are adjusted annually from baseline if projected equipment usage differs from contract assumptions. Furthermore, annual adjustment also compares baseline cost/uncertainty against actual cost/uncertainty spend to calculate either pain or gain share. Annual adjustment compares baseline cost/uncertainty against actual cost/uncertainty spend to calculate gain share. Industry is expected to attain profits between three and ten percent and any deviation from this range cause implications for Industry and the customer by means of savings or additional costs. The variable costs are subject to 50:50 pain/gain share keeping aside a certain percentage for profit. The only information that the

customer agent sends to the solution provider is the price that it will pay for the level of equipment usage and the pain/gain share level. This information embeds the amount of equipment usage requirements. A rule that triggers the “price” information from the customer to the OEM is presented below. A target price level for a specified level of equipment usage is defined and along with this a boundary is specified for the potential equipment usage levels:

```
Contract t = new Contract();
TotalUsageReqd=D1; (Most likely equipment usage)
Price=P1; (Most likely price for equipment usage)
    if(x)TotalUsageReqd=D2; (Maximum equipment usage)
    if(y)TotalUsageReqd=D3; (Minimum equipment usage)
        if(x)Price=P2; (Price for maximum equipment usage)
        if(y)Price=P3; (Price for minimum equipment usage)
t.Qty=TotalUsageRequired;
t.Rate=Cost;
```

### **Original Equipment Manufacturer agent**

The OEM agent is considered to be at the centre of the supply network in terms of distributing information. This agent interacts with both the customer and the suppliers. Driven by this classification there are two sets of variables within this agent, whilst the variable representing “failure rate” has a central feature, as variation in this variable affects both the incentive mechanism and the implications of the risk sharing with the supplier. The first set of variables concentrate on calculating the actual cost, which is also associated to the suppliers’ contribution. The second set of variables focus on building information for the incentive mechanism.

A detailed consideration of “failure” is represented in the model, by defining dynamism in this uncertainty. The dynamism is achieved by varying both the number of spares events over time and the associated uncertainty around the failure expectations. As represented in Table 8.2, the uncertainty around the number of events follows the suggested percentage boundaries. These values follow the AACE guidelines that were

illustrated in Chapter 7 and were acknowledged to be suitable for the bidding stage. One thousand simulation runs are considered to cover a ten year period. Furthermore, each hundred runs constitute a year. For up to year 3 the number of spares events is set at 1, which represents 10 failure events for the given time duration. Additionally, the distribution to represent the variation around this figure is captured through a triangular distribution (1.15, 1, 0.9) and represents the number of failure events that take place on a yearly basis. Table 8.2 focuses on the applied variability in terms of maximum and minimum in percentage values for failure events across the given time durations. The time frame has been fixed at 10 years because it represents a reasonable length of time in CfA until a further review takes place.

Table 8.2 Ranges to capture uncertainty in number of failure events over time

	<b>Year 3</b>	<b>Year 5</b>	<b>Year 7</b>	<b>Year 10</b>
<b>+%</b>	15	20	30	50
<b>-%</b>	10	15	20	30

The failure rate has an initial value of 1 and depending on the rate of change in the spares requirement level, the technical investment changes equally through a multiplier. So if the number of events raises from 1 to 1.5 the technical investment needs to increase with the same proportion in order to avoid any extra spending in procuring from the supply chain and facilitating in-house repairs like more stringent inspection to avoid events such as no fault found. This is a dynamic process, which requires recognition of actual requirements for spares or repairs against the contracted amount. On the other hand, dynamism is also associated to the number of failure expectations over time. As presented in Table 8.3, the number of failures increases over time, with the assumption that increasing equipment operation causes enhanced failures.

Table 8.3 Structure for applying dynamic uncertainty based cost estimation

<b>Simulation run (e.g. years or for 1000 runs)</b>	<b>0-3</b>	<b>3-5</b>	<b>5-7</b>	<b>7-9</b>	<b>9-1</b>
<b>Event (distribution for failure events) through Triangular distribution</b>	1.15, 1, 0.9	1.2,1,0.85	1.3,1,0.8	1.5,1,0.7	2,1,0.5
<b>Number of failures over time</b>	0.2	0.4	0.6	0.8	1

The considerations for dynamism aim to illustrate an approach to assess uncertainty in a comprehensive manner by reviewing the number of failure events and the uncertainty associated to these expectations over time.

The first set of variables focus on calculating the actual cost. These trigger communication between the solution provider and the suppliers, whereby a shift in failure rate may cause to move away from the estimated or expected level of requirements and the OEM obtains the excess from the suppliers. The actual cost is calculated as a sum of the cost generated from the spares and resource suppliers, “other costs” and the cost that arises from using in-house capacity, whilst GFX labour is deducted from the associated costs. “Other cost” represents one of the expected cost level variables, which involves inputs from the Uncertainty Tool for Assessment and Simulation of Cost (U-TASC), as is covered in Chapter 7, concerning the cost estimates and range values for cost drivers such as training, LRU cost and transport cost. The “Other cost” estimate represents the expected cost level and is assumed to be equal for both the expected and actual cost considerations. There are two additional variables that aggregates cost estimate information including: spares and resource costs. The sum of these variables constitutes the initial total cost, and this value is used in calculating the cost that is generated in using in-house capacity for spares and resource. Furthermore, there is an assumption that the in-house capacity can accommodate between 15 to 20% of the actual spares and resources request and the rest is sourced from the suppliers. The estimate value for spares is made up of cost drivers such as storage cost, material availability, and turnaround time. The estimate value for resource involves cost drivers such as labour availability, repair time, and emergent work. As some of the cost drivers contribute to both spares and resource requirements (e.g. failure rate) the spares and resource contribution fraction as an input from the user is used to allocate the contribution of the cost drivers to each of these cost buckets.

The second group of variables are those in relation to the incentive mechanism through the gain/pain mechanism. These are variables that enable information flow between the OEM and the customer and further associated information has been provided in the “Interaction between the customer and OEM agents” section. The focus centres on



calculating the difference between the actual cost and price that the customer pays for the equipment usage level. The key variables considered in this category are “price”, “profit” and the “pain/gain level”, as specified also in the customer agent, which is based on the 3 and 10% profit levels. An illustration of the variables within the OEM agent and their interaction is provided in Figure 8.4.

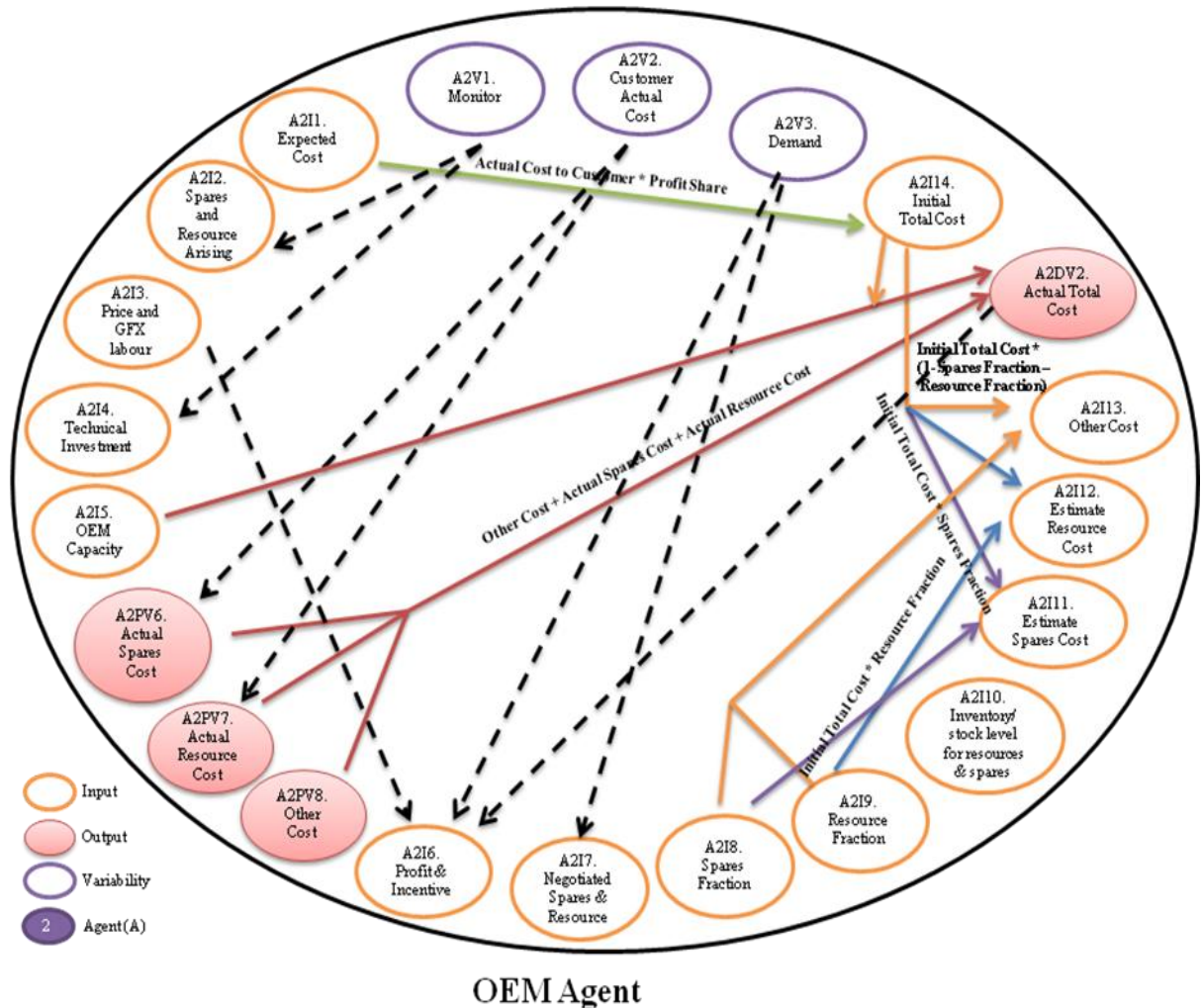


Figure 8.4 Overview of the interaction between the variables within the OEM agent

### Interaction between the Original Equipment Manufacturer and spares supplier

The OEM sets a cost level for a given level of spares and resource requirements from the spares supplier. This represents the expected level of spares for the specified period of time. Driven by the variation in “failure rate” the target level of spares requirements

may deviate. In order to account for this deviation, the model aims to support in comparing across various scenarios that may govern the relationship between the OEM and the supplier. Along these lines, three scenarios are considered for the interaction, where first, the risks are with the solution provider, e.g., any shift from estimated costs is borne by the solution provider. In the second scenario, the spares supplier takes all the risks and thirdly both share the risks. The selected scenarios focus on the solution provider and the supplier, due to the nature of CfA, which pass responsibility from the customer along the supply chain.

***Scenario 1 - Risk with solution provider:***

In this scenario the solution provider is responsible for the technical investment, where there is an incentive to sustain the delivery of requirements by adjusting the capacity. Within this scenario it is assumed that if the customer aims to get more from the gain/pain share mechanism then the solution provider may have an opportunistic behaviour towards investments by passing on responsibilities to the suppliers.

***Scenario 2 - Risk with supplier:***

In this scenario the supplier is responsible for technical investment, where a gap between capacity and maintenance requirements creates an increase or decrease of investment. Depending on the level of requirements the capacity level also varies over time. The uncertainty arises from the time and the quantity of spares requirements. Furthermore, the supplier is paid per unit repair, and there is no incentive to invest unnecessarily to account for the anticipated large amount of repairs.

***Scenario 3 - Solution provider and supplier sharing risk:***

The technical investment is shared between the solution provider and supplier. As the solution provider shares the cost risk, in the case where requirements diminish the supplier is less concerned about reducing the investment level and the capacity level is less likely to diminish. The model similar to the pain/gain share mechanism requires

definition of a risk sharing level in order to allocate the cost level above the estimated value that is generated at the spares supplier through the “OEM Share” variable.

### **Spares supplier agent**

The spares supplier is in charge of fulfilling the demand that arises from the failure rate that the OEM raises. At this point the difference between the technical investment and the expected spares failure rate triggers a change from the estimated cost level to be reflected as actual cost, whereby this is achieved by a multiplier. If there is no difference between the technical investment and spares failure rate, then the actual cost stays the same as the estimated cost. In the agent also for the case that the spares supplier and solution provider share the risk of excess spares cost, there is a variable called “OEM Share” to represent the proportion of cost that the solution provider will take if the actual cost exceeds the estimated cost with the spares supplier. In this case, actual cost for the spares supplier is revised by deducting the cost that the solution provider is responsible for. The responsibility of managing obsolescence is assumed to be with the spares supplier, where a fixed proportion (e.g. 25%) of the expected cost constitutes the associated cost. An overview of the way in which the spares actual cost gets calculated is demonstrated below, which highlights that driven by the variation in the failure rate, a multiplier is generated and this is multiplied with the expected cost level to derive the actual cost:

```
ActualCost=Cost;
ActualCost*=SpareRise;
    if (SpareRise>1 && SpareRise<2) ActualCost=1.5*Cost;
    if (SpareRise>=2) ActualCost=2*Cost;
    if (SpareRise<1) ActualCost=SpareRise*Cost;
SparesSupply newTimer = new SparesSupply(1);
```

### **Interaction between the Original Equipment Manufacturer and resource supplier**

The resource suppliers’ relationship with the OEM follows a similar kind of architecture that has been presented between the spares supplier and the OEM. Though, a less

sophisticated approach has been considered, as the influence of risk sharing does not apply within this case.

### Resource supplier agent

The resource supplier agent is conceptually similar to the spares supplier agent, though it is not included to the risk sharing mechanism. In this case resource failure rate is used as a multiplier to estimate the actual cost for the resource supplier based on the initial estimated value. Initially the actual cost and the estimated cost are assumed to be equal but with the varying failure rate, the actual cost also varies.

### 8.2.2 Agent based model implementation

This section aims to outline an overview of the implementation of the agent based model by covering aspects associated to the inputs, outputs and model application. A step by step process is suggested to collate the required input for the agent based model, as represented in Figure 8.5.

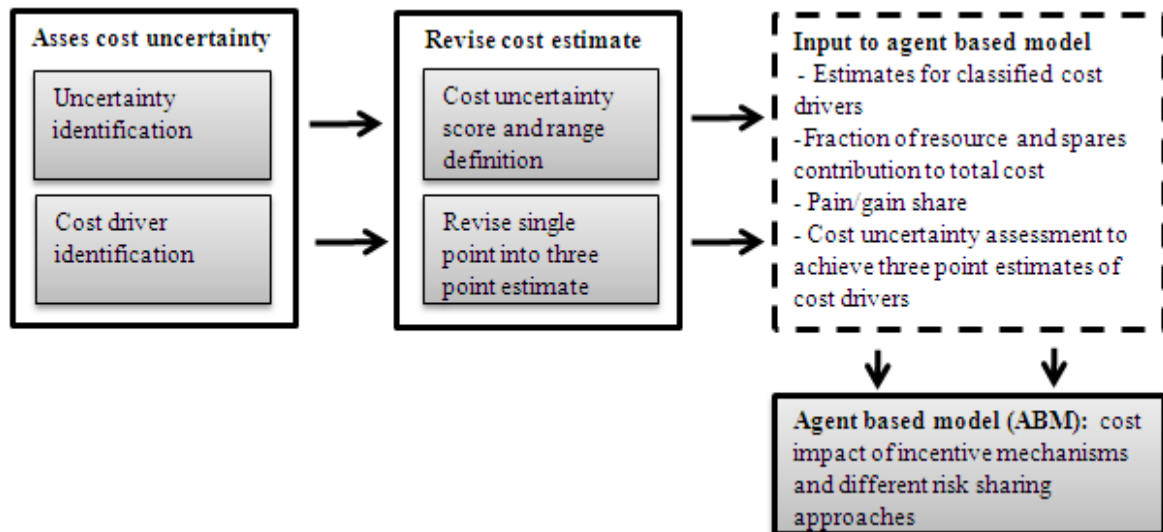


Figure 8.5 Information flow in the agent based model

The process includes: (1) assess cost uncertainty, (2) revise cost estimate, (3) simulate through ABM. The first and second phases produce the expected cost estimate values that are considered in the OEM agent and are generated in U-TASC. There are

additional input requirements that are associated to the context of the associated contract (e.g. pain/gain share). Furthermore, the process of assessing cost uncertainty to define ranges and to revise a single point estimate is defined in Section 7.2.3 and Section 7.2.4, respectively.

The input to the model is partly achieved through an MS Excel data tool, which collates relevant information from U-TASC, whilst there is also information that is input into AnyLogic directly. The outputs generated in AnyLogic are transferred into an additional sheet within the MS Excel data tool. Furthermore, there is flexibility over selecting the data to be collected in the data collection tool, which can be used for further statistical analysis. An overview of the input collected from U-TASC is as follows:

- Pain/Gain share: The percentage contribution of the customer when the actual cost of spares requirements exceeds the expected cost level
- GFX labour rate: The percentage that the customer contributes to the labour requirements within the delivery of maintenance
- Spare cost fraction on overall support cost: across the cost drivers the expected percentage contribution of the spares delivery
- Resource cost fraction on overall support cost: across the cost drivers the expected percentage contribution of the maintenance delivery
- OEM and spares risk sharing level for the scenario of OEM and spares supplier sharing: The percentage of the cost that the OEM is responsible for if the actual cost of spares requirement exceeds the actual cost level
- Single point and Three-point cost estimates generated for relevant cost drivers

There are a number of inputs that are directly entered into AnyLogic. Firstly, limits need to be specified on equipment usage and an associated predefined expected cost level. These involve a set of boundaries reflecting the minimum and maximum equipment usage levels with associated costs to the customer. Secondly, incentive levels are an input as specified at 3 and 10% profitability levels.

The model estimates spares and maintenance associated costs over time, whilst enabling to compare costs across systems/subsystems, and integrating the influence of failure

related uncertainty in a dynamic manner. The model also takes into account the key uncertainties that have been realised from the interactions with industrial collaborators. Along with the uncertainty of “failure rate” that has been explained within the customer agent, the model also takes in to account the following uncertainties:

- equipment usage level: variation of the customer demand in equipment usage
- obsolescence: the degree of obsolescence which creates costs in spares
- other (e.g. emergent work, training): the uncertainty in those areas that have received lesser interest though are increasingly becoming influential across CfA
- stock capacity at the OEM: variation in the degree of stock availability
- incentive mechanism: uncertainty associated to the cost or benefit that the customer and the OEM experiences from the incentive mechanism
- cost outcome of the risk sharing mechanism

The model assumes that a TPPI type arrangement has been agreed between the customer and the OEM. Furthermore, the spare consumption rate is assumed to be stochastic and expressed by a probability distribution attaining values from 1 onwards. Several scenarios are assumed to govern the relationship between the OEM and the spares supplier, where first, OEM takes all the risks, i.e., any changes in spares costs from expected level is borne by the OEM. In second scenario, the supplier takes all the risks and in third both share the risks.

The outputs from the model range across the agents. For the customer it is possible to gather an understanding of the affordability and equipment availability over time. The model enables to visualise and compare the implications of various incentive architectures (e.g. 3-10% profitability threshold) between the customer and the OEM. For the OEM agent, cost estimates for resource and spares are generated, which reflect an account of the influence of uncertainty. Additionally, it is possible to make a comparison of the associated costs across systems/subsystems. The spares and resource supplier agents can make an assessment of the actual failure events and to compare these values against the expected level.

### **8.3 Validation**

The framework was validated using expert opinion and a pilot case study in order to identify the limitations, weakness and benefits of the model.

#### **Expert opinion**

The first respondent was part of Organisation A who had over 20 years of experience in project management highlighted that for the early stages of the bidding the framework was able to represent the events in maintenance delivery. It was mentioned that the framework would be too tedious to follow at the line replaceable unit (LRU) level and a systems view would be more adequate. It was highlighted that the approach would facilitate learning across projects due to the uncertainty assessment scheme in that is built in from U-TASC. It was also highlighted that the framework enables to understand the influence of specific uncertainties on cost drivers. In the agent based model it was suggested to have further consideration of obsolescence by considering the influence of different types of obsolescence on cost and also the way in which responsibility is allocated across the supply chain.

The second respondent has over 25 years of experience in modelling maintenance costs largely in the naval domain at Organisation A. It was highlighted that after the initial stages of bidding, when information regarding service requirements becomes clearer it would be necessary to take account of the complexities of the supply chain, including issues such as supplier reliability, and variation in costs arising from different suppliers. The models' TPPI considerations would have to be considered on a project by project basis and it would not be possible to apply generic values for this purpose. The presented models' focus on three scenarios was suggested to be reasonable; however, detailed estimation of various key performance indicators such as availability could also be considered as useful outputs. Furthermore, at the more mature phases of the bidding stage the model would need to account for different scenarios in relation to the equipment usage conditions (e.g. weather conditions, humidity). Also, it was highlighted that the model would need to take account of different requirements for the

air and naval domains. This refers to the fact that in an aircraft all parts of a system have to work, whilst for the naval context this does not apply. It was also suggested that rules for interaction between agents could be considered in more detail (e.g. delivery of items varies). Overall, the expert suggested that the model was sufficiently flexible to capture the cost uncertainties early on during bidding and it was emphasised that the approach was a useful way forward to model maintenance costs.

The third respondent whom has over 31 years of experience in cost estimation in various phases of the life cycle at Organisation A. The respondent was interested in the benefits of visualising the variation in cost based on changing various parameters such as pain/gain share. Also comparison among the scenarios was suggested to be a good feature to organise the interaction across the supply chain. It was highlighted that the model shows a good representation of how costs varies based on changes in equipment usage level and failure rate over time, however visualising the interplay between cost and availability would also be a good output.

The fourth respondent is an expert in risk and uncertainty modelling with over 4 years of experience at Organisation G. It was highlighted that one limitation of the framework is related to making sure that all the uncertainties and cost drivers have been captured. One key outcome of the expert opinion was the need for the ABM framework to be applied in an integrated manner with U-TASC. This enables a systematic approach which helps to understand the root cause of variation in cost estimates. Also, the affect of uncertainties on cost drivers can be assessed in an iterative manner through Phases 1 and 2. This in turn enhances confidence in the estimates.

### **Pilot Case Study**

The case study is a very large military system-of-systems project in the naval domain involving over 60 sub-systems of which only a minority are manufactured in-house. The project is currently engaging with the customer to establish the maintenance requirements and the company is challenged to develop credible cost models. Three subject matter experts participated in running the current ABM in the case study. The goal of the case study was to assess the suitability of the ABM framework in terms of



comparing different scenarios for the early phases of the bidding stage where there is a lack of information. For this purpose three experts initially went through the list of uncertainties and scored those uncertainties that were expected to affect their project (Phases 1 and 2). A small system was considered for costs, in pounds at the thousand pound level. A what-if analysis was performed to compare how the actual cost would vary by changing the solution provider share of risk taking for the scenario of solution provider and spares supplier sharing the risk.

Three alternatives are considered as shown in Table 8.4. This is done in order to assess the suitable level of risk to be taken by the solution provider. The other inputs are kept equal, such as pain/gain share (30%), spare cost fraction (45%), resource cost fraction (35%), and GFX labour (80%), initial total cost (£10,000), failure rate cost (£430,48), turnaround time cost (£207,32), LRU cost (£131,53), transport cost (£1458,08), packaging cost (£184,05), repair cost (£170,0), demand rate-spare cost (£436,56), storage cost (£430,58), emergent work (£430,58), GFX supply cost (£410,95), material availability cost (£826,34), labour availability cost (£1643,21), customer demand usage (£92,70), customer actual usage (£207,32), NFF cost (£430,58), BER cost (£933,14), number of students (£863,87), number of trainers (£282,24), facilities for training (£430,58). In total one hundred runs were conducted in the simulation.

The what-if analysis represented in Table 8.4 shows that as the solution provider takes on more of the share of uncertainty in funding the excess cost arising from the increased failure rate the actual cost increases. The mean values indicate a smooth increase from scenario 1 (11,170.30), 2 (11,268.48) and 3 (11,293.78). However, driven by the failure rate by taking on more of the responsibility the uncertainty, assessed through standard deviation, diminishes. Thus meaning there is a trade-off between additional costs and attaining lower uncertainties. As indicated by the high standard deviations, there is high uncertainty in the outputs, which reflects the conditions of the bidding stage. The lack of information is represented through large triangular distributions for each cost driver, which in turn causes large variation in the actual cost estimate. As can be seen across the scenarios there is a trend which indicates that as the solution provider takes a higher proportion of the uncertainty, then the overall level of uncertainty in actual cost estimate

reduces. The results also indicate that the initial total cost estimate was under estimated and would potentially cause profitability issues for the solution provider and it may also reflect optimism bias. Furthermore, at the 95 percent confidence level the range between the lower cost limit and the upper cost limit is narrowing, from the first scenario to the third suggesting that the level of uncertainty is reduced. The decision making regarding which scenario to select would need to be based on the standard deviation, and scenario 3, with the lowest level, would be the suitable option to arrange the interaction between the spares supplier and the solution provider.

Table 8.4 Comparison of risk sharing between solution provider and spares supplier

	Scenario 1	Scenario 2	Scenario 3
<b>OEM Share in sharing uncertainty with spares supplier</b>	0.1	0.5	0.7
<b>Mean</b>	11,170.30	11,268.43	11,293.78
<b>Standard deviation</b>	720.374	685.101	594.207
<b>Lower cost limit at 95% confidence</b>	9,729.59	9,898.23	10,105.37
<b>Upper cost limit at 95% confidence</b>	12,611.12	12,638.63	12,482.24

The agent based model also enables to gather information about the evolution of the actual cost, where the focus is on the OEM agent. The associated results are demonstrated in Figure 8.6. Over a 10 year period three trends were observed regarding the variability in the actual costs. The first trend represents the initial period of the contract, where a highly stable outlook is expected. There are a number of reasons for this output mainly driven by the fact that the failure rate is expected to be relatively low, whilst additionally the uncertainty associated to the failure rate is also low. The slight reduction between year 5 and 6 may have originated, due to the diminishing spare costs. This may have resulted from the enhanced understanding of the customer in operating the equipment, which may have caused a reduction in failure and spare parts demand. This may additionally be an outcome of training. Also, the reduction in cost may arise as the cost of replacing parts might have been postponed (e.g. contractual review or the defence budget constraints). Subsequently, after year 6, the uncertainty associated to the failure becomes increasingly influential over the actual costs. The drastic increase in costs represents the second trend in the output. It is observed that between years 6 and 7 much more failures and replacement costs are experienced. The degree of rise in the

failure may be associated to the change in equipment operating conditions or capability upgrades, which introduce major cost increases. The final trend illustrates the drastic reduction in costs. Within this phase the uncertainty level is the highest due to the reduction in the ability to foresee the future service requirements. However, the results indicate the end of the unexpected event, which drastically increased costs in the previous time frame. The actual cost in this phase is higher than in the first phase due to an increase in the number of failure events.

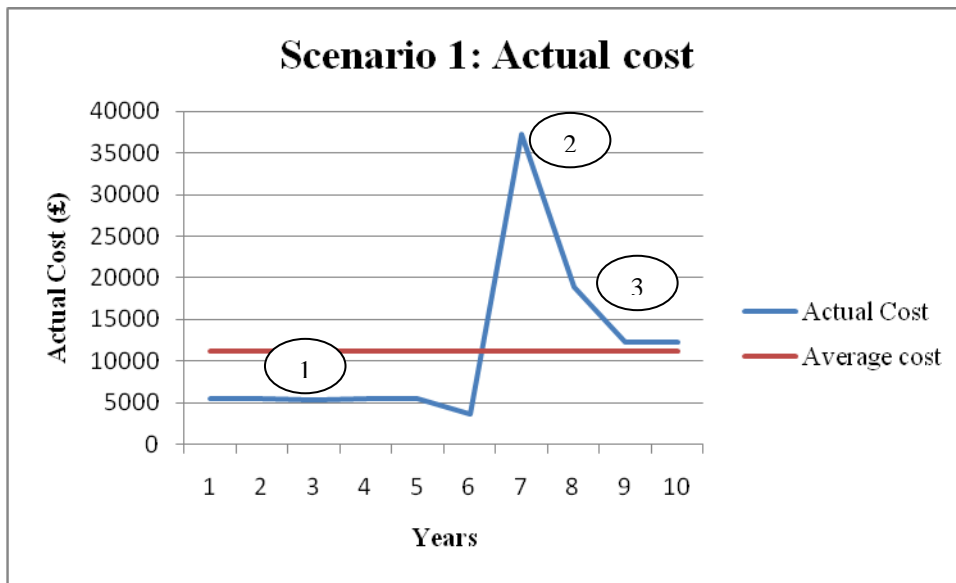


Figure 8.6 Output for OEM actual cost

Another output from the agent based model is the comparison of profits along the supply network. Such information may hold benefits when considering the sustainability of stakeholders over the given duration of a contract. As shown in Figure 8.7, there is a large difference between the potential profit that the OEM can make compared to the spares and resource suppliers. Furthermore, the evolution of the profits at the OEM appears to be correlated with the resource supplier, whilst a positive relationship with the spares supplier is also observed up to year 4. The correlation between the customer agent and the resource supplier may be associated to the fact that in the model the OEM in any case requires support from the resource supplier, whilst the OEMs' capacity refers to the spares content and varyingly affects the spares supplier. Based on the results, the spares supplier may have an agreement for the initial

four years, which sets a closer relationship with the OEM. In the subsequent period the OEM may demand less from the spares supplier due to its sufficient capacity to provide parts to the customer.

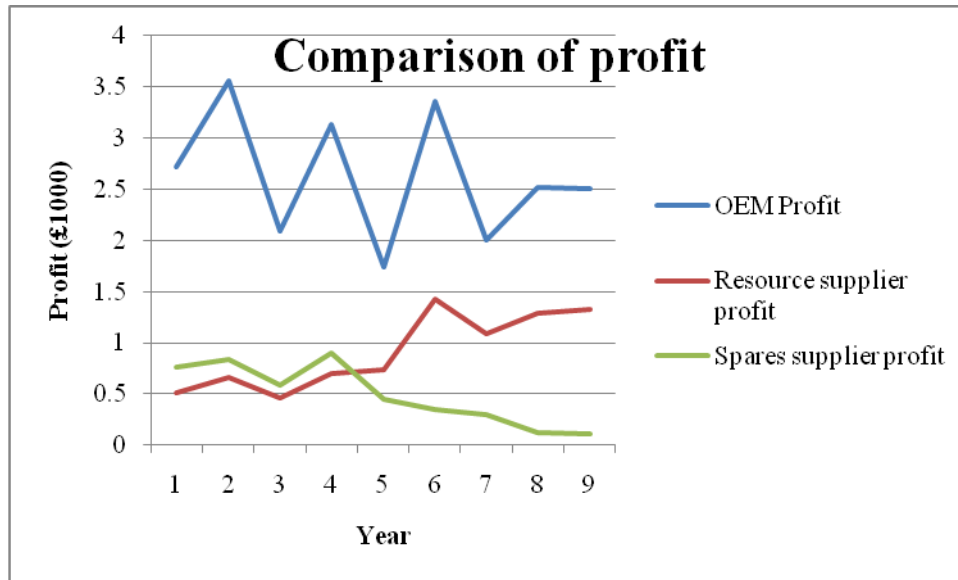


Figure 8.7 Comparison of profit along the supply network

The case study showed that the required data for the ABM framework can be provided and the requirements were realistic. Some of the key outcomes of the pilot case study regarding the presented simulation framework include:

- Costs can be predicted for specified periods as well as for the long term. Though, the model specifically suits the early stages of bidding where there is very limited information
- Intelligent management of the influence of uncertainty can be achieved over cost early on in order to negotiate across the supply network
- Driven by uncertainty in failure rate the cost responsibilities in a TPPI type arrangement across the supply network can be visualised. The solution provider and the customer have a better understanding between the interplay between performance requirement and cost
- Sensitivity to costs deriving from variation in failure rate can be examined
- Exploration and evaluation of different uncertainty sharing approaches can be compared to reach a desirable solution between the spares supplier and the OEM

## 8.5 Summary

The chapter initially introduces agent based modelling by covering aspects associated to the context including incentive mechanisms, and the overall context of the model. The focus of the model is on maintenance costs, whilst a novel approach is applied by considering the dynamic aspects related to failure rate. Additionally, the detail of the model suits the early phases of bidding for CfA, while focusing on a Target Price Performance Incentive (TPPI) mechanism, which is commonly agreed in CfA.

In Section 8.2 the development of the ABM is presented, which includes four phases: (1) understanding context, (2) developing research protocol, (3) framework development and (4) validation. Literature review enabled to position the application of ABM to existing research, whilst industrial interaction enabled to get a better understanding of the context of CfA and its application through incentives. In Section 8.3 the agent based model is presented, which includes four agents: customer, solution provider, spares and resource supplier. The model focuses on visualising the cost implications across the supply network given the dynamism in resource and spares costs. The model focuses on the influence of failure rate on cost across the supply network, whilst an incentive mechanism is adopted to represent the relationship between the customer and the OEM. Furthermore, the relationship between the OEM and the spares supplier is managed through risk sharing options.

In Section 8.4 through validation with four subject matter experts and a pilot case study in the naval domain it is indicated that the rules and the dynamism considered in the model enables to capture uncertainty more realistically compared to the traditional approach of cost uncertainty modelling. Some of the key outcomes of the case study are captured in relation to (1) Visualising the influence of uncertainty across the supply network, (2) Understanding of the sensitivity to the failure rate and, (3) Exploring and evaluating different incentivisation and risk sharing approaches across the supply network.



## **9 VERIFICATION AND VALIDATION**

In this chapter results gathered from verification and validation through three case studies involved at the bidding stage of CfA is presented. The focus is on U-TASC, which detailed explanation of the embedded frameworks has been covered in Chapter 6 and 7. In Section 9.1 the initial verification that took place internally is presented, which covers an assessment of the accuracy of calculations within U-TASC. Subsequently, for each of the case studies gathered information about the verification, input, output and validation results is presented. The same procedure was followed for each of the case studies. In Section 9.2 the focus is on a naval electronic system, whilst the context is naval radar in Section 9.3 and an aircraft carrier in Section 9.4. Participants of each case study initially verified the calculations and modifications were made as a result. Subsequently, the input was collected for “uncertainty level”, “uncertainty weight”, “selection of uncertainty mitigation strategy”, “selection of cost drivers”, “cost driver weight” or “cost estimate for each cost driver” and “future expectation of uncertainty”. Based on the gathered information from the case studies, the outputs include “uncertainty identification”, “uncertainty prioritisation”, “uncertainty mitigation suggestion”, “evolution of uncertainty over time by storing data”, “project level cost uncertainty score” and “Three-point estimates for current and future expectations”. Validation results also cover an assessment of considerations in U-TASC through a questionnaire that was gauged through semi-structured interviews. The questionnaire aimed to assess aspects such as generalisability, framework logic, applicability, and results. In Section 9.5 a comparison across the case studies is made.

### **9.1 Internal verification**

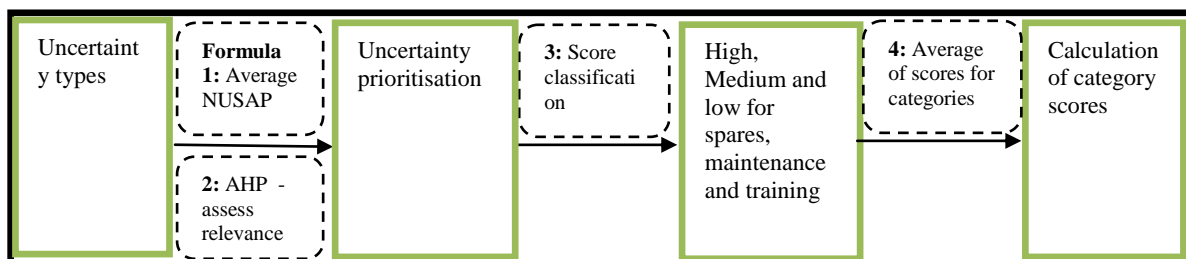
Internal verification involved the development of a map of the calculations for each of the features within U-TASC. In turn, this was used to make an assessment of the accuracy, and relevance of the calculation. Initial verification was conducted with Professor Rajkumar Roy, which lasted for one hour. The calculations within U-TASC

were considered to be suitable and provided expected results. Some of the key suggestions gathered at the meeting included:

- Provide examples for the severe, medium, and low scores of uncertainty to enhance understanding of uncertainties
- Write for each input sheet – if “ability to tick” is ticked all 3 criteria needs to be ticked and a recommendation should be highlighted if the input is false
- Define a Nomin checker for formulas

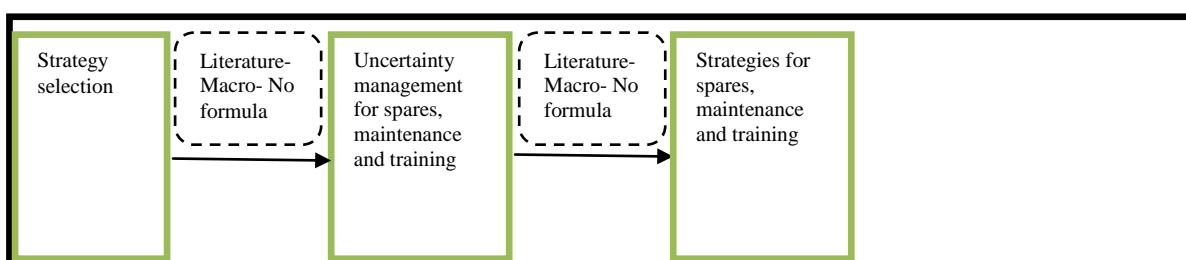
An overview of the calculations and their purpose in U-TASC is illustrated below and during the initial verification each of these were assessed. In Table 9.1 the calculations for uncertainty prioritisation is presented, which covers the prioritisation of the uncertainty categories. An uncertainty score for each type of uncertainty is calculated by multiplying the uncertainty level from the NUSAP matrix and the uncertainty significance level from the AHP analysis. Subsequently, the uncertainty scores are aggregated at the uncertainty category level and prioritisations are made for the services maintenance, spares and training.

Table 9.1 Calculation of uncertainty prioritisation



In Table 9.2, it is highlighted that a macro in MS Excel is used to allocate selected uncertainty mitigation strategies for the prioritised uncertainties and these get represented as a management report for the services spares, maintenance and training.

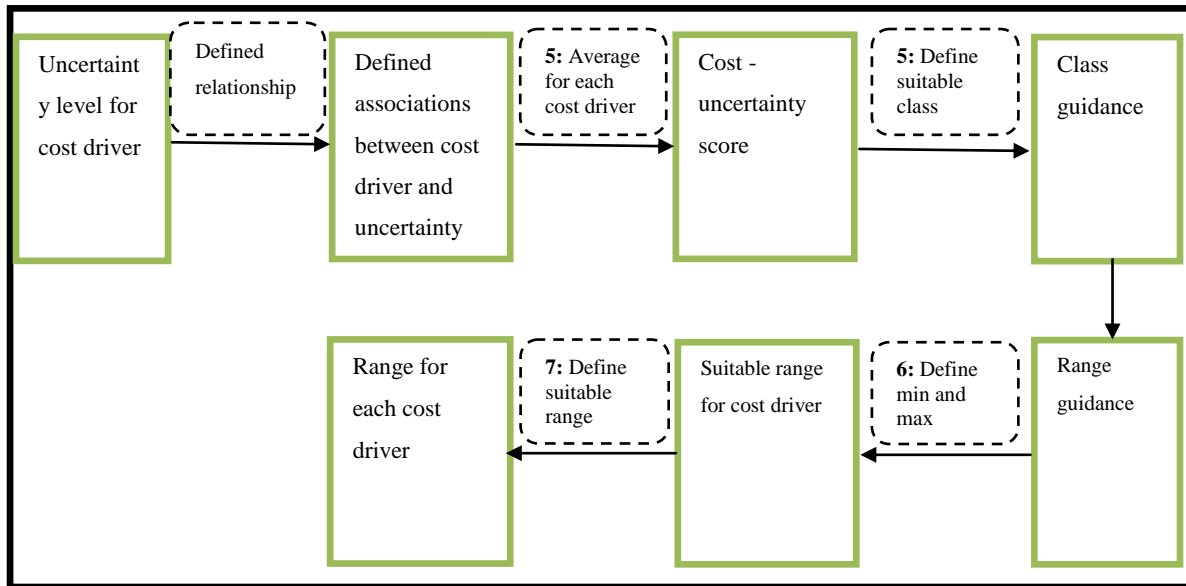
Table 9.2 Approach for uncertainty mitigation selection





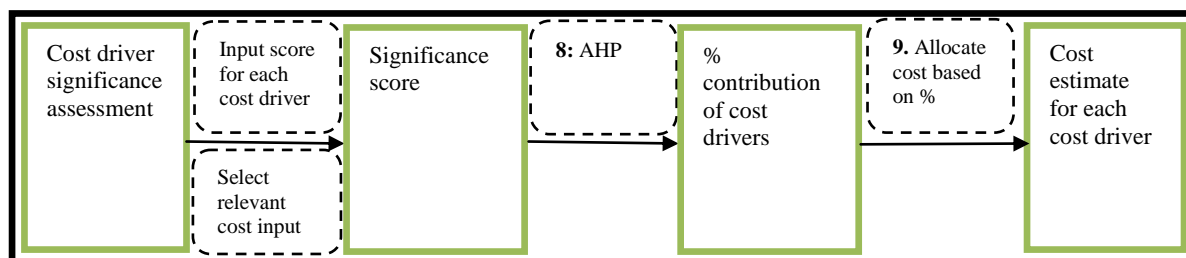
In Table 9.3 the process of calculating the minimum and maximum range suggestions for the cost drivers is covered. Initially, the average of the “Uncertainty levels” is aggregated based on the pre-defined relationships between uncertainties and cost drivers, which yields a “Cost uncertainty score”. Based on the AACE (1997) suggestions this score gets allocated to a suitable range for each relevant cost driver.

Table 9.3 Calculation of minimum and maximum range for cost drivers



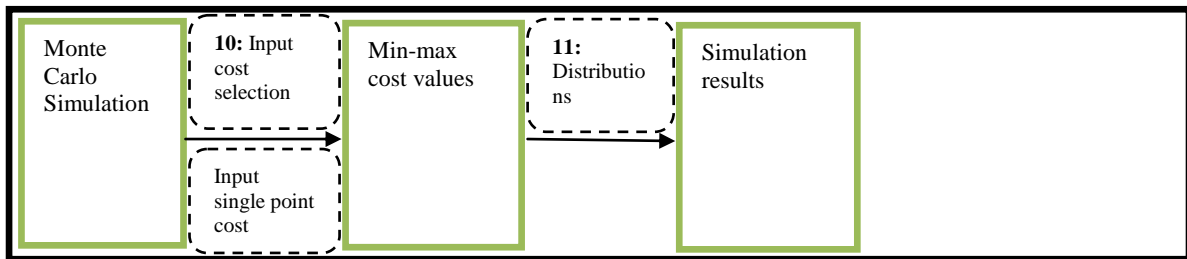
In Table 9.4, for the case where only a single point estimate is available at the project level this calculation enables to allocate the cost across the selected cost drivers. During this process, the AHP is conducted to define a percentage significance level for each of the cost drivers. This value enables to apportion the total cost estimate.

Table 9.4 Calculation of cost estimates for each cost driver



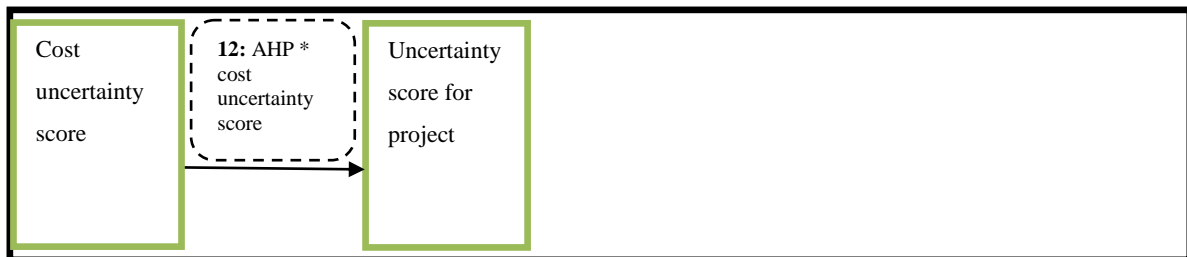
In Table 9.5, it highlighted that the cost estimate and the Three-point estimates are used to generate the results from Monte Carlo simulation. The algorithms for the simulation are built into MS Excel.

Table 9.5 Calculation of Monte Carlo simulation



In Table 9.6, the calculation of the cost uncertainty level at the project level is presented. The uncertainty level and the significance level for each cost driver are multiplied and subsequently the values are aggregated across the relevant cost drivers.

Table 9.6 Calculation of project level cost uncertainty score



## 9.2 Case Study 1: Naval Electronic System

The case study involved a naval carrier in the UK at the early stages of the bidding stage for the in-service phase. The case study was selected because it represents a sample for the CfA context at the bidding stage. The case is part of a large project which has been broken down into a number of sub-categories focusing on delivering support, including spares, maintenance, provision of design authority and integration. The focus is on *an example representative of a complex electronic system*. The initial contract period is considered to reach 10 years, while the defence customer is intending to conduct a review midway. The financial value of the case study is expected to be in the region of £15 million. Furthermore, the equipment availability level is yet to be set. The case study has limited information compared to some programmes which are highly internally managed and requires much information from the many sub-contractors that are associated to the case study. This in turn brings about much uncertainty driven by the lack of confidence in the provided information (e.g. cost).

The validation process followed an iterative process with a Principal Reliability Specialist involved in the case study who had over 20 years of experience in cost uncertainty modelling. The interaction involved semi-structured interviews, which focused on the application of U-TASC on the case study. The total amount of interaction exceeded over 15 hours. During validation, semi-structured interviews were conducted face to face, through WebEx and through telephone, whilst also feedback was received through e-mails. The focus of the query covered (1) assessment of the completeness of the uncertainty list, (2) assessment of the systematic nature of the framework that draws connections between the uncertainty and cost drivers and the management of uncertainty, (3) assessment of the level of confidence respondent's gain from the outputs, (4) assessment of the usability of the outputs. The respondents' goal of the study was to see how U-TASC could be used in practice to place confidence levels on the costs associated to an example taken from the naval domain.

### **9.2.1 Tool verification**

In the course of the study, a few implementation issues were noted. In addition, some minor changes were made, primarily to the sheet which links uncertainties and cost drivers, in order to assist data capture and extendibility. In the Uncertainty Row on the "Linkage" sheet, text describing cost drivers was replaced with references to the appropriate cell, to ensure that changes made on the Input sheets would flow through.

### **9.2.2 Framework input**

The input to the tool was classified in to two areas. Firstly the level of uncertainty was quantified using expert opinion. Secondly, the cost estimates for the selected relevant cost drivers were specified. For the first area, three of the uncertainty categories were considered to be relevant to the project, including Operation, Engineering and Commercial. For operation 15 uncertainties that can potentially influence support costs were identified as relevant. For 5 of these, the degree of uncertainty was characterised by quantifying the level of confidence in the basis of estimate, rigour of assessment and level of validation. The others were allowed to default to their maximum uncertainty

value of 7. For Engineering, 2 uncertainties were scored as relevant, with relatively high uncertainty scores. For the commercial category 7 of the uncertainties were characterised, typically using low values in the range 1-7 (indicating low level of uncertainty). This reflects the difference in uncertainty levels between Operations, Engineering and Commercial areas, and hence between the Unplanned and Planned Maintenance cost drivers. Figure 9.1 illustrates a snapshot of U-TASC regarding the input for the commercial category of uncertainty.

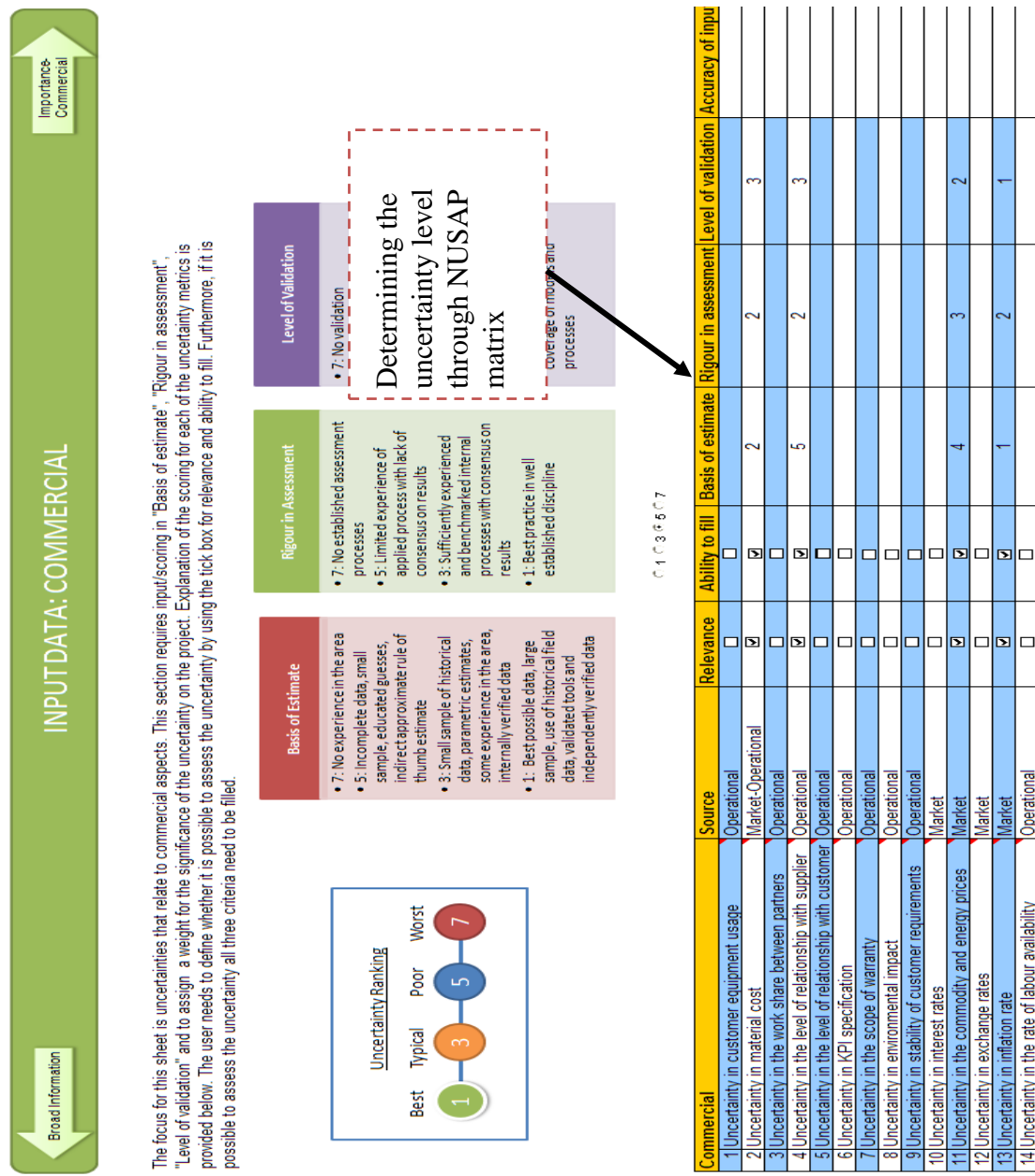


Figure 9.1 Snapshot of input for the commercial category

The identified uncertainties within each of the categories were also assessed in terms of their relevance to the project. The input to AHP enabled to support the calculations in the uncertainty prioritisation. The respondent scored the relevance level between 1 and 9 as explained in Section 6.4.2. Sample input for the operation category of identified uncertainty is represented in Table 9.7. The green cells represent the input provided by the respondent. Furthermore, “Percentage significance” refers to the degree of relevance of each type of uncertainty to the project. “Normalised weight” illustrates the normalised score of the “Percentage significance”. The combination of uncertainty level and uncertainty weight enables uncertainty prioritisation.

Table 9.7 Input for operation category of uncertainty relevance assessment

<b>Operation Uncertainty</b>	<b>Input significance</b>	<b>Percentage significance</b>	<b>Normalised weight</b>
Uncertainty in quality of component(s)	3	0.05	0.68
Uncertainty in quality of manufacturing	3	0.05	0.68
Uncertainty in the maintainer performance	5	0.13	1.00
Uncertainty in equipment utilisation rate	5	0.13	1.00
Uncertainty in OEM logistics	4	0.09	1.00
Uncertainty in the rate of repairability	3	0.05	0.68
Uncertainty in the mean time between failure data	2	0.02	0.37
Uncertainty in the no fault found rate	2	0.02	0.37
Uncertainty in supply chain logistics	4	0.09	1.00
Uncertainty in the availability of maintenance support resources	3	0.05	0.68
Uncertainty in the turnaround time	3	0.05	0.68
Uncertainty in the rate of beyond economical repair	2	0.02	0.37
Uncertainty in the operating parameters	3	0.05	0.68
Uncertainty in the effectiveness of maintenance policy	5	0.13	1.00
Uncertainty in the failure rate of hardware	4	0.09	1.00

The respondent suggested adjustments to the names of three cost drivers: “Failure rate”, “Turnaround time” and “Line replaceable unit” in order to apply U-TASC to the Naval example. The respondent highlighted that the change was made because these cost drivers did not have associated absolute cost values (or it was difficult to assign a cost estimate) but do impact the value of cost items. Firstly, “Failure rate” has been considered as “Unplanned maintenance cost” due to the close association between these two aspects. Secondly, “Turnaround time” has been renamed as “Planned maintenance

cost”. Thirdly, “Line replaceable unit” was changed to “Systems and Engineering” in order to adapt to the Naval context of data, which refers to a similar existing cost driver of “Unit Costs”. In total three cost drivers were defined relevant: “Planned Maintenance costs” of £3,000,000, “unplanned maintenance cost” of £1,000,000, “Systems and Engineering” of £2,000,000. The respondent assessed outputs for various percentile values. These costs represent example data only due to the sensitivity involved.

### **9.2.3 Framework output**

The respondent suggested that there are three key areas of outputs from U-TASC. Firstly, by linking uncertainties and cost drivers a cost uncertainty score is calculated for the selected cost drivers. The second beneficial output was suggested to be outputs from Monte Carlo simulation, which take into account the calculated minimum and maximum cost estimates. The third output was considered to be the suggested uncertainty mitigation strategies. Table 9.8 illustrates the uncertainty scores for the given cost drivers, whereby the scores for the relevant uncertainties are aggregated and normalised to calculate the cost uncertainty score for each of the cost drivers. For instance, in the case of “Unplanned maintenance cost” the numerical value of 0.86 has been normalised by dividing the average of the uncertainty scores for each cost driver with 7, which is the highest possible uncertainty score. The table also shows the minimum and maximum range suggestions, represented as a percentage, by assessing which class the cost uncertainty score falls under in the AACE (1997) guideline.

The ranges (in terms of percentage variation from the mean) placed around the “Planned maintenance cost” and “Unplanned maintenance cost” drivers differed, with the Unplanned Maintenance range being larger, as expected (-30% to +50% as opposed to -20% to +30%). It was highlighted that the range bounds are typically skewed upwards as a result of applying the AACE guidelines to the calculations. This is presumably based on the assumption that the general tendency is to under-estimate rather than over-estimate. The respondent further assessed this finding by comparing with results from an in-house built tool, and it was confirmed that such skewness also manifested itself when similar data were being captured for cost drivers.

Table 9.8 Cost uncertainty score and range suggestions for selected cost drivers

Uncertainties		Cost drivers		
Categories	Types	Unplanned maintenance cost	Planned maintenance cost	Systems and engineering
Commercial	Material cost		2.3	2.3
	Level of relationship with supplier		3.3	
	Commodity and energy prices		3.0	
	Inflation rate		1.3	1.3
	Labour hours		1.3	1.3
	Labour rate		3.7	3.7
	Labour efficiency		2.3	
Operation	Quality of components	3.7		
	Quality of manufacturing	2.0		
	Maintainer performance	4.3	4.3	
	Equipment utilisation rate	6.0		
	OEM logistics	5.3	5.3	
	Rate of repairability	7.0		
	Mean time between failure data	7.0	7.0	
	No fault found rate	7.0	7.0	
	Supply chain logistics	7.0		
	Availability of maintenance support resources	7.0		
	Turnaround time	7.0	7.0	
	Rate of beyond economical repair	7.0		7.0
	Operating parameters	7.0		7.0
	Effectiveness of maintenance policy	7.0		
Failure rate of hardware	7.0			
Engineering	Rate of capability upgrades	5.3		5.3
	Level of obsolescence		4.3	4.3
Cost uncertainty score		0.86	0.59	0.63
AACE (1997) Class		4	3	3
Minimum range		-30%	-20%	-20%
Maximum range		+50%	+30%	+30%

From the Monte Carlo simulation perspective, with 50% the percentile value “Planned maintenance cost” of £3,000,000 came to approximately £4,250,000. This value (as opposed to 4,000,000) was calculated because the confidence bounds were skewed. With a 90% input the cost came to approximately £4,900,000. It was highlighted that such information would be highly beneficial to the project manager. It tells him that based on the uncertainty and cost driver information entered, the likelihood of the programme costing £4,900,000 or less is 90%, or conversely that the risk of spending more than this amount is 10%. Furthermore, the results were highlighted to be intuitively believable based on the inputs provided.

#### **9.2.4 Validation results**

The representative of the case study was queried concerning various aspects related to U-TASC including the logic, generalisability, responsibility of using the tool, benefits, limitations, usability, confidence in results, and rigour in calculations in the tool. These aspects were scored (1-10), where 10 refers to total suitability/comprehensiveness. The main focus of the respondent was on the cost uncertainty modelling side of U-TASC. The logic of the tool refers to the methodological steps that are applied to reach the end results. This aspect was scored 9 out of 10 by the respondent, who highlighted that a reasonable approach was applied and it fit to the requirements of the case study, where a large set of the uncertainties originate from the sub-contractors, which have been considered in the uncertainties that the tool suggests. Additionally, it was emphasised that the principles of the tool very much applies to the bidding stage, and the adopted concepts are mature to be used in supporting decision making in cost estimation. The respondent also mentioned that U-TASC could be used throughout reviews in stages other than bidding, because of the emphasis on uncertainty in cost, which is a key aspect in any review. Furthermore, the application of the tool was suggested to be generalisable within the service context across the defence industry, and other industries (e.g. nuclear) which have major industrial projects.

U-TASC was noted as a major bridge that potentially could enable communication across the supply network, referring to the customer, the solution provider and the



suppliers. For this purpose all stakeholders should be responsible of using the tool, but at this point there is a challenge that arises from getting the buy-in from the major information provider. This relates to the fact that providing a complete picture of the uncertainty level, cost and profitability may not be desirable. It requires trust across the network to be managed; however conversely it may facilitate to enhance confidence in estimates. U-TASC needs to be used by a cost specialist, whilst based on organisational architectures various approaches may be used to allocate the responsibility of using the tool (e.g. integrated project teams or a cost estimation department).

The respondent underlined that there were two major benefits of using U-TASC. Firstly, it provides the opportunity to generate a potentially more reliable Three-point estimate. This refers to the fact that the sources of variation in the cost drivers are assessed with reasonable justification. Secondly, it enables to recognize the risk of overspending by understanding the level of uncertainty and its impact on cost estimates. This also relates to the opportunity to identify the uncertainty drivers and to define areas that need more information, which suggests the tools' ability to support planning.

A limitation of the tool was suggested to be the high level approach taken with regards to some of the cost drivers. It was suggested that a differentiation between cost drivers and cost categories (a lower level) would be beneficial to further understand the implications of uncertainty on specific cost categories. This comment particularly applies to the cost drivers "Failure rate" and "Turnaround time". Also, the reliability of the information provided by the user was suggested as a key factor which requires adequate consideration in selecting appropriate people to fill U-TASC. Though, this factor was mentioned irrespective of the presented tool, while it was highlighted that the guidance and the clarity of the concepts in the tool supported in reaching uniform results across participants. The required time to fill the tool was referred to depend on the context; whether it be applied at a system or subsystem level and it would need to justify the cost-benefit for a given project. It was highlighted that the data requirements were rather intensive and would potentially be applied only on major projects. The framework was also assessed from a number of dimensions related to the comprehensiveness and calculations in U-TASC. The completeness of the list and

categories of uncertainties received a score of 9 out of 10, whereby the respondent highlighted that such lists could be further adjusted based on specific cases, however based on his knowledge the list was considered to be comprehensive across CfA. The calculation of the uncertainty level using the scoring mechanism was suggested to be reasonable, while the flexibility in choosing a number between 1 and 7 was suggested to contribute to achieving flexibility. Furthermore, the provided list of uncertainty mitigation strategies was considered to be 9 out of 10, due to the useful support provided. In terms of the cost drivers, it was suggested to be comprehensive, but flexibility to account for varying project requirements was mentioned to be necessary.

The defined sources of variation in cost drivers were also suggested to be reasonable and highly applicable for the given context (a score of 8 out of 10). In terms of the suggested ranges, using the AACE guidelines, the respondent found the ranges for each level of cost uncertainty score satisfactory, however it was highlighted that there was a major step change when moving from class 4 to 5 in terms of the suggested ranges, and with a score at the borderline the user would need to be cautious with which range to select. The application of the AHP to define the percentage contribution of the cost drivers was also suggested to be a suitable approach (score of 8 out of 10), though the respondent emphasized that the input scores would need to rely on existing cost data and should avoid the subjective input of users. The complete framework to turn a single point estimate into three was declared to be very suitable for the bidding stage (a score of 9 out of 10). As an overall conclusion, the respondent highlighted that “U-TASC offers a scientific basis for deriving the ranges considered in Monte Carlo simulation, based on analysing the underlying uncertainties”.

### **9.3 Case Study 2: Naval Radar**

The second case study was applied on a project at the bidding phase for an in-service support contract for a Naval Radar, where the focus was on the delivery of availability. The bid is initially made for the initial 7 years; however the long term focus of the support solution reaches 25 years. Furthermore, the project is about to enter the in-service phase. The project is managed by a major company in the defence industry and

the size of the contract is in the region of £50 million. Furthermore, the availability level for the radar, driven by customer affordability constraints, has been set at 85%. If the customer affordability level was to increase then the availability level would also increase. The author selected this case study driven by two reasons (1) the context of bidding in CfA, (2) relevance of cost uncertainty modelling and management processes.

The validation process followed an iterative process with a supportability engineer involved in the case study who had over 12 years of experience in this particular field. The interaction involved semi-structured interviews, which focused on the application of the tool on the case study, exceeding over 10 hours. For validation, semi-structured interviews were conducted face to face, through WebEx and through telephone. The focus of the query covered (1) assessment of the completeness of the uncertainty list for projects, (2) assessment of the systematic nature of the framework that draws connections between the identification, prioritisation and management of uncertainty, (3) assessment of the level of confidence respondents gain from the outputs, (4) assessment of how useful the outputs are early on for projects. The goal of the respondent was to assess the tool in terms of its ability to support new bids concerning uncertainty considerations.

### **9.3.1 Tool verification**

The respondent made a number of suggestions following the initial input process. The author made corrections for aspects that were realised during the verification process. The following sections associated to this case study represent the final data. Some of the key areas acknowledged during tool verification included:

- Circular reference warnings were suggested to arise during data entry
- The output was observed to contain #VALUE errors
- Some of the sheets were mentioned to be jumbled.

A particular interest of the respondent was with regards to how U-TASC may get used after the bid phase when the equipment is in service. It was recognised that the tool as currently presented would still be applicable after the bid phase, however with the

enhanced information flow and experience new uncertainties and cost drivers would potentially emerge, which would need to be dynamically added.

### **9.3.2 Framework input**

The inputs to the framework followed the sequence of areas that is provided below:

- Through tick boxes the relevant uncertainties to the project were specified. The respondent highlighted that all of the specified uncertainty categories were relevant. Similarly, the ability to make an assessment of the relevant uncertainties was questioned. This enabled to consider whether there was sufficient information available to make an assessment of uncertainty
- The uncertainty level using the provided guidance to fill the NUSAP matrix was assessed. For this purpose the subject matter expert input a score (1-7) for the relevant uncertainties within the uncertainty categories
- The relevance of the uncertainty to the project was assessed through the AHP. For this purpose, following the guidance for scoring (1-9), a score was provided illustrating the level of relevance of each relevant uncertainty to the project.
- Subsequently, for the high, medium and low uncertainties that were calculated based on input from the subject matter expert a set of uncertainty mitigation strategies were defined by the respondent.

Reliability, supportability and maintainability driven measures were selected by the respondent, which the case of reliability is illustrated in Figure 9.2 as a snapshot from U-TASC. The same procedure is followed for severe, medium and low level uncertainties. The respondent highlighted that mitigation strategies would be selected only for uncertainties with severe implications, which was the focus for the case study. Relevant cost drivers were specified and scores to define the contribution of cost drivers were defined as represented in Table 9.9. It was highlighted that “Turnaround time” contributes the most to the overall cost estimate.



equipment operating parameters also showed high uncertainty. For the maintenance service among the uncertainty categories results for customer affordability was the highest uncertainty, while operation and performance followed suit. The main reason behind these results is driven by the customers' role in sharing information.

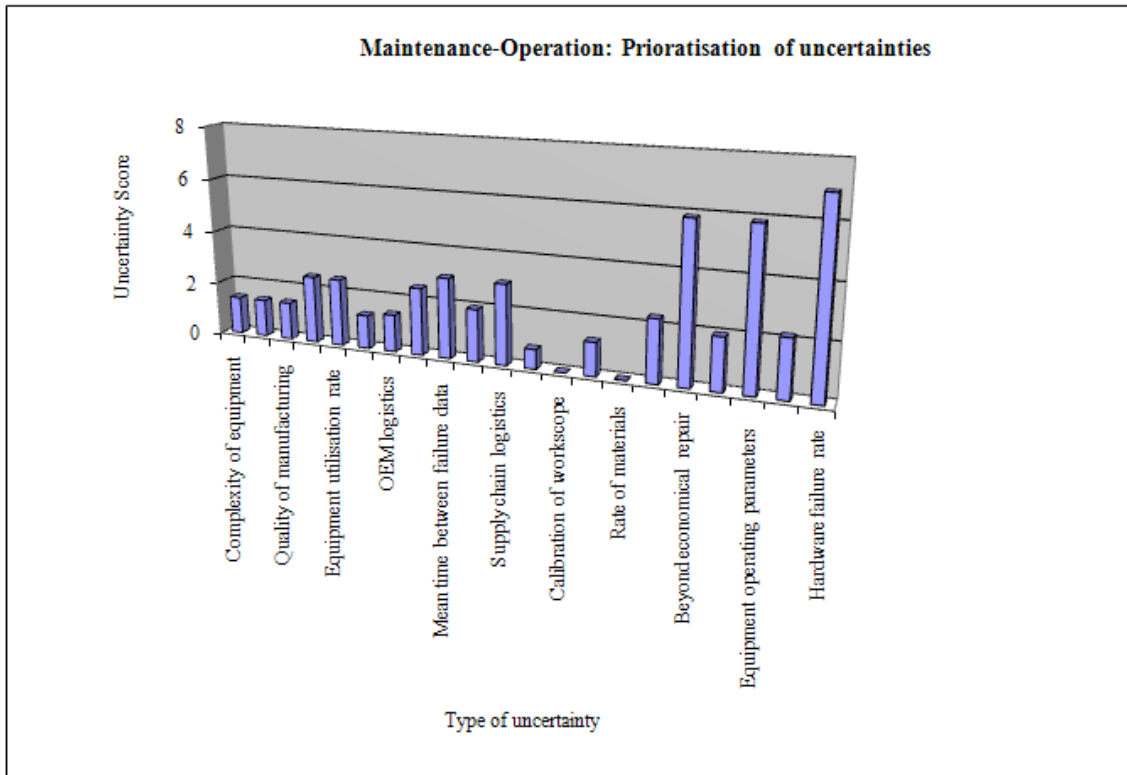


Figure 9.3 Maintenance-operation service uncertainty prioritisation

Table 9.10 List of severe uncertainties

Maintenance	Spares	Training
Environmental burden	Interest rates	Interest rates (i.e. loans)
Interest rates	Environmental burden	Commodity and energy prices
Commodity and energy prices	Commodity and energy prices	Level of relationship with customer
Economy	Exchange rates	Economy
Calibration of work scope	Economy	Cost estimating data reliability or quality
Rate of materials	Calibration of work scope	
Beyond economical repair	Equipment operating parameters	
Equipment operating parameters	Beyond economical repair (BER) rate	
Hardware failure rate	Hardware failure rate	

As an outcome of the prioritisation process the respondent was able to identify the severe uncertainties for the delivery of maintenance, spares and training services, as represented in Table 9.10. This enabled to focus the attention to the key uncertainties.

The respondent selected suitable mitigation strategies for the high, medium, and low level of uncertainties. Table 9.12 shows the reliability associated strategies that have been selected for the given set of uncertainties in Table 9.10. The unselected strategies in Table 9.12 were not considered suitable for a number of reasons. Firstly, in the case of providing methods of updating reliability predictions it was mentioned that this does not apply to the case study as the methods do not need to be provided to the customer. Secondly, the size and skill level of the required maintenance crew will have already been decided and would not need to be assessed again at this stage. Thirdly, abuse of the equipment is a customer driven outcome, which depending on the level of interaction between the customer and solution provider it may not be possible to influence such activities.

Table 9.11 Results for selected cost drivers

<b>Cost driver</b>	<b>Cost uncertainty score</b>	<b>Minimum range (%)</b>	<b>Maximum range (%)</b>	<b>Cost significance (%)</b>
<b>Failure rate</b>	0.57	-20	+30	27
<b>Turnaround time</b>	0.45	-15	+20	54
<b>Material availability</b>	0.45	-15	+20	13
<b>Customer actual usage (fleet time)</b>	0.55	-20	+30	7

The respondent considered four cost drivers to be relevant to the project including “Failure rate”, “Turnaround time”, “Material availability” and “Customer actual usage (fleet time)”. Among these cost drivers “Failure rate” and “Customer actual usage” emerged as the cost drivers with the highest amount of uncertainty. The respondent confirmed that the resultant range suggestions for the minimum and maximum figures were accurate given the expectation that sufficient information may not be received from the customer. In terms of the degree of impact of cost drivers on the total estimate, “Turnaround time” constituted the highest amount of cost, followed by “Failure rate”.

The cost significance value was used to allocate the system level cost estimate of £50 million. The results are represented in Table 9.11.

Table 9.12 Uncertainty mitigation for reliability for severe uncertainties

Reliability response measures	Selection
Implement an integrated reliability engineering and product assurance program in purchasing, quality control, inspection, etc.	✓
Obtain the required data and prepare reliability bathtub curves, which define the failure rate for that part or equipment is plotted versus its age.	✓
Study the types of failures experienced by parts, components, products and systems to minimise failures.	✓
Establish what failures occur at what time in the life of equipment and be prepared to cope with them.	✓
Determine the time to failure distribution of parts, components, products and systems.	✓
Establish suitable parts, components, products and systems for redundancy.	✓
Study the effects of age, mission duration, and application and operation stress levels on reliability.	✓
Predict the reliability of equipments, products and systems to see if the established goals can be met.	✓
Indicate areas in which design changes would be most beneficial from the reliability improvement and cost reduction point of view.	✓
Provide a basis for comparing two or more designs and for choosing the best from the reliability point of view.	✓
Estimate the required redundancy to achieve the specified reliability.	✓
Conduct failure modes, effects and criticality analysis to identify areas which should receive concentrated design, research and development effort.	✓
Study the consequences of failures.	✓
Provide methods of updating reliability predictions as more data and test results become available.	
Predict at the design stage the reliability being designed into parts and components via the stress/strength interference approach and thereby optimise the designed reliability.	✓
Design systems to be more capable to withstand worse environments, and to last longer than necessary.	✓
Establish a failure reporting system to scientifically gather the vitally needed reliability data.	✓
Determine who is responsible for the failures.	✓
Guide corrective action decisions to minimise failures and reduce maintenance and repair times.	✓
Conduct trade-off studies among reliability, maintainability, availability, cost, weight, volume, operability and maintain for their life.	✓
Determine the size and skill level of the required maintenance crew for each type of equipment.	
Minimise design and manufacturing errors through reliability checks.	✓
Avoid user abuse of the equipment by providing warning labels and load and speed limiters and controls.	

In Figure 9.4, the cost results as a uniform distribution for this case study are presented. Whilst the most likely cost estimate was an input, the maximum value was observed to



be £61,674,943 and the minimum value was calculated as £41,662,529. The respondent highlighted “a robust figure was presented with a transparent flow of information that would be useful to communicate to the customer”.

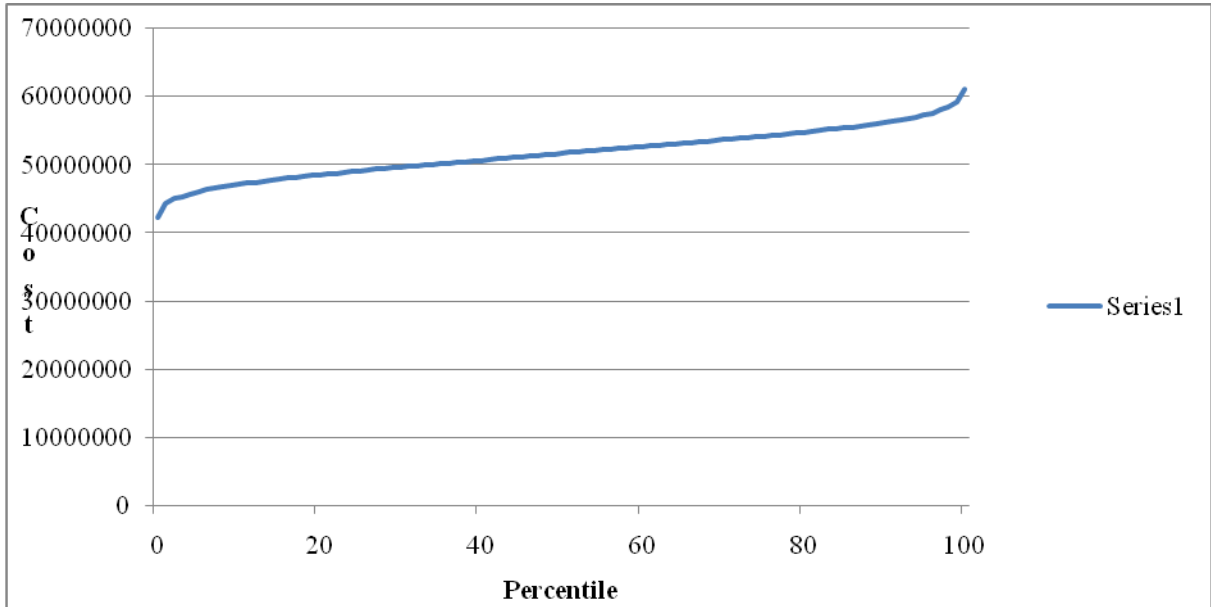


Figure 9.4 Uncertainty based cost estimates for Case Study 2

### 9.3.4 Validation outcomes

The validation outcomes are based on a semi-structured interview using a questionnaire with the participant of the case study. The focus was on aspects such as generalisability, logic, objectivity, reliability, usability, benefits and limitations of the framework.

The *logic* of the framework was declared to be suitable with minor deficiencies at the bidding stage, with a score of 8 out of 10. The logic was highlighted to be especially good in terms of its systematic process in focusing the interest in uncertainties. Furthermore, the respondent highlighted that a complete tool would be able to provide the impossible (e.g. predict the unexpected uncertainties). The input procedure was highlighted as a *limitation* due to the use of Excel, which causes the input procedure to be laborious compared to other software packages. It was emphasised that the framework was particularly *suitable*, with a score of 9 out of 10, for the bidding phase

due to the depth of the uncertainty guidance. It was suggested that the application of the framework would enhance the efficiency in considering uncertainties during the bidding process. Besides, it was mentioned that the framework could also be used within the in-service phase with the goal of understanding the influence of modifications in the service delivery and to communicate the consequences with the customer. The framework was declared to be very *generalisable* across the defence industry and it could also be applied outside the scope of this case study of radars, in even areas such as combat management systems, which hold particularly different characteristics. In terms of the implications of the use of the framework across the supply network, it was emphasised that the solution provider would need to be *responsible* internally and the outcomes would need to be communicated with the customer and suppliers. Thus, from this perspective a major role of the framework is to facilitate the communication across the supply network. As a major *benefit*, the framework allows realising what is important during the bidding in terms of uncertainties and the results are impartial representations of the input, as there are no intuitive results. It was also mentioned that the background of the people filling the framework would affect the outcomes and a good level of knowledge in the product would be necessary. In order to fill the framework it was suggested that different approaches could be adopted, whether it be a team working together or an individual working alone and then a validation exercise could take place within a team. The *usefulness* of the output depends on the reliability of the input, which relates to how much time is provided to fill the framework. The subject matter expert highlighted that through a rapid input process it took around 2 hours to fill the framework, which led to the following statement from the participant: “The value of the provided output is very good compared to the level of effort that is required to fill the tool”. The *usability* of the framework was specified to be easy and required only a limited amount of training particularly for the purpose of familiarity. Another key feature of the framework was highlighted in relation to the *flexibility* of using the tool with varying levels of available information.

The validation also covered an assessment of the specific features of the framework. Firstly, the covered list of uncertainties was specified to be totally comprehensive and was given a score of 10 out of 10. The calculation of the uncertainty level was declared

to be unique, and offered advantages over the current internal approaches, which create challenges in differentiating between risk and uncertainty. The emphasis in the assessment on aspects that cause uncertainty was suggested to be beneficial and this feature received a score of 9 out of 10. Furthermore, the weight assessment procedure using AHP was also considered to be suitable and the results from the assessment followed expectations. It was highlighted that the calculated uncertainty score, based on the uncertainty level and weight, followed company best-practice and was justifiable. In terms of the suggested uncertainty management strategies, defined based on literature review, the list was suggested to be comprehensive and also followed the internal applications and customer expectations. It was also suggested that these could be used as a checklist to follow in managing uncertainties. Furthermore, the provided list of cost drivers was also considered to be comprehensive receiving a score of 9 out of 10. The considered sources of uncertainty were defined to be suitable and essentially offered the user of U-TASC the ability to understand the root causes of variation. The AACE guidelines for specifying the ranges were also considered to be suitable, whereby a score of 9 out of 10 was awarded. The approach adopted to assign weights to cost drivers was considered to be reasonable and beneficial given the time pressure. The approach to turn a single point estimate into three was specified to give a high level of return on effort (Scored 10 out of 10). The respondent emphasised that it was necessary to avoid the commonly applied approach of adding  $\pm 10\%$  to cost to account for the influence of uncertainty.

To conclude the validation outcomes, the outputs were defined to be at the expected level of detail for bidding and the range of outputs was specified to be particularly suitable and useful in project planning, visualisation of uncertainties and capability management. The respondent was particularly satisfied with the provided uncertainty mitigation and cost uncertainty range suggestions. Furthermore, the results conformed to the expected levels. The respondent specified that “the approach is highly repeatable, and to a large extent the results would be similar across respondents”.

## **9.4 Case Study 3: Aircraft Carrier**

Project C is a very large military system-of-systems project (value £100s million) involving over 60 functional sub-systems of which only a minority are sourced in-house. The financial value of the case study is expected to be in the region of £50 million. The project is now anticipating the need to engage with the customer on in-service support, though it is at a very early phase (conceptual). Some of the key services offered within this project include, technical support (e.g. operation defect analysis and management), spares (e.g. spares management responsibility), management (e.g. efficient delivery of support), design authority (e.g. continuous assurance of the system performance and safety in-service), quality assurance (e.g. application of systematic quality assurance), and continuous improvement. The project is initially expected to be agreed for a length of seven years. The case study was considered to be suitable driven by the range of services to be offered including maintenance, and spares.

The interaction was achieved with an Integrated Logistics Support manager, who has over 18 years of experience. The objective of the respondent was to gather an understanding of the balance between cost and uncertainty. Furthermore, it was also specified that the project only had parametric estimates, which refers to single point estimates and the tool would enable to guide with the uncertainty considerations in the parametric model. The interaction was achieved through a number of means including face to face semi-structured interviews, WebEx meetings, and e-mails. The total of the interaction exceed 20 hours during the course of the validation process.

### **9.4.1 Tool verification**

The respondent provided feedback in an iterative manner, which in consequence alterations to U-TASC were made. An overview of some of the comments includes:

- The uncertainty importance assessment sheets require at least two inputs to be selected for the AHP calculation to work.

### 9.4.2 Framework input

The input from the case study consisted of scoring the uncertainty level and uncertainty relevance, selection of relevant cost drivers, scoring relevance of cost driver, system level cost estimate, and definition of uncertainty management strategies. As illustrated in Table 9.13, the respondent selected 29 types of uncertainties across all the uncertainty categories apart from “Training” to be relevant to the project. The set of uncertainties were chosen driven by the ability to make an assessment of the uncertainty level, which is associated to the degree of available information. Table 9.13 provides the input for each of the uncertainties across the relevant categories concerning the uncertainty level and the uncertainty relevance. Furthermore, the uncertainty score is an output, which is calculated by multiplying the uncertainty level with the uncertainty weight (calculated through AHP). The uncertainty score is used to prioritise the uncertainties, where the results are colour coded to reflect the differences between the uncertainties. Red represents those uncertainties that show areas that a lesser degree of information exists. The orange and green coloured uncertainties respectively depict relatively lower levels of uncertainty.

The second area of input was concerning the selection of the relevant cost drivers. The respondent highlighted that the following eight cost drivers emerged to be relevant to the project: repair cost, demand rate (spares), emergent work, material availability, labour availability, customer actual usage (i.e. fleet time), NFF cost, and BER cost. Furthermore, it was highlighted that a rough cost estimate had been produced at the system level, which constituted to be £54,000,000. In order to allocate this figure for each of the cost drivers the respondent input an importance figure for each of the cost drivers, as represented in Table 9.14. Furthermore, the percentage significance figures illustrate the outcome from AHP, which depicts the percentage contribution of each cost driver. Within this case study it was anticipated that cost of spares would constitute the highest amount of cost.

Table 9.13 Spares service input and output for uncertainty prioritisation

Uncertainty category	Type of uncertainty	Uncertainty level: Average input	Uncertainty relevance assessment: Input	Uncertainty weight: Output	Uncertainty score: Output
Commercial	Customer equipment usage	3	3	0.25	1
Commercial	Material cost	7	1	0.15	1
Commercial	Level of relationship with supplier	7	5	0.48	3
Commercial	Level of relationship with customer	7	5	0.51	4
Commercial	KPI Specification	7	9	1	7
Commercial	Stability of customer requirements	7	7	1	7
Affordability	Project life cost	4.1	5	1	4
Affordability	Customer willingness to spend	3	2	0.47	1
Affordability	Economy	1	9	1	1
Performance	Rate of surge	6.3	9	1	6
Performance	IT	7	8	0.73	5
Performance	Performance against KPIs	7	8	0.73	5
Operation	Maintainer performance	7	9	1	7
Operation	Equipment utilisation rate	7	5	0.58	4
Operation	Rate of emergent work	7	9	1	7
Operation	Rate of repairability	7	5	0.58	4
Operation	Mean time between failure (MTBF) data	7	5	0.58	4
Operation	No fault found (NFF) rate	7	8	1	4
Operation	Supply chain logistics	7	4	0.27	2
Operation	Rate of materials	7	5	0.58	4
Operation	Turnaround time	7	5	0.58	4
Operation	Provision of consumables	7	5	0.58	4
Operation	Operating parameters	7	5	0.55	4
Operation	Failure rate for hardware	7	5	0.58	4
Engineering	Rate of capability upgrades	7	2	0.18	1
Engineering	System integration issues	7	9	1	7
Engineering	Efficiency of engineering effort	7	9	1	7
Engineering	Failure rate for software	7	9	1	7
Engineering	Level of obsolescence	7	6	0.57	4

Table 9.14 Input and output for cost driver relevance

Pairwise Comparison	Input Significance	Percentage significance
Repair cost	3	0.15
Demand rate (spares)	9	0.29
Emergent work	6	0.17
Material availability	4	0.10
Labour availability	3	0.05
Customer actual usage (i.e. fleet time)	2	0.09
No fault found cost	6	0.13
Beyond economical repair cost	1	0.02

### 9.4.3 Framework output

Whilst some of the outputs from U-TASC for Case Study 3 have been demonstrated in Section 9.4.2 (including percentage contribution of each cost driver and uncertainty score), within this section other outputs associated to Case Study 3 are explained. Based on the results from the uncertainty prioritisation it was highlighted that the only ‘high’ uncertainties would be focused on for management purposes. Furthermore, the respondent suggested that all covered measures that were allocated under reliability, maintainability and supportability would be applied in order to manage the consequences of ‘high’ uncertainties. A comparison of the uncertainty categories for the delivery of maintenance is illustrated in Figure 9.5, whereby it is indicated that the uncertainty in achieving the performance requirements poses the highest amount of uncertainty.

The respondent pre-dominantly focused on the results that were generated from the Monte Carlo simulation. For this purpose the minimum and maximum range suggestions were calculated based on the input for the NUSAP matrix criteria. Table 9.15 indicates that across the selected cost drivers a high level of uncertainty is experienced in most areas. Using the AACE guideline the cost uncertainty score is allocated into the suitable AACE class, which suggests the suitable range for the cost driver.

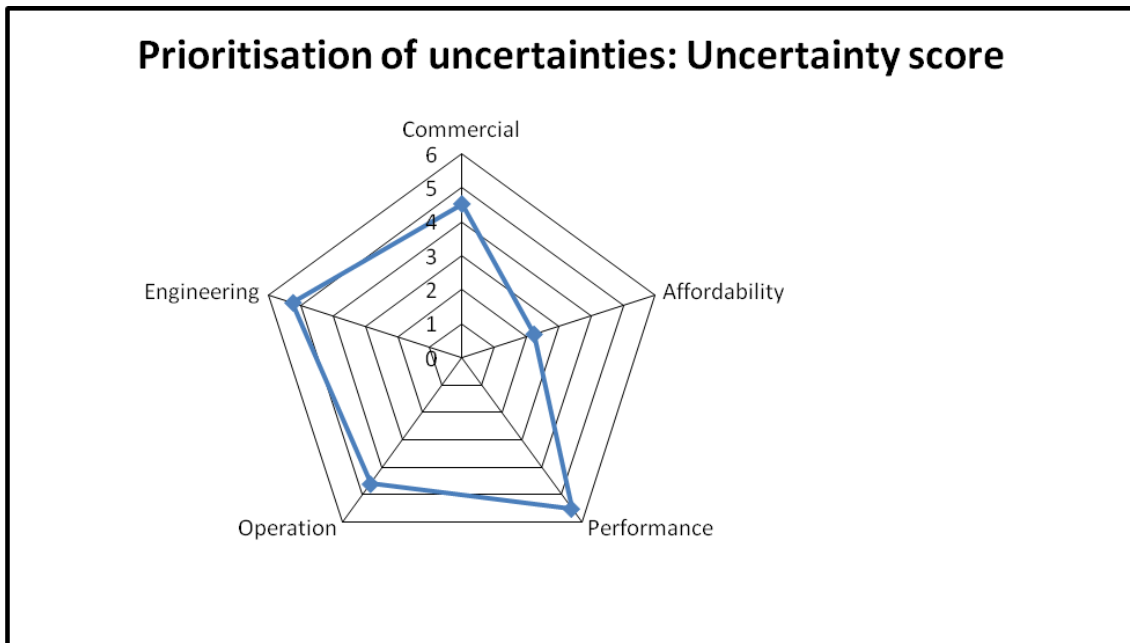


Figure 9.5 Maintenance service uncertainty category prioritisation

Using the ranges for the cost drivers highlighted in Table 9.15 in the Monte Carlo simulation, the respondent added a cost for the 7 years at £54,000,000 and let the model indicate the range of values it may receive across the cost drivers and the final answer. With the current data, the range of approximately £100 million maximum (the total for the maximum values was £101,040,639) to £30 million minimum (the total for the minimum values was £29,783,744) was referred to be sensible.

Table 9.15 Range suggestions for cost drivers in Case Study 3

Cost Drivers	Cost uncertainty score	AACE class	Min range (%)	Max range (%)	Minimum cost	Maximum cost
Repair cost	0.96	5	-50	100	4,089,617	16,358,471
Demand rate (spares)	0.92	5	-50	100	7,871,975	31,487,903
Emergent work	0.71	4	-30	50	6,448,965	13,819,211
Material availability	1	5	-50	100	2,784,186	11,136,745
Labour availability	0.93	5	-50	100	1,319,281	5,277,127
Customer actual usage (i.e. fleet time)	0.82	4	-30	50	3,294,139	7,058,870
NFF Cost	0.92	5	-50	100	3,486,656	13,946,626
BER cost	0.93	5	-50	100	488,920	1,955,683



Figure 9.6 represents the results for the triangular distribution, where the 80% percentile value constituted £67,061,251. The respondent did not have a view on the split across the cost drivers because an analysis of the cost driver level had not been conducted in the project, but it was highlighted that the outputs appeared to be reasonable at the total cost level.

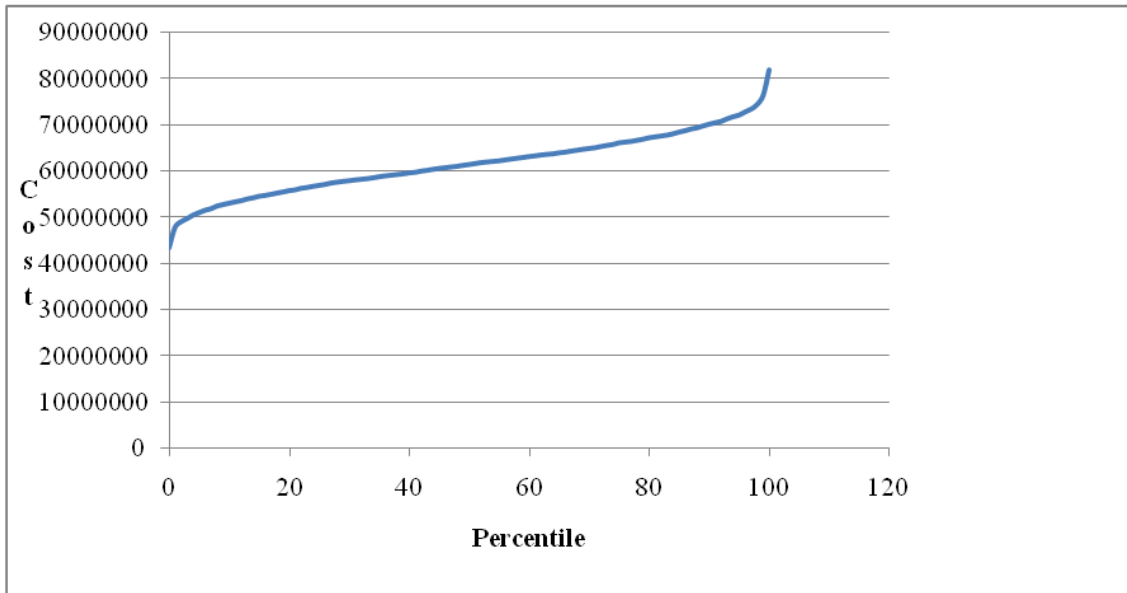


Figure 9.6 Monte Carlo simulation results for triangular distribution

#### 9.4.4 Validation outcomes

The outcomes of the validation were gauged through a questionnaire, which took one hour for the correspondent to answer, while the information was collected through a telephone interview. With regards to the applied frameworks in U-TASC the respondent made an assessment of aspects such as logic, generalisability, ownership, benefits, limitations, usability, reliability of results and comprehensiveness of the framework.

Initially the respondent emphasised that the applied logic for uncertainty considerations and the suitability of the framework for the bidding phase were regarded highly, receiving scores of 9 out of 10. Furthermore, the respondent highlighted that the framework was highly applicable across the whole life cycle of the in-service phase,

where the bid may be made. However, the respondent made suggestions concerning applicability using MS Excel. It was suggested that U-TASC contained too many sheets, which affected the duration of using the tool. In terms of generalisability, the participant highlighted that the framework was very general, even to the extent that it could be applied not just in CfA but also in any other form of service and support based arrangement. It was also mentioned that there were potential benefits for the design phase in terms of supporting with the service considerations.

The ownership of the tool was suggested to be distributed across the supply network, though it was mentioned that at the early stages this would be a costly approach, whereby it was mentioned that it would be beneficial for the solution provider to take this responsibility. Furthermore, the respondent highlighted that no particular department (e.g. finance, cost estimating) needed to take sole responsibility of U-TASC, as there were potential benefits across these stakeholders. In terms of maintaining the tool, the respondent highlighted that supportability engineers would be most suitable due to their cross functional involvement.

The major benefits of the tool were referred to be the ability to improve understanding of cost drivers. This was considered in light of the influence of uncertainties on cost and subsequently on the agreed price. The outputs from U-TASC were suggested to be an input to the bid considerations. Though, it was emphasised that the tool, as is the common approach, would be one of the approaches that gets considered and would not contribute single alone to the bidding in terms of the uncertainty considerations.

The limitations were referred to include (1) amount of training required, (2) necessity of data and/or judgments, (3) a reasonably rigorous approach required whilst filling U-TASC (for administration purposes). Furthermore, the background of people was mentioned to be an area that could affect the outputs due to the potentially adopted pessimistic or optimistic approaches. For this reason, it was emphasised that it was necessary to provide adequate training, whilst clear terminology and sufficient guidance would need to facilitate intuition. Concerning the usability of U-TASC the respondent suggested some of the strongest features included the low level of breakdown of the

uncertainties and the ability to add new uncertainties. On the other hand, the weakness was suggested to be in relation to the lack of visibility of some of the calculations. The respondent highlighted that the terminologies were clear and supported in effectively using the tool. Though, the number of sheets offered to the user was suggested to be high, whilst a reduction was suggested as a measure to increase usability. The amount of time required to fill the tool was referred to vary based on the amount of information available. An overview of the outcomes is presented in Table 9.16.

Table 9.16 Assessment of framework features in Case Study 3

Assessment criteria	Score out of 10 for comprehensiveness /usefulness	Comments
List and categories of uncertainties	9-10	Across the service context the uncertainties provide a highly comprehensive overview of uncertainties
Calculation of uncertainty level (through three criteria in NUSAP matrix)	10	The measures considered in NUSAP matrix enable a sufficient understanding of the degree of uncertainty
Data storing concerning the uncertainty level	5	Difficult to implement, however might be easier with a different tool set
Calculation of weights for uncertainties through AHP	8	Requires some degree of thought into the scoring procedure, though it is a highly applicable approach
Calculation of uncertainty score based in uncertainty weight and level	9	Applied a straight forward approach for uncertainty prioritisation
Provided list of uncertainty management strategies	10	A sufficient set of list is provided for guiding users to mitigate the uncertainties
Provided list of cost drivers	9	The list covers the many areas that cost may arise in the service context, though a clear association between material cost and obsolescence would be good
Considerations for the cost uncertainty linkage	9	Reasonable associations, which are justifiable
Suggestions for the ranges based on AACE recommendations	10	The suggestions offer a good set of ranges to base the thinking process
Calculation of the cost driver weight through AHP	10	Good approach to support understanding of cost drivers
The process of turning a single point estimate into three	10	Very good feature which enables to understand the minimum and maximum cost estimates
Conducted approach for Monte Carlo simulation	10	Normally in the project 100 runs are conducted U-TASC conducts 2000 runs, which is more than enough. In the project only triangular distribution is developed

When evaluating the outputs from the frameworks the respondent highlighted that the tool provided a list of work to do based on the prioritised outcomes, which would be useful for the project manager. It was also mentioned that the output is logically

consistent with the provided data. The key aspects associated to the framework were also assessed through the questionnaire.

## 9.5 Comparison across Case Studies

This section aims to demonstrate a comparison of the case studies in light of their context and the calculated results. The case studies in common have been selected from the naval domain focusing on different areas including complex electronics system, radar and aircraft carrier, respectively. Based on the level of information availability, Case study 1 is at a stage whereby a significant amount of information about the cost drivers has been realised, though there is a degree of uncertainty that further needs to be examined until the bid is made. Case Study 2 is the most mature bid, whereby the respondent highlighted that a reasonable level of understanding of uncertainty was already established. In Case Study 3 it was recognised that the project was at the very early stages of the bidding process, which indicated the high degree of uncertainty. Thus, the case studies reflect different phases of the bidding process and results indicate that U-TASC can be applied across the phases.

Table 9.17 Comparison across case studies of uncertainty scores for “maintenance”

	Uncertainty scores for maintenance		
Uncertainty category	Case Study 1	Case Study 2	Case Study 3
Commercial	2.17	2.10	4.53
Affordability		3.10	2.24
Performance		2.65	5.51
Operation	4.48	2.61	4.60
Engineering	4.83	1.92	5.25

In Table 9.17 a comparison between the case studies concerning the uncertainty scores for delivery of maintenance is presented. It is observed that across the categories of uncertainty a trend can not be realised, which indicates that for each project uncertainties are experienced in a unique manner. Given that the highest uncertainty score is ‘7’ it can be noticed that the highest uncertainties are experienced in Case Study 3, which follows expectations. Furthermore, a direct link between the uncertainty score and project maturity can be established. The values in Table 9.17 take into account both

the uncertainty level and its relevance to the project. It was recognised that by understanding the evolution of this score over time, targets could be set and during the bidding adjustments could be made to the contract in order to reduce the degree of uncertainty to the desired levels.

Table 9.18 shows a comparison across the case studies concerning the cost uncertainty scores. The table indicates that although each of the case studies has a service orientation the relevant types of cost drivers vary due to the differences in project scopes, which in parallel the sources and degree of uncertainty differ.

Table 9.18 Cost uncertainty scores across case studies

Cost drivers	Cost Uncertainty Score		
	Case Study 1	Case Study 2	Case Study 3
Repair cost			0.96
Demand rate (i.e. spares)			0.92
Emergent work			0.71
Material availability		0.45	1
Labour availability			0.93
Customer actual usage (i.e. fleet time)		0.55	0.82
NFF Cost			0.92
BER cost			0.93
Failure rate (or Unplanned Maintenance Costs)	0.81	0.57	
Turnaround time (or Planned Maintenance Costs)	0.59	0.45	
LRU cost	0.57		

U-TASC also provides a measure to understand the degree of uncertainty at the project level. This value is calculated by considering the cost uncertainty score and the relevance level of each of the cost drivers to the project. A score between 0.7 and 1 indicated a 'high' degree of uncertainty, whilst medium and low levels receive scores between 0.3 to 0.7 and 0 to 0.3, respectively. Case Study 3 reflected the highest degree of uncertainty with a score of 0.89, whilst Case Study 1 and 2 received scores of 0.66 and 0.49, respectively. The ability to realise the different levels of uncertainty along the bidding process indicated that the tool is highly flexible to various time-spans.

Uncertainty grows when forecasting the future, because the perceived clarity of the future increasingly diminishes driven by lesser available information. Thus, the

reliability of conducting uncertainty analysis is reduced as the contractual duration of interest grows over the foreseeable future. In light of this, through the case studies it was further confirmed that a bid is typically made for a maximum of a 7 to 10 years period, whilst indications for follow-on contracts may be built in for the subsequent period. This sets a limitation to the contractual time duration that U-TASC could potentially be applied to generate reliable results. Though, it is worth recognising that there are no time constraints from the operational side of the tool, as by applying the tool to different time frames it is possible to derive a road map for data collection.

The financial value of the case studies ranged between £15 million and £54 million. Although, the tool is capable of operating for projects with any financial value, the cost-benefit of using the tool needs to be recognised. For instance, the duration of input to U-TASC varied between one week and one day across the case studies driven by the availability of time and funds, along with the available information that is associated to the maturity of the bid. If a quick and not so much detailed analysis of uncertainty is aimed, then the financial value of the project or the expected profitability level becomes less of an issue compared to the case when a detailed analysis needs to be made using the tool. In the latter case, the duration allocated to populate the tool needs to be justifiable to the customer. Based on the received feedback from the case studies, it was suggested that the systematic approach offered in the tool derives operational efficiencies with reliable results. Though, further research would be needed in order to understand the financial benefit of utilising U-TASC compared to the current practices. Thus, the tool is useful to get a quick initial view of uncertainty early on, though with relatively higher financial valued projects (e.g. above £5 million) further analysis would need to be applied to realise the value of utilising the tool.

The contents of U-TASC in terms of the service considerations are specifically suitable to the most commonly offered services in CfA, including maintenance, spares and training. Across the case studies, support was delivered at various degrees. This means that irrespective to the type of equipment if the specified services are offered the tool can be applied. The case studies, indicated that differences across the air and naval domains were minimal, referring to the broad applicability of U-TASC.

## 9.6 Summary

In Section 9.1 the internal verification that was undertaken for U-TASC was presented, whereby some of the key suggestions were made to enhance usability, user friendliness, and calculations.

In Section 9.2 the initial case study was presented, which focused on a sample complex electronics system. The case was specified to be at a relatively early stage within the bidding stage, where an understanding of the cost drivers had been realised. Furthermore, 'high' uncertainties were still experienced in a number of areas such as (1) equipment utilisation rate, (2) rate of repairability, (3) availability of maintenance support resources and supply chain logistics.

In Section 9.3 the second case study focused on naval radar, which was at a relatively mature stage in the bidding process. The respondent considered four cost drivers to be relevant to the project including "Failure rate", "Turnaround time", "Material availability" and "Customer actual usage (fleet time)". Among these cost drivers "Failure rate" and "Customer actual usage" emerged with the highest uncertainty.

In Section 9.4 the third case study is presented where the focus is on an aircraft carrier, which is at the conceptual phase of the bidding process. With the provided data, the range of approximately £100 million maximum (the total for the maximum values was £101,040,639) to £30 million minimum (the total for the minimum values was £29,783,744) was referred to be sensible.

In Section 9.5 a comparison between the case studies is covered, whereby the uncertainty, cost uncertainty and the project uncertainty scores are presented. It is realised that in alignment to the degree of available information or project maturity the degree of uncertainty changes in parallel. It was acknowledged that the third case study, which is the most at the conceptual phase, faces the highest degree of uncertainty and suitable areas to manage the uncertainty were illustrated to the case study respondents. In the following chapter the discussion and conclusions for the research is presented.





## **10 Discussion and Conclusions**

This chapter presents a discussion over the key themes considered throughout this thesis, along with conclusions. Section 10.1 presents a discussion of the research findings. Section 10.2 focuses on quality, generalisability and implications of findings. The contribution to knowledge with respect to theory and practice is presented in Section 10.3. Research limitations are covered in Section 10.4, whilst the focus moves to future research expectations in Section 10.5. Finally, in Section 10.6 the conclusions to this study are covered.

### **10.1 Discussion of Research Findings**

In this section, a discussion of the key observations and research findings related to the presented material throughout this thesis is covered. The considerations include literature review, strength of research methodology, emergent and transformed uncertainties, cost uncertainty management and modelling frameworks, agent based modelling application and framework application and testing.

#### **10.1.1 Literature review**

As presented in Chapter 2, the author merged three research fields including “Industrial Product-Service Systems - IPS<sup>2</sup>”, “cost uncertainty modelling”, and “cost uncertainty management” in order to gather a better understanding of delivering Contracting for Availability (CfA). The focus for the research in IPS<sup>2</sup> centred on the applied business models and the cost and uncertainty implications of the shift to IPS<sup>2</sup>. Within the IPS<sup>2</sup> domain, the service content was focused on due to its high emphasis on CfA delivery. From the “service” side the focus was on determining the main characteristics of services and to build an understanding of the potential sources of variation that may affect costs. It was acknowledged that there are a number of schemes that have been developed in order to recognise the processes and implications of service delivery. Furthermore, the involved uncertainty has typically been classified based on supply and demand sources. Uncertainty in supply is influenced by various aspects such as fault

freeness of service or responsiveness. On the other hand, for demand some of the uncertainties include timing of request, volume and variety of demand. At a high level, literature enabled to define the uncertainties that originate from the service supply chain, including aspects such as scale of the supply chain, skill requirements, degree of customisation and changes in requirements. However, a detailed list of uncertainties were not identified, whilst the differences across the delivery of various services was also a gap.

From the “cost uncertainty modelling” side, it was identified that whilst there are many definitions of the term uncertainty the descriptions vary largely driven by the context of interest. However, there is a commonality with regards to defining the nature of uncertainty. This means that with the presence of uncertainty a difference between the actual and expected outcomes is highly likely to occur. The author recognised a trend in literature which classifies techniques to be used based on aleatory and epistemic characteristics of uncertainty. A number of papers have illustrated appropriate methodologies to follow for each of these scenarios. However, this classification was commonly not acknowledged across industrial participants, due to the difficulties associated to understanding these terminologies. Along these lines, the author recognised a number of relevant research gaps including:

- Systematic elicitation of expert knowledge to build a three point estimate
- Specification of a comprehensive set of cost drivers for CfA
- Explanations of the causes of uncertainty in specific types of cost drivers
- Guidance to choose cost uncertainty modelling approaches across services such as training, health monitoring or defect response
- Selecting suitable uncertainty modelling methods for specific types of uncertainties (e.g. failure rate, emergent work) that arise in service delivery

From the “cost uncertainty management” side, an emphasis on risk management was realised, whilst a growing range of authors are becoming aware of the differences between risk and uncertainty and the implications in terms of managing these terms. The author recognises that uncertainty is an umbrella term, whilst embracing risk and requires an explicit approach. The literature in cost uncertainty management needs

practical examples for the implementation of systematic methodologies for cost uncertainty management. A number of additional research gaps were also realised:

- Lack of research that aims to reduce the subjectivity in processes including prioritisation of uncertainties, cost uncertainty modelling and management
- Lack of research linking between cost uncertainty management and modelling
- Lack of research that guides with suitable strategies to mitigate or control the influence of uncertainties

### **10.1.2 Strengths of the research methodology**

There were a number of strengths in the research methodology driven by the selection of participants, adopted methods for data collection, and the form of interaction with participants. Firstly, the author had wide interaction with the customer and key organisations across the defence industry in the UK. As a result the author was able to gather an understanding of cost uncertainty across the industry in a comprehensive and realistic manner. Gathered information from each organisation were compared and contrasted in order to get a general perspective of the defence industry. Furthermore, sponsoring organisations were heavily supportive of this research, and industrial leads across the organisations initially directed the researcher to the key members involved in cost uncertainty modelling and management across their organisations. Through referrals the author managed to get close interaction with key members involved in cost uncertainty across the industry. In selecting the participants an emphasis was put on service involvement within the context of cost uncertainty.

The qualitative nature of the research from the perspective of industry interaction required a sufficient understanding of the suitable methods to adopt when collecting data. The author aimed to use a number of methods in order to ensure that the weakness of a particular method did not influence the gathered results. As presented in Chapter 3, the key methods used in this thesis included interview, workshop, survey, and case study due to the capability of these approaches in collecting qualitative information from subject matter experts.

The author actively collected data along the research, whilst taking notes during interviews and case studies. Industry participants to a large extent did not allow any form of recording due to sensitivity concerns. Furthermore, in order to clarify the results from the interactions and to reduce any kind of bias the author (e.g. defining results according to the research problem) developed reports that were validated with industrial collaborators. This feedback process served the purpose of a sanity check and was followed throughout the data collection process.

For the case studies a range of areas were selected from the naval domain, whilst the background of the participants and further interviews with subject matter experts with experience in other domains also enabled to verify that the research is applicable across domains. Furthermore, the author paid due attention to the relevance and requirements of this study whilst selecting the case studies. The case studies were implemented with the goal of minimising the authors' ability to influence the participants. Along these lines, the author paid a large amount of time to familiarise the tool with experts, whilst the input process was managed by the respondents. The approach taken with the case studies during validation are considered to be suitable given the unique characteristics of the frameworks embedded in U-TASC and the sensitivities that industry have over publishing cost related data.

### **10.1.3 List of uncertainties**

Based on literature review a research gap was identified with regards to understanding the specific types of uncertainties that are experienced in CfA. Additionally, the author aimed to define the explicit differences in terms of uncertainty that are experienced in CfA compared to the traditional approach of contracting. Along these lines, as presented in Chapter 5, the explicit areas of uncertainty in CfA were classified into emergent and transformed uncertainties. At the centre of emergent uncertainties lies the "equipment availability", which is affected by a number of uncertainties originating from the customer and the manufacturer. The customer contributes with its varying equipment usage needs, intangible expectations, and changing capability requirements. The manufacturer needs to tackle variation in human performance during service

delivery, and evolving constraints in resources for support. Across the supply chain the level of information and knowledge flow is a key source of uncertainty that affects the process of co-creation of value. The degree of dependency across the members of the supply network causes this to be a new form of uncertainty. On the other hand, the transformed uncertainties are particularly driven by the shift in responsibilities, while the change in the source of revenue promotes the need to take adequate measures to tackle these uncertainties due to the threat to profitability. The shift in these uncertainties is associated to the changing customer and technological requirements.

Table 10.1 Link between emergent uncertainties and cost drivers

<b>Emergent uncertainties</b>	<b>Cost drivers</b>
Equipment availability	Failure rate, turnaround time, storage, transport cost, packaging cost, repair cost, demand rate (spares), emergent work, material availability, labour availability, customer actual equipment usage, LRU cost
Payment based on performance	Turnaround time, repair cost, packaging cost, material availability, labour availability, no. of trainers
Human performance	Labour availability, turnaround time, repair cost, no. of trainers
End user equipment usage	Customer actual usage, no fault found rate, beyond economical repair, LRU cost, emergent work
Change in evolving constraints for support	Material and labour availability, storage
Intangible expectations	GFX supply, storage, labour and material availability, trainee availability
Change in capability requirements	Failure rate, LRU cost, storage, facilities for training, material and labour requirement
Lack of information and knowledge sharing	Turnaround time, failure rate, repair cost, storage, LRU cost, material and labour availability, beyond economical repair, no fault found rate, emergent work
Supplier dependence	Material availability, GFX supply, beyond economical repair, no fault found rate, facilities for training, turnaround time, storage
Training for availability	No. of trainers, facilities for training, no. of trainers

The impact of the emergent and transformed uncertainties is experienced on cost drivers, which are creating challenges in the cost estimation process. Lack of understanding of various cost drivers causes uncertainties. Table 10.1 describes links between the emergent uncertainties and the cost drivers for the CfA context. Based on validation results, managing failure rate emerges as the most important uncertainty when moving into CfA, where the inter-linkages between the customer, manufacturer and suppliers trigger the degree of the uncertainty. This refers to the sharing of

information and knowledge concerning the equipment usage and health, while the concept of co-creation of value has particularly promoted collaboration.

#### **10.1.4 Cost uncertainty management framework**

In Chapter 6, the author emphasised the importance of cost uncertainty management, where it was identified that a range of researchers along with industrial experts have been suggesting to increasingly adopt suitable uncertainty management processes. It was highlighted that compared to the traditional approach of risk management, deterministic assumptions are neglected. This enables to avoid decision making to be based on data that is inherently wrong. The risk management perspective relies on the assumption of perfect knowledge, which supports in conducting quantitative analysis. Along these lines the application of uncertainty management takes a more so qualitative approach compared to risk management in order to question the validity or accuracy of available data. Subjectivity is present throughout the cost uncertainty management process including uncertainty identification, prioritisation and mitigation. Though, there has been a lack of research that has demonstrated the application of methodologies to manage cost uncertainty.

U-TASC offers a standard procedure to elicit expert opinion that guides with uncertainty management. As a result of the architecture, the expert gets the opportunity to question systematically the validity of the input data for uncertainty management. Furthermore, it becomes possible to consider questions that will affect the planning early on and ultimately the performance of the delivered support solution. The tool enables improved uncertainty visualisation by facilitating communication with the customer and realising the evolution of uncertainties. Also, capability management is improved by being able to define those areas that require further information driven by understanding the uncertainties and how to manage uncertainty. There are also benefits in project planning by capturing the uncertainties in a systematic manner.

The suggested list of uncertainties have, through validation, been realised to be comprehensive for the bidding stage, while the tool offers flexibility to include further

uncertainties. The combination of uncertainty level and relevance to prioritise uncertainties was considered to follow the common practice. However, the author introduced the use of NUSAP matrix and AHP for these processes, respectively. A major benefit of the approach was realised in relation to the standardisation in comparing the level of uncertainty across variables. On the other hand, whilst the application of AHP is wide, it has not commonly been used to prioritise uncertainties within the cost estimation literature. A major benefit of the approach was realised in terms of its ability to translate the user knowledge into a reasonably sound comparison across many cost uncertain items. Whilst the uncertainty management strategies across literature are diverse, driven by the service context, the key principles from reliability, maintainability and supportability were adopted. This approach was found to be suitable as the validation showed that the subject matter experts followed similar principles to combat the influence of uncertainty. The added value was highlighted to be in relation to the ability to use a single framework embedded in a tool to conduct a comprehensive study of cost uncertainty management systematically.

### **10.1.5 Cost uncertainty modelling framework**

In Chapter 7, the author presented the bid cost uncertainty modelling framework. It was highlighted that in common Three-point estimates are used as an input for quantitative risk analysis. Furthermore, Monte Carlo simulation was suggested to be the typical approach in the defence industry to construct probability distributions. The approach enables to replace single points with probability distributions of possible values based on the Three-point estimates. With the adoption of CfA, cost estimation was highlighted to further emerge as a major challenge at the bidding stage due to the uncertainty that arises from the dynamic behaviour experienced in service delivery (e.g. changing usage conditions and equipment health) and the manipulation of customer requirements. The degree of uncertainty is associated to the length of the contract (e.g. 30 years).

Through interaction with industry it was recognised that the application of Monte Carlo simulation required better handling of the inputs. Along these lines the author focused on a number of challenges that influences cost uncertainty modelling. These included

uncertainty identification, prioritisation, visualising the boundaries between uncertainties, and defining the degree of uncertainty in cost through a three point estimate. In common these challenges possess qualitative characteristics, whilst a step by step procedure has been developed to tackle these challenges as follows:

- Development of an uncertainty score: focuses on representing the level generated from applying the NUSAP matrix.
- Linking uncertainties and cost drivers: aims to reflect the major sources of uncertainty in cost drivers. The applied methodology to devise these relationships using fishbone diagrams and the validation that followed enabled to realise a comprehensive set of relationships that enables to recognise the sources of uncertainties in cost drivers.
- Defining range for cost drivers: considering the cost uncertainty score as a maturity indicator in the AACE (1997) guidelines reflects the degree of confidence for given data and it is reasonable assume such a relationship.
- Defining Three-point estimates: the AACE (1997) guidelines to define the specified ranges were considered to be sufficient by the author driven by their recommendation to apply it in the defence industry and the feedback received during interviews and case studies.
- Monte Carlo simulation: the author did not apply external simulation packages to U-TASC, but instead inbuilt algorithms were used to conduct Monte Carlo simulation. Although, the approach is not unique it was conducted with the aim of developing a single tool capable of achieving multiple purposes.

The respondents from the case studies indicated that the framework was comprehensive with its approach across the key steps along the framework, whilst particularly emphasising the significant benefit of the framework in transforming a single point estimate into three.

### **10.1.6 Agent based model application**

The focus on ABM in Chapter 8 centred on a strategic level problem that arises at the bidding stage in determining the form of interaction across the supply chain given



dynamic uncertainty through incentive mechanisms and various risk sharing approaches between the solution provider and the spares supplier. A major strength of ABM is related to capturing emergent behaviour of a system or a supply chain over a life cycle. It is particularly beneficial in modelling more dynamic conditions (e.g. failure rate) where interaction requires adaptation over time, due to independent decision making architectures, as is the case in the service oriented approach of CfA. However, it is hard to define boundaries around the way in which ABM should be constructed as in literature a universally accepted design methodology is missing.

One of the most distinctive characteristics of services is their process nature. Unlike physical goods, services are dynamic, unfolding over a period of time through a sequence of events and steps. Furthermore, with manufacturing based industries typically experiencing a shift towards service orientation major challenges have emerged due to the nature of services. Cost estimation, which has significant financial implications, has been challenged by various factors such as determining the arising rate, obsolescence and technology refresh. The common theme across these complexities is the dynamic nature, which is increasingly challenging their representation through static models. To the contrary of static models, dynamic models (e.g. ABM) are able to reproduce the evolution of a system over time. The simulation framework covered in Chapter 8 considers the early bidding stage where there is limited information available for a Target Price Performance Incentive (TPPI) type arrangement in CfA. In the agent based model failure rate is considered as a dynamic uncertainty that triggers variation in cost drivers that are typically the most important uncertainty variable in a CfA. Furthermore, the uncertainty in the cost drivers are considered by defining a range to each cost driver based on the uncertainty assessment. This proved to be an effective way to address the financial risk questions associated to providing maintenance services. The complex, interactive and dynamic effects of the supply chain in terms of varying customer equipment usage requirements, satisfying the demand for spares and resource requirements made the simulation approach effective for the early stages. The generated results are particularly suited to arranging the incentive and risk sharing mechanisms along the supply network at the bidding stage.

### **10.1.7 Framework application and testing**

The bidding process in the defence industry, particularly for service, offers limited amount of time to make in-depth analysis of the uncertainties that influence cost drivers. Along with this, it has been recognised that there is a gap between cost uncertainty management and modelling considerations (Erkoyuncu et al., 2009b). Driven by these two aspects U-TASC has been developed with the goal of providing support in decision making in an effective and efficient way by applying systematic processes as discussed across Sections 10.1.4 and 10.1.5. Furthermore, an agent based model has been developed in order to introduce the approach to the cost estimation community as covered in Section 10.1.6.

The identification of uncertainties through a question and answer format was considered to be beneficial particularly in narrowing and guiding the focus. However, there were a number of challenges that affected the development of this feature in U-TASC. Firstly, similar to any software package that requires expert knowledge the input needs to be collected in an objective manner and the level of subjectivity needs to be minimised. From the uncertainty identification perspective this refers to achieving a common understanding of the definition and scope of each suggested uncertainty. In order to achieve consistency a definition and examples for each uncertainty were provided as comments in U-TASC. Furthermore, the participants of the validations confirmed that sufficient guidance was provided. A second challenge was associated to achieving a comprehensive list of uncertainties. A number of means to collect data about the types of uncertainties was considered including interviews, workshops, and surveys across subject matter experts involved in CfA and cost estimation at the bidding stage in the defence industry. Moreover, the adopted methodology facilitated to capture a comprehensive view across projects.

From the uncertainty prioritisation perspective in order to reduce subjectivity an emphasis was put on the definitions of the scores used in the NUSAP matrix when determining the uncertainty level. Along these lines, the author conducted a number of workshops and validation sessions that enabled to alter the definitions of the scores in

the NUSAP matrix. The alterations were made in particular to capture a language that is understandable to the stakeholders. On the other hand, the use of AHP to determine the degree of relevance of the uncertainty was considered to be suitable to elicit expert opinion to determine an importance level for each uncertainty. The tick box approach adopted in MS Excel to specify the uncertainty mitigation strategies was considered to enhance the applicability of U-TASC, whilst also visualising the selection process.

Since traditionally uncertainties have not been considered in relation to specific cost drivers, developing the linkages was particularly challenging, especially due to the qualitative nature of many uncertainties. These relationships generate detailed information about the reasons of uncertainty in the cost drivers. As the relationships are embedded in U-TASC the user of the tool does not need to add new relationships unless new cost drivers and uncertainties get included in the tool. The Monte Carlo simulation calculates and adjusts the probability curve in real time, which makes the tool highly time effective.

It was also suggested that with the growing influence of dynamic uncertainties, suitable approaches would need to be considered to reflect these influences on cost drivers. Driven by this challenge the use of ABM was considered to be particularly suited to assist in linking cost drivers and uncertainties, while the rapid growth in ABM is expected to influence its application in cost estimation in the defence industry. During the interaction with industry it was highlighted that a steep learning curve was required to understand the programming behind the modelling.

The overall results from validation with industrial collaborators show that the proposed frameworks offer a reasonable set of steps, which can yield beneficial outcomes in achieving robust cost estimates and in managing uncertainty.

## **10.2 Quality, Generalisability and Implications of Findings**

The author, in this section discusses a number of aspects associated to the quality, generalisability and implications of the study. Also an insight into the business impact of the research is provided.

### **10.2.1 Quality of research findings**

The author paid due importance to the selection of the suitable data collection methods and followed a formal research strategy as presented in Chapter 3. Along these lines, semi-structured interviews, workshops, received documents, surveys and case studies were applied to collect data and follow on interactions either through developed reports or interviews was conducted in order to verify the understanding. Furthermore, when possible, triangulation of data and methods was implemented, whilst also collecting data from multiple organisations for the purpose of gathering a general view of the defence industry.

Throughout the case studies, a structured approach was followed, where initially adequate time was spent to make the user aware of how U-TASC should be used. During this process an iterative process was followed through face-face interviews, e-mails, WebEx presentations, and telephone conversations in order to clarify any misunderstandings that the participants may have experienced. In parallel the verification enabled to make changes to the tool and further enhanced the reliability of the results. Across the case studies a mixed approach (including face to face interviews, WebEx, and telephone conversations) was followed to elicit required information driven by the degree of interaction that the participants preferred. When the author was confident that the tool had been filled correctly and captured sufficiently the depth of the available information or maturity of the case study then feedback was requested.

The validation for each case study consisted of both qualitative and quantitative perspectives. Qualitatively the considered concepts and their applicability or relevance were assessed within each sheet. Additionally, a questionnaire was used to capture the

experts' opinions about the effectiveness and efficiency of implementing U-TASC. On the other hand, the quantitative perspective focused on comparing the numerical results generated in the tool with the expectations of the estimators.

### **10.2.2 Generalisability of research findings**

In this section the author discusses the generalisability of the research findings. The proposed cost uncertainty management and modelling framework and the agent based model was illustrated to be applicable at the early stages of bidding for CfA in the defence industry. Although, the defence industry was the source of information, whilst commonalities across similar industries (e.g. aerospace, nuclear, and oil) in delivering maintenance, spares, and training (e.g. complex engineering services) provides applicability opportunities for this research in other industries as well. This was highlighted during the validation process, where it was suggested that some adjustments or additions to the uncertainties and/or cost drivers may potentially be required. Additionally, the steps provided in the cost uncertainty management and modelling frameworks can be applied without major modifications. However, in order to justify these expectations the research would need to be applied in other industries.

There is various level of responsibility transfer within the CfA context, where through interaction with a number of CfA oriented projects the research has captured the diverse needs in integrating uncertainty to cost estimation for this context. It is also worth highlighting that the respondents came from different organisations across this industry, which enabled to avoid industry wide deductions from company specific findings. Furthermore, the depth of the range of experience of some of the respondents across domains in the defence sector helped to gather a complete picture of the defence industry in terms of the list of uncertainties, cost drivers, links between the cost drivers and uncertainties, terminologies for the scoring in the NUSAP matrix and the applicability and usefulness of the frameworks. The research also benefitted from cross domain data collection. For instance, in defining the cost drivers and the relationships between cost drivers and uncertainties the author conducted a number of workshops in the air domain to elicit expert knowledge, which the collected material was

subsequently validated with participants from the naval domain and suitable refinements were made as found fit. Although the author has not had direct interaction with participants from the land domain throughout the research, feedback from case studies has indicated that the research is highly applicable.

### **10.2.3 Applicability of findings and business impact analysis**

The focus of this section is on discussing the applicability of findings and the potential business impact of the research, in terms of the implementation of U-TASC for cost uncertainty management and modelling and the agent based model.

By applying a pre-defined step by step procedure as suggested in U-TASC organisations, in particular large size organisations, can be assisted to adopt standardised processes for cost uncertainty management and modelling. This can benefit in enhancing learning across projects as differences can be realised in a systematic manner by utilising the flexibility that U-TASC provides in areas such as adding new uncertainties, cost drivers, relationships between uncertainties and cost drivers, and uncertainty mitigation strategies. This also refers to the ability of the tool to store data that can be retrieved in a standard format over time, whilst also enabling to automate the process of visualising the progress or performance in a project in terms of the levels of costs and uncertainties. It is also worth recognising that the use of MS Excel as the means for application in U-TASC is suited to the defence industry, as it is commonly used. Although it has been emphasised that the tool is particularly suited to the early stages of bidding, due to the flexibility of U-TASC, it may also be possible to use the tool throughout the bidding process (e.g. phase reviews), in addition to the period after the contract award. The flexibility in this case refers to the ability to adjust the input, whilst the framework still holds applicability. Although, the duration of the application of the tool varied across the case studies, it is envisaged that the tool can enhance efficiency and effectiveness during the bidding process.

The cost uncertainty management framework offers a systematic process to be applied to any service driven context across complex engineering systems. By applying the

framework the expert can realise in a robust manner the relevant uncertainties, prioritise the uncertainties and select the suitable mitigation strategies. It is worth mentioning that the agile approach, which provides real time results, guides the bidding team to understand the key areas that require attention and provides a comprehensive set of ideas to combat the influence of uncertainties. It was recognised that the framework particularly enables to focus the effort. Furthermore, the ability of U-TASC to store data about the uncertainty prioritisation scores at the uncertainty category and project level enables to make comparisons over time (e.g. during bidding or after bid acceptance).

From the cost uncertainty modelling side it is recognised that the framework is highly adaptable in terms of selecting the relevant uncertainties and cost drivers, while realising the consequences of various scenarios. The particular benefit of this framework is its ability to extend the current process of the organisation that estimates single point estimates by transforming these estimates through the calculation of the minimum and maximum cost estimates. This functionality has promoted one of the case studies to further use the tool in an actual bid, where the organisation had found an opportunity to turn single point estimates into three. The reasons for applying the framework were highlighted to be associated to the enhanced ability to communicate the reasoning behind the uncertainty considerations. This may also mean that the bidding team may take actions to reduce the uncertainties that are highly affecting cost drivers in order to reach more competitive offerings. It is also worth recognising the ability of the tool to support decision making through agile calculations of the percentile values from the Monte Carlo simulation, whilst also increasing the confidence of the user concerning the degree of uncertainty. As a result the expert is able to specify confidence limits and thresholds when agreeing new contracts.

The implementation of U-TASC within the current processes, in industry, should not require any major additional enhancements. The only adjustments would be made to add new uncertainties and cost drivers driven by the very specific needs of projects, whilst the tool can currently automatically incorporate provided text for five uncertainties and cost drivers into the analysis without any further efforts from the experts. This is particularly beneficial for industry as it does not require any major

resources or financial backing. The author has developed a training and maintenance manual, along with a recorded video of thirty minutes that assists the experts with how to use the tool. It is envisaged that this level of material for training will be sufficient to be able to use U-TASC. The challenge concerning the utilisation of the tool is largely considered to be driven by cultural aspects, which requires users of the tool to be convinced that the tool and its results are reliable and credible, which can only be assessed through an initial test period at an organisation.

The developed agent based model offers a number of benefits to industry in defining the incentive mechanism between the customer and the solution provider and the risk sharing mechanism between the solution provider and the spares supplier. The dynamism in the failure rate constitutes a major aspect of the agent based model, whilst representing uncertainty in a unique manner. Though there currently are various aspects that are affecting the applicability of the model. Firstly, the application of the agent based model is achieved through AnyLogic, which is a multipurpose built software simulation package and in order to run the model, users need a licensed copy of the software. Although, this poses a limitation to the applicability of the study, given the recent growth in popularity of the software it is envisaged that this limitation will gradually diminish over time. Secondly, the applicability issue lies in the necessity of programming knowledge of Java, if the user would like to alter the model or understand the dynamics. Thirdly, ABM is not yet widely known by industrials in the defence industry, which influences the perception towards to model and its applicability.

### **10.3 Key Research Contributions**

This research provides an increased understanding into modelling and managing uncertainty in cost estimation within the context of CfA at the bidding stage by setting out detailed frameworks, which have been embedded in a software prototype. The focus is distributed across uncertainty identification, prioritisation, classification, management, linking uncertainties and cost drivers, defining range for cost drivers, three-point estimating and Monte Carlo simulation. Additionally a novel approach to capture the dynamism in cost through agent based modelling was developed that



contributes to the cost estimation literature. The author also set out the types of uncertainties that are prevalent in CfA, whilst also explaining the unique characteristics of CfA in terms of uncertainties. It is believed that each of these studies contribute to literature with novel considerations. To summarise, the research has contributed towards formalising the considerations that are associated to uncertainty, which commonly involve subjectivity and informal processes (e.g. range specification for cost drivers). Based on the presented research gaps in Section 2.7, the key research contributions of this research are summarised in the following areas:

- **Understanding the *shifts* in uncertainties with IPS<sup>2</sup>:** Based on the research gap associated to demonstrating the specific types of uncertainties experienced with CfA, this research presents a list of uncertainties consisting of seventy types. Both literature review and industrial interaction facilitated the development of the list. The key categories of uncertainties were classified as: commercial, affordability, performance, training, operation and engineering. Furthermore, the unique characteristics of CfA were illustrated by classifying relevant uncertainties into emergent and transformed sources
- **Systematic framework to *manage cost uncertainties* in IPS<sup>2</sup>:** The cost uncertainty management framework transforms the traditional emphasis on risk management, by formalising a procedure that questions assumptions and enables to assess the influence of uncertainty. From a detailed perspective the framework provides a novel approach to prioritise uncertainties in a systematic manner. Additionally, it offers an exhaustive list of strategies to reduce or eliminate the influence of uncertainty based on reliability, maintainability, and supportability measures
- **Systematic framework to *model cost uncertainty* in IPS<sup>2</sup>:** The framework contributes to knowledge driven by the research gap that was identified in eliciting expert knowledge whilst building Three-point estimates. The framework defines the sources of uncertainty in cost

drivers, in order to understand the degree of its influence. The framework also contributes by providing a list of cost drivers that are experienced in CfA. The degree of influence is used to assist in revising a single point estimate into three

- **Reflecting the influence of *dynamic uncertainty* in IPS<sup>2</sup>:** A novel approach to integrate the influence of dynamic uncertainty was considered for cost estimation using agent based modelling. The model visualises the cost implications along a representative CfA supply network, where incentives and a risk sharing mechanism facilitates interaction. The focus was on the dynamism of the uncertainty in “failure rate”, where both the variability of the failure events over time and the associated uncertainty over time was applied. As for outputs, decision making across the supply network is supported concerning structuring the incentive mechanism and the risk sharing given the cost implications.

## 10.4 Research Limitations

This section presents the limitations of the research in terms of the adopted methodology and findings. The limitations associated to the methodology are considered with respect to the applied qualitative research, case studies and interviews. On the other hand, the limitations in the research findings are discussed in relation to scope and context of applicability.

Application of qualitative research in common causes issues in terms of replicability of results due to the human driven nature of the approach. This also means that the findings cannot be extended to wider populations with the same degree of certainty that quantitative analysis offers. For example, it has often been suggested that it is difficult to generalise findings from a case study. This is associated to the limited opportunities to conduct statistical analysis of data with small populations, which makes it difficult to realise whether the data is statistically significant or the results are due to chance. For

instance, the investigator in the collection and analysis of data can influence the results by adding his/her perception to the results.

The generated results from a case study are driven by the behaviour of the participants, whilst there is the threat that the captured results do not represent the views of most people. The duration of each case study varied, whilst the author aimed to minimise his influence during the data input process. The duration of the case studies was determined by the time limitations, resources and availability of experts. However, a proactive approach was adopted in order to cope with the limited time that was available during the case studies. These actions consisted of: (1) close interaction prior to the case study to familiarise with the case before hand, (2) demonstrating the frameworks before hand in order to clarify any potential misunderstandings, (3) supporting data input if required through various means (e.g. telephone, e-mail, and face to face), and (4) following up the understanding about the results from the case studies.

Throughout the research, the author took notes to collect data from semi-structured interviews and case studies. To a lesser extent the author also recorded the discussions. The author aimed to avoid basing research findings that focus on what happens in small groups of people, because such an approach limits the ability to generalise the results. It is recognised that during an interview, note taking and continuing the discussion can be demanding, and could potentially affect the amount of data that is collected. In order to combat the influence of this the author distributed reports for validation purposes. In terms of the scope of the findings the frameworks do not take into account uncertainties in the form of unknown-unknowns, which refer to events and outcomes that were not considered by an observer at a given point in time.

## **10.5 Recommendations for Future Research**

The focus of this section is on suggesting potential areas for future research that have been derived from the research findings. Furthermore, the suggestions are classified based on the key themes covered within this thesis.

### **10.5.1 Research themes**

From the literature review perspective the author has identified two areas that require further research. Firstly, it is necessary to recognise that the service literature does not offer adequate ways to classify services, although limited research in marketing and operational approaches have been developed. Furthermore, there is limited research that considers the in-service phase in a holistic manner (e.g. integrating the combined influence of different services) by taking an activity based approach for service delivery.

The second area of research is with regards to capturing and visualising the dynamic nature of service supply and demand in cost uncertainty modelling. However, there is a lack of link between service literature and cost estimation to identify the types of uncertainty and modelling approaches. Based on the uncertainties that have been realised in literature it is apparent that epistemic and aleatory type uncertainties need to be defined for service delivery and suitable modelling approaches need further classification to guide the selection of the modelling approach. Advanced techniques that show promise to quantify in-service uncertainty which is typically in the form of epistemic uncertainty are artificial neural networks, fuzzy set theory, case based reasoning, genetic algorithms, and a combination of these. Furthermore, interest in various simulation approaches such as discrete event, systems dynamic and agent based modelling is growing. Such approaches need to support in realising the influences of uncertainties in CfA that can have interdependent and dynamic characteristics. However, there is a need for research that applies the various techniques that are available in the service context in order to compare and contrast results.

### **10.5.2 List of uncertainties**

For future work, with the expected shift to capability contracts from CfA, there is a need to understand the potential uncertainties that will be experienced. The emergence of capability contracts will enhance the solution providers' responsibility in operating the equipment rather than focusing on supporting it. There are a number of reasons for

this need, mainly driven by the increase in demand by the customer (e.g. Ministry of Defence in the UK) to pass on further responsibilities to industry. Thus, areas of concern include how to measure the suitable level of uncertainty transfer, and trade-off assessment for both the customer and the solution provider concerning the potential long term impact of such contracts including the future of manufacturing. Additionally, it will also be necessary to identify the types of uncertainties that will be experienced with capability contracts. For delivery of CfA further research requirements include ways to measure co-created value, designing internal organisational structures, designing service supply chains and methodologies to define the appropriate service and product combinations, while the role of uncertainty needs to be addressed within each of these areas. Another area of research requirement is associated to supporting industry when transforming the business model into various CfA options that have different levels of service concentration. Such research would need to aim to reduce the impact of uncertainty in terms of cost, schedule, performance and business return.

### **10.5.3 Cost uncertainty management**

There are a number of areas that U-TASC and the practice of cost uncertainty management could be developed, including:

- Firstly, the framework could also include the influence of risk on projects. Addition of this aspect will enable to enhance the rigour in cost estimates as well as supporting project planning.
- Secondly, whilst currently the framework focuses on the influence of uncertainty on cost, this could be advanced by considering the influence on schedule as well. This would benefit project planning.
- Thirdly, uncertainty mitigation strategies can further be classified based on the influence of specific uncertainties.
- Fourthly, uncertainty mitigation strategies can be classified for specific services.
- Fifthly, mitigation strategies can be classified over the life cycle
- Sixthly, various forms of analysis can be applied to understand the potential outcomes (e.g. cost and schedule) of the selected uncertainty mitigation strategy

- Seventhly, there is need for further research to assess the ability of data elicitation techniques (including NUSAP matrix and AHP) to be able to compare across approaches.

#### **10.5.4 Cost uncertainty modelling**

There are a number of areas that are promising to enhance cost uncertainty modelling. Firstly, U-TASC aims to incorporate uncertainty to an established cost estimate; however there is a need to also support in generating reliable cost estimates. This means that to the existing set of cost drivers a lower level of cost categories can be associated in order to fully understand the components of the cost drivers (particularly for “Failure rate” and “Turnaround time”). This exercise would enable to further understand the root causes of cost in Monte Carlo simulation. Secondly, approaches other than Monte Carlo simulation, including dynamic simulation approaches such as agent based simulation, discrete event and systems dynamic need to be applied to the uncertainty context in cost estimation. Such studies will need to assess the suitability of each approach to the CfA context. There are a number of additional areas that need research, including:

- There is a need for guidance to select the suitable probability distributions for various contexts
- U-TASC can further be developed to represent Weibull and other forms of distributions that are currently not considered in the tool
- The application of Monte Carlo simulation can further be examined to reflect the variability inherent in uncertainty over time
- There is need for better understanding the correlation across cost drivers that affects the development of probability distributions
- The scope of the application of AACE (1997) needs further validation to illustrate how the suggested ranges may change across different time frames and available information

### **10.5.5 Uncertainty tool for Assessment and Simulation of Cost (U-TASC)**

U-TASC was developed as a prototype software tool. Based on discussions with two software developing organisations in cost estimation (Galorath and Price Systems) and the feedback received from the case studies it has become promising that the tool can further be developed to become a professional tool to be used across industry, whilst embedding industry best practice. However, in order to achieve this, the tool will need to enhance its ability to store data, particularly Monte Carlo results with a view to making comparisons over time.

### **10.5.6 Agent based modelling**

One of the aims of Chapter 8 has been to apply ABM in cost estimation, in order to set out a map for the use of this simulation approach, within the cost estimation literature, where limited research has been conducted. The future of the application of ABM within the cost estimation domain would need to take into account the challenges that are currently experienced. In order to take account of the increased range and scale of cost uncertainties typical of CfA the following challenges will need to be considered:

- The need for improving the prediction of uncertainties such as equipment reliability or failure rates, repair time, demand rate for spares, obsolescence, and technology refresh that have dynamic characteristics with their influence on cost estimation for a 10-15 year time frame
- Representation of the sensitivity associated to expert opinion with highly subjective data that is gathered from the subject matter expert in cases of limited data and poor timeliness of its availability
- Application of quick and rigorous approaches to build uncertainty based cost estimates, where the approach needs flexibility in order to take account of the be-spoke nature of offerings
- Visualisation of the behaviour of the service supply chain, where some challenges arise from the flow of information from the customer, sustainability of the supplier, communication between suppliers, the aggregate influence over work breakdown structure, timely and quality provision of service. Also, as a

source of complexity, suppliers do not show homogeneous characteristics. This means that it may also be used to visualise the implications of the varying degrees of capabilities along the supply network.

## 10.6 Conclusions

This thesis has achieved all six objectives that have been outlined in Chapter 3. The initial objective focused on defining an uncertainty checklist to assist with the identification of uncertainties and to explore the unique characteristics of CfA in terms of uncertainties. In order to achieve this objective the author conducted the following:

- Developed a comprehensive list of seventy types of uncertainties based on interaction across the naval and air domains in the defence industry
- Classified the uncertainties into commercial, affordability, performance, training, operation and engineering categories
- Validated the proposed list of uncertainties where validation results indicate that the proposed set of uncertainties for CfA are comprehensive and provide a good basis to build a bid
- Examined the unique characteristics of CfA in terms of uncertainties and classified these into emergent and transformed aspects
- Emergent uncertainties are created by focusing on performance. Some of the examples include equipment availability and payment based on performance
- Transformed uncertainties are driven by factors including (1) shifts in responsibility, (2) time of service consideration, (3) information flow, (4) stakeholders' dependency and alliance, (5) capability or knowledge, (6) definition of value/importance and (6) source of revenue
- Validated the unique characteristics of CfA in terms of uncertainties, based on industry and academic feedback, which led the author to believe that the considerations are reasonable and would potentially benefit during bids

The second objective involved defining an uncertainty prioritisation process to assist in cost uncertainty management and modelling, which consisted of:



- Defining a scoring mechanism to consider both the uncertainty level and the relevance of uncertainty to the given project
- Measuring the uncertainty level by adjusting the NUSAP matrix, which classifies three dimensions including basis of estimate, rigor in assessment and level of validation
- Developing scores to assist the user of U-TASC to define the uncertainty level
- Measuring the relevance of uncertainty through AHP, which enables to transform expert knowledge to allocate a percentage contribution of uncertainty to the overall project
- Through validation both the uncertainty level and relevance assessments were reviewed. The applicability of the approaches were considered to be highly suitable to the defence industry

The third objective was to formalise the subjective process of determining Three-point estimates, which are used in Monte Carlo simulation. In alignment with the cost uncertainty management framework the application is achieved through a developed MS Excel based software prototype, which has been called Uncertainty Tool for Assessment and Simulation of Cost (U-TASC). Some of the main reasons for the cost uncertainty modelling challenge were recognised to include:

- Uncertainty identification within the service context
- Understanding the root causes of uncertainty
- Realising the degree of variation in cost estimates.

As inputs these aspects have a direct influence over the results acquired from Monte Carlo simulation. The developed bid framework enables to elicit expert knowledge for each of these areas and uses the information to transform a single point estimate into three. In this process the user is also able to recognise the root causes of the uncertainty in cost drivers using traceable and scientifically justifiable techniques. The author considered a number of aspects to develop the framework:

- The results achieved for the uncertainty level from the second objective are used in defining the uncertainty level in cost drivers

- A total of nineteen cost drivers are suggested, which have been validated through workshops and semi-structured interviews across the naval and air domains and have been confirmed to be comprehensive
- The sources of uncertainty in cost drivers were established by the defined standard set of relationships between the uncertainties and cost drivers. In the air domain the author applied workshops to elicit these relationships using fishbone diagrams, whilst the results were further validated with naval based experts
- Based on the relationships between the uncertainties and cost drivers a cost uncertainty score is calculated, which represents the maturity level. This is used to define the minimum and maximum ranges by considering AACE (1997)
- Flexibility was built into the framework in order to operate U-TASC at various levels of detail, e.g. individual analyses may be performed for different systems or subsystems, or the platform may be analysed as a whole
- The results from three case studies indicate that outputs are highly relevant, useful and reliable. The two main benefits of U-TASC in cost uncertainty modelling have been captured to be in association with developing potentially more reliable Three-point estimates and enabling to realise the risk of overspending by understanding the level of uncertainty and its impact on cost estimates

The fourth objective focused on defining an integrated cost uncertainty management framework. The developed framework concentrates on the early phases of the bidding stage in CfA. The cost uncertainty management framework provides grounded evidence into what cost uncertainty related questions managers deem important and a systematic framework is presented, which helps managers to address important questions to qualify uncertainty before it is actively managed. Similar to the cost uncertainty modelling framework, the scope of the framework is limited to service offerings including spares, repair and training for equipment, which has a high net value physical product core, and involves transactions in a business to business context. In fulfilling this objective the author took into consideration a number of aspects:

- The framework combines the results from uncertainty identification with uncertainty prioritisation in order to specify the types of uncertainties that require additional attention
- The prioritised uncertainties are suggested a set of mitigation strategies that have been classified in to reliability, maintainability and supportability measures
- Through validation on three case studies it has been realised that the framework provides benefits in identifying and assessing aspects that have immeasurable outcomes in service delivery, while directly supporting with project planning, visualisation of uncertainty and capability management
- From a literature point of view, the framework is considered to contribute to project management by enhancing on the traditional application that centres on risk management, while the missing link in project planning is considered to be uncertainty management
- The focus on uncertainty, rather than the traditional perspective which focuses on risk, provides implications for management of risk and uncertainty, where the traditional assumption of ‘perfect’ knowledge is avoided by raising questions about the validity of the input data.

The fifth objective focused on developing an agent based model capable of capturing the dynamism experienced in service delivery, while reflecting the interactions across the supply chain. The presented ABM sought to justify precisely why ABM is suitable for considering complex and distributed networks in CfA early on in the bidding stage within the TPPI context. The benefit of the approach was considered driven by the fact that static models lack the ability to replicate the real world by relying on average long term performance, while ABM offers a dynamic approach. The following aspects are relevant to accomplishing this objective:

- The application combines information from U-TASC with a simulation software package called AnyLogic
- Through the presented model a systematic framework is suggested, in order to conduct what-if analysis to better understand the influence of uncertainty in cost estimates early on, while visualizing the cost impact of incentives and risk sharing across the supply chain

- The dynamism in the presented model is generated through the variable ‘failure rate’, which is applied by considering a variation of the number of failure events, along with the potential variability in the failure events
- Validation of the ABM model enabled to reflect that the rules and assumptions and the framework was suitable for the early stages of the bidding phase.
- Improvements to the presented ABM would need to take account of further complexities that arise from the supply chain. The importance of the ABM approach will increase as the complexity of the service solution grows. For instance, this may be associated to the increase in the number of customers, suppliers or scope of service delivery and complexity of maintenance
- It is anticipated that the presented model makes a contribution towards growing the use of ABM in cost estimation.

The findings of the agent based study indicate that the research will contribute towards systematically eliciting expert knowledge in cost uncertainty modelling and management. Furthermore, the ABM considerations form an application of the approach in an area that has not typically been used in the cost estimation literature and proves to be a highly promising area for future research.

The sixth objective involved validation of the frameworks through real life case studies and experts opinion. In achieving this objective the following areas were considered:

- An iterative approach was followed for validation, whereby the author in a dynamic manner engaged with the industrial experts.
- For the agent based model, the validation relied on expert opinion, as comparison to actual cost figures was not possible. This was associated to the fact that the model was highly unique and required a new set of data.
- For U-TASC three case studies were conducted in: (1) naval electronic, (2) naval radar, and (3) aircraft carrier. Although, the case studies are in common within the naval domain, applicability to other domains was realised based on the industrial interaction

- In comparing the case studies associated to U-TASC it was possible to recognise projects with higher uncertainties, the suitable measures to tackle the issues and the implications on costs
- The case studies showed that the integrated framework in U-TASC is highly relevant and flexible within the bidding stage where there is limited amount of information and time to conduct analysis.

Through validation the major benefit of the integrated framework was recognised in relation to scientifically transforming subjective views of cost uncertainty across individuals into a justifiable measure whether it be for its management or modelling at the bidding stage within the context of CfA or IPS<sup>2</sup>.



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# APPENDICES

The following subsections present relevant material that aims to further enhance the readers' understanding of the research from various aspects.

## Appendix A Questionnaires

### A.1 Pilot Phase and Initial Interaction

#### A.1.1 Identification of stakeholders: Collaboration with PSS-Cost project researchers

- Which particular individuals should we contact concerning the two capability 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?
- Which particular individuals are involved in measuring affordability?
- Could we broadly identify the stakeholders of two key contracts in order to understand locations to visit, and to establish forms of communication?

#### A.1.2 Familiarisation Questionnaire: Collaboration with PSS-Cost project researchers

##### A. Scope of the estimate (9 Mins)

**SE.A.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.A.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.A.3** Are disposal costs considered within the life cycle cost considerations?

##### B. Programme Baseline (4 Mins)

**SE.B.1** Is there an agreed master data and assumptions list (MDAL) e.g. that supports translation of programme requirements into a defensible cost estimate?

##### C. Cost Breakdown Structure (10 Mins)

**CBS.C.1** Describe the CBS that you employ in capability contract?

**CBS.C.2** Does the CBS for capability contracts differ from the CBS' of the past?

**CBS.C.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.C.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.C.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.C.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)?

#### **D. Data Collection & Analysis (4 Mins)**

**DCA.D.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/capability contracts?

#### **E. Method Selection (20 mins)**

**MS.E.1** What commercial or in-house tools are used to make estimates (e.g. parametric, simulation, optimisation, decision support, historical trends analysis)?

**MS.E.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?)

**MS.E.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.E.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.E.5** Where do we focus within a contract? Which areas should we concentrate on?

#### **F. Whole life cycle cost estimation (3 mins)**

**WLCC.F.1** How does the WLC estimation process change when a WLC approach is taken?

**WLCC.F.2** Which are the main cost drivers in capability contracts? (E.g. major 3)

**WLCC.F.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)

#### **G. Capability/Availability Contract Process (10 Mins)**

**CCP.G.1** How do you agree a price with the customer? (e.g. Competitive or single supplier)

**CCP.G.2** Could you please describe the issues for each capability contract? (What are the challenges, expectations, cost drivers, uncertainties and risks?)

**CCP.G.3** What has changed from delivering just a product to a Availability Contract in terms of customer relations?

**CCP.G.4** Do you have standard pro-formas for capability contracts? If so what are they?

**CCP.G.5** What is the effort at the bidding stage? (e.g. hours)

#### **H. Summary (10 Mins)**

**S.H.1** What are the main questions that need to be addressed?

**S.H.2** What kind of future interaction can we embark on?

### **A.1.3 Uncertainty Based Questions**

#### **1.3.1 Questions used at the initial semi-structured interviews**

- Compared to regular contracts, to what extent do capability/availability contracts influence associated risks of projects?
- In capability/availability contracts how are risks, associated with the cost estimation process, predicted?
- Within this mentioned context, what kind of procedure is followed to understand the risks of throughout the whole life cycle? (Design, maintenance, upgrade, spares, repairs, technical support, maintenance training, operational, disposal)
- How is the influence of risk and uncertainty reflected on to costs? (Within the bidding stage of capability contracts)
- How do you identify risk and uncertainty in models? And how do you differentiate them?
- What methods do you use to model uncertainty and risk in cost estimation?

### **A.1.4 Detailed Industrial Interaction**

#### **Semi-structured interviews**

##### *Generic set of questions*

- How do you differentiate between uncertainty and risk?
- What process do you follow to incorporate uncertainty and risk into cost estimation? (MDAL)
- What methods are used?
- What specific uncertainties are considered in the in-service phase?
- How are these selected?
- Why do cost estimates go wrong? –what uncertainties cause this to occur?
- How are multiple uncertainties dealt with?
- Is there an established method of consideration for uncertainty of affordability? If yes, what is the procedure? (Give examples)
- How do uncertainties change when the business model changes from a traditional product sale structure into one of a PSS? What are the challenges in the servitization process? (Give examples)
- Why do cost estimates go wrong? –what uncertainties cause this to occur?
- How are multiple uncertainties dealt with?

##### *Software cost estimation related interview*

- In software development what kind of uncertainties are present at the bidding stage? What are the reasons for these uncertainties? How are these incorporated into cost estimation?
- How are these uncertainties incorporated into cost estimation
- Does the approach vary between software and hardware?
- In systems engineering what kind of uncertainties are involved? What are the reasons for these uncertainties? How are these incorporated into cost estimation at the bidding stage?
- What is the process to incorporate these uncertainties?
- How are costs forecasted in software and systems engineering?

##### *Risk expert*

- Generic model that pictures all uncertainties for each type of service offering. Developing a risk register is a subjective task, how can this subjective process become more so objective?
- Is a generic model that contains potential risks and uncertainties a route to standardize risk registers'?

- Specification of types of uncertainties for;
  - Spares service:
  - Repair service:
  - Defect response:
  - On-call service:
  - Health checks:
  - Performance assessment:
- Engineers tend to be risk averse, is there a way to account for this?
- How is uncertainty for operational activities considered in PSS type contracts?
- What are the issues faced in cost estimation in delivering functional offerings?
- How does uncertainty change when availability type contracts are agreed?
- In developing a risk matrix, which classifies risks based on likelihood and impact, how can this process be made less subjective?
- How does uncertainty that may derive potential benefits for the service provider get incorporated into cost estimation?
- Is there a distinction between aleatory and epistemic uncertainty in your organisation?
- How does uncertainty modelling change in cost estimation (based on techniques used-how does available data influence the process)? Are there any new trends that are recently emerging?
- In literature there are a number of papers that suggest the usage of fuzzy set theory and/or neural networks in cost estimation instead of parametric analysis, is there such a tendency in your organisation?

### ***Financial expert***

- What role does the finance division have in uncertainty based cost estimation?
- How is uncertainty in service included to the costing?
- What are the types and sources of uncertainties related to in-service stage including service networks (availability contract type agreements)?
- What kinds of issues arise in selecting the types and sources of uncertainties?
- How would you improve the process of selecting types and sources of uncertainties?
- How do the above uncertainties differ from design and manufacturing based contracts? Are there any new issues that arise?
- How is uncertainty considered at the bidding stage for in-service activities?
- What are the challenges in incorporating uncertainty based estimating?
  - How could this be improved?
- How would you improve the process of incorporating uncertainty to cost estimation in-service activities?
- What level of information about the project definition is available at the bidding stage so that could be used to analyse uncertainties?
- How are cost drivers identified in each service activity?
- How do you estimate costs of services?
- What challenges are present in this process and how would you improve processes in view of these challenges?
- Who is in charge of the dealing with uncertainty for services at the bidding stage?
- Do you select uncertainties in service, and how do you prioritize them?
- What issues are present in this process?
- How would you improve the process of selecting and prioritizing uncertainties?
- What is the structure/framework of uncertainties for in-service activities?
- What limitations do you feel you have in incorporating uncertainty to the cost estimation of service activities?

### **2.1.5 Cost estimators involving in Contracting for Availability**

- Is there a standard bidding process?



- What are the followed steps?
- How is cost uncertainty managed?
  - How uncertainty is represented?
  - How are key uncertainties identified?
- What are the important sources of information that is used during the bidding process for uncertainty based cost estimation?
- At what stage of the bidding process does uncertainty get considered?
  - What are the types of uncertainty considered?
  - How are uncertainties incorporated to cost?
- What are the current challenges in uncertainty based cost estimation?

## A.2 Survey to capture the key services and associated uncertainties

### Purpose of questionnaire

Within the PSS-Cost project at Cranfield University, this research aims to enhance understanding of uncertainty in cost estimation for the in-service phase of availability type contracts. The research specifically focuses on the bidding phase, where limited information and lack of time highly influences decision making. The purpose of this questionnaire involves the development of an exhaustive list of uncertainties, where each project may benefit from a framework that enhances effective selection of uncertainties for each project. This questionnaire will facilitate the development of a 'Customisation framework'.

### Benefits to the defence and aerospace industry

- Increased effectiveness in integrating in-service phase uncertainty into cost estimation at the bidding stage
- Systematic consideration of uncertainty, where organisations benefit from a cross range of projects and experiences to consider uncertainty

### Questionnaire structure

The questionnaire requests the participant in the defence and aerospace industry to select three services that have been part of a project that they have been involved in. Thereafter, based on the frequency and impact of uncertainties in associated services participants are invited to exhaustively fill boxes. An example is provided in the questionnaire. As follow-on, the most challenging services in terms of uncertainties are requested. Subsequently, a number of generic uncertainties that may apply to any project are given to prioritise, where further suggestions are welcomed.

### Selected project characteristics (Setting the context)

Please fill in the following boxes according to the characteristics of the project that you have selected in filling the questions.

Platform/sector (i.e. Sea, air, land)	Size of project: (Turnover £)	Phase in the CADMID cycle and duration:	Individuals' year of experience in particular field:	Job title:

**Address to return questionnaire by the 31<sup>st</sup> of October 2008**

Participants are requested to either e-mail this document or fax it to the following:

E-mail: [j.a.erkoyuncu@cranfield.ac.uk](mailto:j.a.erkoyuncu@cranfield.ac.uk)

Fax: +44 (0) 1234 754605

All comments and feedback are welcome.

### **Questionnaire**

#### **Uncertainty definition**

In view of the interviews with industrial collaborators this project defines uncertainty as:  
 Uncertainty involves lack of clarity, where an event is prone to occur, though the outcome is vague, i.e. mean time between failure

1. Please list three services that you have been involved in a recent project

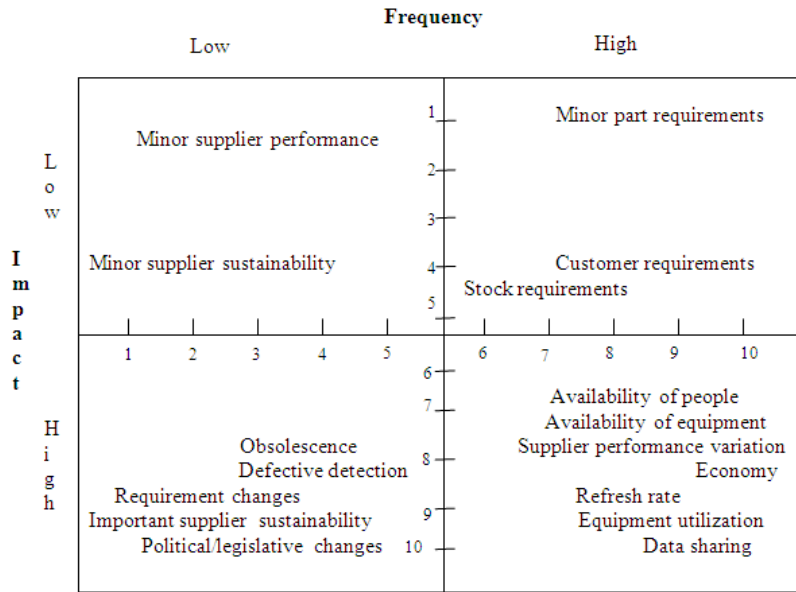
i) .....

ii) .....

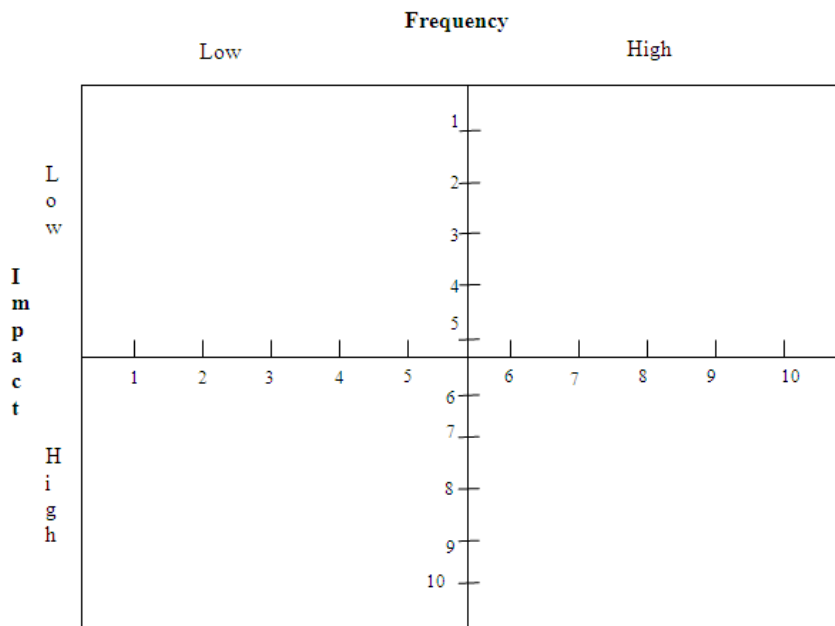
iii) .....

2. Taking into consideration the frequency and the impact of uncertainties for the selected services above, please locate as many of them as you can on the maps, below. An example is provided.

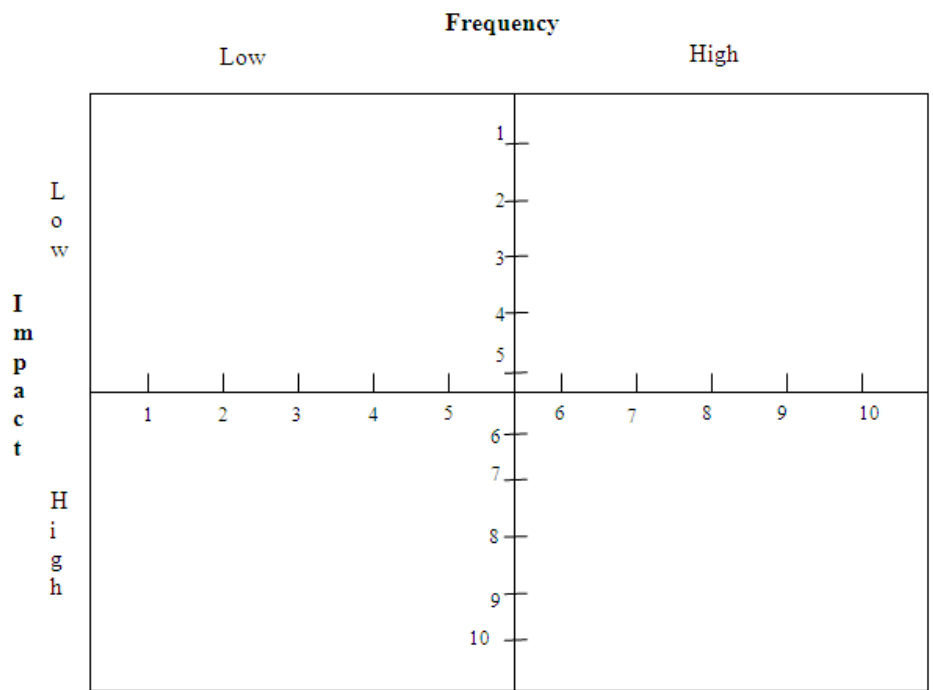
Example: Spares service



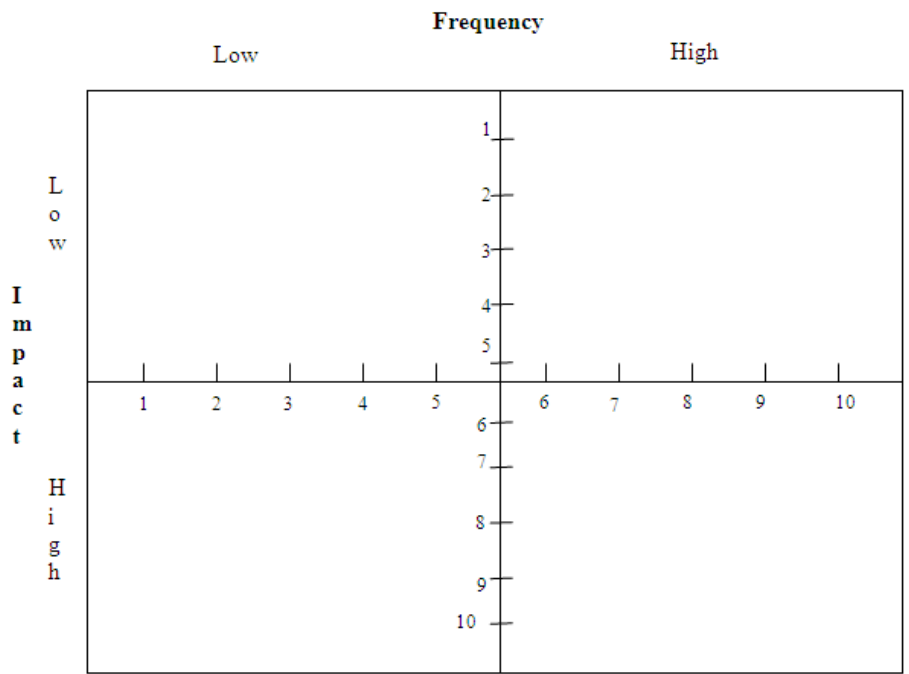
Service 1: .....



Service 2: .....



Service 3: .....



3. Please prioritise the three most uncertainty prone services (i being the highest)  
i).....

ii).....

iii).....

4. Please prioritise the generic uncertainties set out below by writing “1” for the highest priority in associated boxes and “2” for the next highest, and continue until you are unable to differentiate between the remaining themes. If appropriate please add other generic uncertainties.

Economy

Regulation

Requirement changes

Technology

Supply chain

Organisational change

Any other generic uncertainties .....

**Thank you for your time**

### **A.3 Initial tool validation: Questionnaire to gather feedback at the initial stage of tool development**

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 “uncertainty identification tool”

Name of respondent .....

Organisation name .....

Field of expertise .....

Knowledge in: Uncertainty

Obsolescence

Design Rework

Affordability

Year(s) of experience .....

**Question 1.** Please tick a suitable box for the following questions.

- a) Would an uncertainty identification 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 

--	--	--	--	--

 High

1                      2                      3                      4                      5

**Question 2.** Please tick the suitable boxes to justify the statements about the benefits of the presented tool to industry.

No.	Statement: the benefits of the tool	Yes	No	Adequate
1	Effective way to identify uncertainties at the bidding stage			
2	Enables to grade uncertainties based on likelihood			

Please suggest other possible benefits to industry below.

.....  
 .....

**Question 3.** Please tick the suitable boxes to justify the statements about the features of the presented tool.

No.	Statement: the features of the tool	Yes	No	Adequate
1	Selection of services are <i>sufficient</i>			
2	Types of uncertainties are <i>relevant</i> to each type of service			
3	Project characteristics are <i>sufficiently</i> captured			
4	Selected categories of uncertainties are <i>aligned</i> with industrial practice			
5	Grading of uncertainties are made with <i>sufficient</i> reasoning			

**Question 4.** Please list strengths & weaknesses of the presented tool.

Strengths	Weaknesses
<ul style="list-style-type: none"> <li>•</li> <li>•</li> <li>•</li> <li>•</li> <li>•</li> </ul>	<ul style="list-style-type: none"> <li>•</li> <li>•</li> <li>•</li> <li>•</li> <li>•</li> </ul>

**Question 5.** Apart from the weaknesses you have mentioned above, please suggest what improvements are needed to the presented tool to use it efficiently in your industry?

- .....
- .....

**Question 6.** As a next step, how can the presented tool be used to derive uncertainty management strategies at the bidding stage?

- .....
- .....

**Question 7.** Please define in what format you would prefer the frameworks to be delivered

.....

**Thank you for your time, patience and contributions**

## A.4 VALIDATION

### A.4.1 Questionnaire to assess the emergent and transformed uncertainty list

<b>Respondent name:</b>	
<b>Position:</b>	
<b>Research focus:</b>	

#### Task 1. Provide your perspective

Please input the following information based on your understanding of availability contracts:

- The new uncertainties that emerge
- Explanation about the new uncertainties

New uncertainties	Comments

**Task 2. Assess the proposed new uncertainties**

Please use the explanations below for the scores to fill the box related to ‘Relevance of the uncertainty’.

Strongly irrelevant	Irrelevant	Neither relevant nor irrelevant	Relevant	Strongly relevant
1	2	3	4	5

New uncertainties	Relevance of the uncertainty	Comments
Equipment availability		..... .....
Payment based on performance		..... .....
Human performance		..... .....
End user equipment usage		..... .....
Change in evolving constraints for support		..... .....
Intangible expectations		..... .....
Change in capability requirements		..... .....
Lack of information and knowledge sharing		..... .....



**Task 3. Provide your perspective**

Please input the following information based on your understanding of availability contracts:

- The changing uncertainties that were also existing in the traditional contractual context
- What are the reasons for the change in the uncertainties?
- How are the uncertainties changing in terms of the transfer of uncertainties across the supply network?

Changing uncertainties	Why are they changing? (Reasons)	How are they changing? (Transfer across supply network)

**Task 4. Assess the proposed changing uncertainties and the factors that influence the change in uncertainties**

Please use the explanations below for the scores to fill each box in the table.

Strongly irrelevant	Irrelevant	Neither relevant nor irrelevant	Relevant	Strongly relevant
1	2	3	4	5

Changing uncertainties	Relevance of the Uncertainty	Relevance of the reasons for change						
		<i>Responsibility</i>	<i>Time</i>	<i>Information</i>	<i>Stakeholders' dependency and alliance</i>	<i>Capability or knowledge</i>	<i>Definition of value</i>	<i>Source of revenue</i>
Failure rate for hardware								
Spare parts storage								
Rate of capability upgrades								
System integration issues								
Failure rate for software								
Severity of obsolescence								
Technology refresh								
Rate of emergent work								
Transport								
MTBF data								
Spares requirements								
No fault found rate								
Operating parameters								
Repair time								
Rate of materials								
Rate of beyond economical repair								
Material cost								
Component stress and load								

**Task 5. Additional areas to consider**

Please specify if there are any areas that need to be added

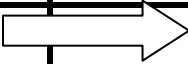
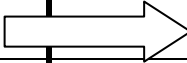
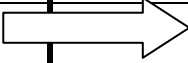
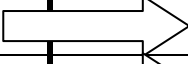
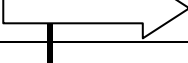
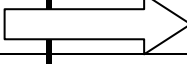
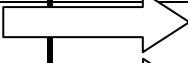
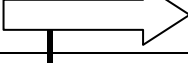
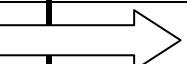
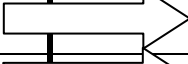
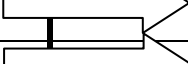
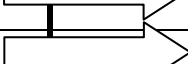
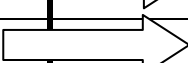
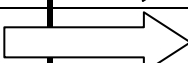
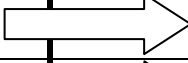
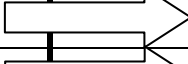
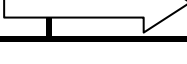

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**Task 6. Flow of uncertainty across the supply network**

Please use the explanations for the scores to fill the box related to ‘Relevance of the uncertainty’. The arrows represent the flow of uncertainties from one stakeholder to another driven by changing responsibilities.

	Customer	OEM	Supplier	Validity of the change
Failure rate for hardware				
Spare parts Storage				
Rate of capability upgrades				
System integration issues				
Failure rate for software				
Severity of obsolescence				
Technology refresh				
Rate of emergent work				
Transport				
MTBF data				
Spares requirements				
No fault found rate				
Operating parameters				
Repair time				
Rate of materials				
Rate of beyond economical repair				
Material cost				
Component stress and load				

**Explanation of the considered concepts**

**A. 7 factors causing the transformation for existing uncertainties**

**Responsibility:** How risk is shared?

**Time:** At which decisions are made concerning the service delivery

**Information:** The source and flow of information changes across stakeholders

**Stakeholders' dependency and alliance:** The collaboration across the supply network (co-creation of value and co-production of value between customer, solution provider and supplier)

**Capability or knowledge:** Requirements in terms of know-how to fulfil the needs of the new context in service delivery

**Definition of value:** Change in what the customer considers as added value

**Source of revenue:** The change in the architecture of generating revenues

**B. New uncertainties emerging:**

**Equipment availability:** Performance requirement

**Payment based on performance:** The variation in payment

**Human performance:** Including the variation over time due to the learning curve, and the individuals motivation

**End user equipment usage:** Aspects related to utilisation rate, and misuse, also the customer misdiagnosing a problem

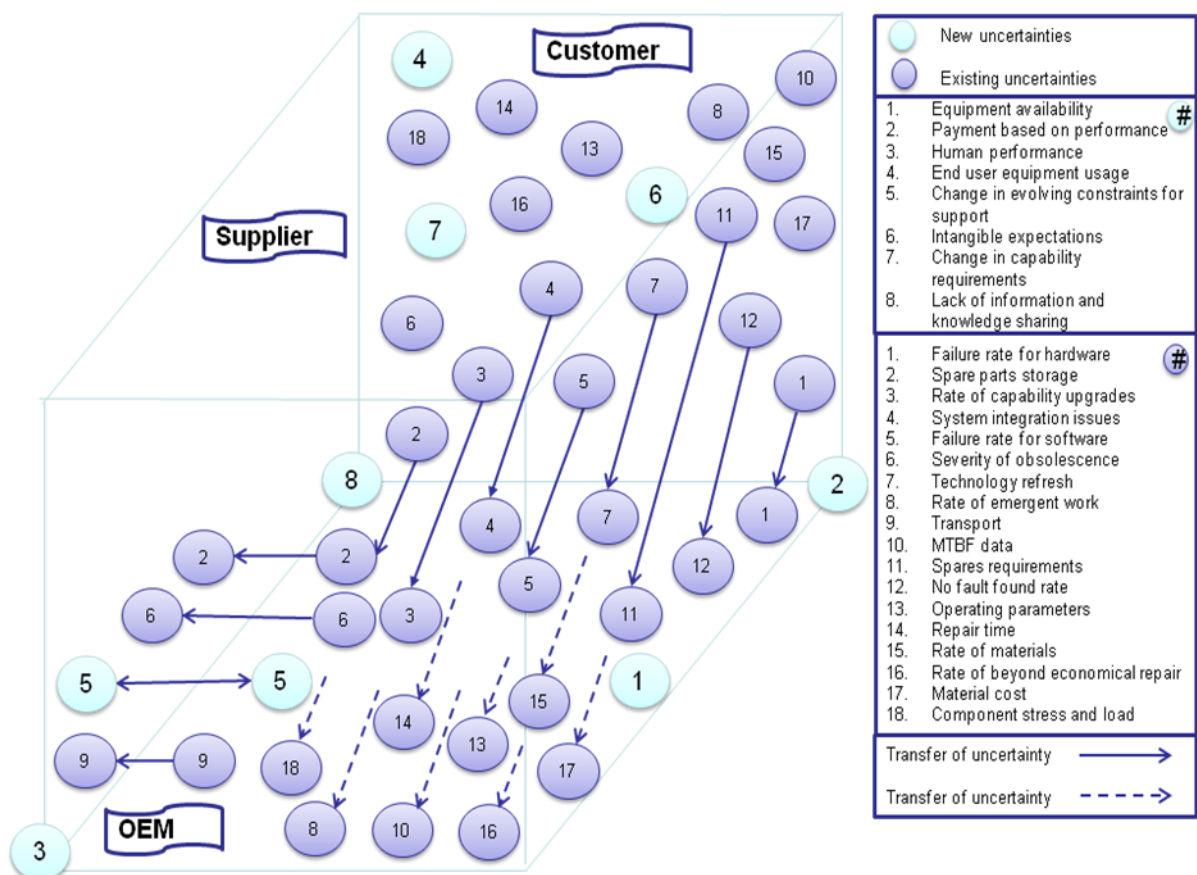
**Change in evolving constraints for support:** The adaptability of capabilities

**Intangible expectations:** Satisfaction or happiness

**Change in capability requirements:** customer driven

**Lack of information and knowledge sharing:** data about equipment usage

**Stakeholder Viewpoint of Uncertainties in Availability Contracts**



The figure above illustrates the way in which uncertainties shift/are transferred across the supply network, including the customer, OEM, and the supplier. The figure also differentiates the new and existing uncertainties.

## A.5 Validation of the Uncertainty tool for Assessment and Simulation of Cost (U-TASC)

PSS-Cost Project

Researcher: John Ahmet Erkoyuncu, E-mail: j.a.erkoyuncu@cranfield.ac.uk

Supervisors: Prof. Rajkumar Roy, Dr. Essam Shehab

Project Manager: Dr. Kalyan Cheruvu

### A. General:

1. Name: .....
2. Organisation: .....
3. Role: .....
4. Years of experience (in uncertainty): .....

### B. Overview of the case study

1. Description of the case study (including years of contract and CADMID phase)  
.....  
.....
2. The information that is available  
.....  
.....

### C. Logic

1. How logical is the uncertainty considerations in the framework (Assign a circle around the suitable number)

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

If there are deficiencies please describe them:

.....  
.....

2. Is the framework suitable for the bidding phase?

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 the reasons:

.....  
.....

Are there any improvement suggestions:

.....  
.....

3. Can the framework be applied in alternative phases to the bidding stage? Yes No

If yes, please specify which phases

.....  
.....

**D. Generalisability**

1. Please comment on how generalisable the framework is within the defence industry

.....  
.....

2. Please comment on how generalisable the framework is for other sectors (e.g. Nuclear)?

.....  
.....

**E. Responsibility**

1. How should the framework be used across the supply network? (e.g. only solution provider (OEM), or with the customer and/or suppliers) Why?

.....  
.....

2. What team or department should have ownership or responsibility of the model within the company?

.....  
.....

3. How could the team or department owning the framework maintain it?

.....  
.....

**F. Benefits of using the framework**

1. How would the framework benefit the bidding team?

.....  
.....

2. How would the framework benefit uncertainty considerations?

.....  
.....

**G. Limitations of the framework**

1. What are the potential limitations and challenges in using and implementing the tool?

.....  
.....

2. What are the potential organisational limitations and challenges that arise in using the software tool?

.....  
.....

3. How could the background of people filling the tool affect the output?

.....  
.....

**H. Usability of the software prototype**

1. Assessment of the usability of the tool in terms of features

a. What are the strongest features?

.....  
 .....

b. What are the weakest features?

.....  
 .....

2. Assessment of the usability of the tool in terms of features

a. How clear and appropriate are the considered terminologies in the framework?

.....  
 .....

b. Please suggest possible improvements

.....  
 .....

3. Does the tool provide sufficient amount of information to guide the user? Yes  No

If no, please explain:

.....  
 .....

4. Assess the time required to populate the tool for implementation on a project

.....  
 .....

5. Please assess the following aspects in the tool

- a. Layout .....
- b. Use of colour .....
- c. Ease of navigation .....
- d. Level of intuition .....

6. Is the tool flexible enough to be applied with different levels of information availability?

.....  
 .....

**I. Assessment of the framework**

Please assess the completeness/suitability of the framework for the following questions

a. The list and categories of uncertainties

1	2	3	4	5	6	7	8	9	10
Totally Incomprehensive	Suitable with major deficiencies				Suitable with minor deficiencies				Totally comprehensive

If it is not totally comprehensive, please explain the reasons:

.....  
 .....

b. Calculation of the uncertainty level by considering the average of uncertainty criteria's (including data availability, rigour of assessment method and validation)

1	2	3	4	5	6	7	8	9	10
Totally Incomprehensive	Suitable with major deficiencies				Suitable with minor deficiencies				Totally comprehensive

If it is not totally comprehensive, please explain the reasons:

.....  
 .....

c. The feature of data storing concerning the uncertainty level for the specified categories

1	2	3	4	5	6	7	8	9	10
Totally Incomprehensive	Suitable with major deficiencies				Suitable with minor deficiencies				Totally comprehensive

If it is not totally comprehensive, please explain the reasons:

.....  
 .....

d. The approach to define the weight of the uncertainty through the analytic hierarchy process

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 the reasons:

.....  
 .....

e. Calculation of the uncertainty score based on the multiplication of uncertainty weight and uncertainty level.

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 the reasons:

.....  
 .....

f. The provided list of uncertainty management strategies that is based on literature review

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 the reasons:

.....  
 .....

g. The provided list of cost drivers

1	2	3	4	5	6	7	8	9	10
Totally Incomprehensive	Suitable with major deficiencies				Suitable with minor deficiencies				Totally comprehensive

If it is not totally comprehensive, please explain the reasons:

.....  
 .....



h. Considerations for the cost uncertainty linkage

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

If it is not totally suitable, please explain the reasons:

.....  
 .....

i. The suggestions for ranges based on the AACE (1997) guidelines

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

If it is not totally suitable, please explain the reasons:

.....  
 .....

j. The approach to define the weight of the cost drivers through the analytic hierarchy process

1	2	3	4	5	6	7	8	9	10
Totally Incomprehensive	Suitable with major deficiencies				Suitable with minor deficiencies				Totally comprehensive

If it is not totally comprehensive, please explain the reasons:

.....  
 .....

k. The suggested distributions through literature for the cost drivers

1	2	3	4	5	6	7	8	9	10
Totally Incomprehensive	Suitable with major deficiencies				Suitable with minor deficiencies				Totally comprehensive

If it is not totally comprehensive, please explain the reasons:

.....  
 .....

l. The process of turning a single point estimate into a three point estimate

1	2	3	4	5	6	7	8	9	10
Totally Incomprehensive	Suitable with major deficiencies				Suitable with minor deficiencies				Totally comprehensive

If it is not totally comprehensive, please explain the reasons:

.....  
 .....

m. The considered number of distributions generated in the Monte Carlo simulation

1	2	3	4	5	6	7	8	9	10
Totally Incomprehensive	Suitable with major deficiencies				Suitable with minor deficiencies				Totally comprehensive

If it is not totally comprehensive, please explain the reasons:

.....  
.....

**J. Results**

1. Evaluation of the output of the tool after populating it with information from the case study  
.....  
.....
2. Evaluation of the repeatability of the tool after populating it with the same information from the case study  
.....  
.....

**A.6 Pilot case study validation questionnaire for the agent based model**

- What are the key benefits of the agent based approach compared to the traditional perspective?
- How suitable is the agent based approach to the Contracting for Availability context?
- What are the limitations of the agent based approach?
- How reliable are the captured results?
- How applicable is the approach? And are the input requirements realistic?

**Appendix B Sample interview result**

This section provides a sample interview and the collected results.

Interview with ..... from Organisation A on 07/04/2008

Duration: 45 Minutes

**Section A: Benchmark questions**

*(1) How do you differentiate between risk and uncertainty?*

Risk is an event, where things can go wrong. On the other, hand uncertainty relates to clarity of something, i.e. requirement. These may change from project to project and within the duration of a project. At the bidding stage, factors that affect cost and schedule are considered.

Examples: - What are the planning assumptions? (Are the requirements clear enough?)

- Technical specification?
- For each activity different departments may produce performance attributes, these may contain holes and/or double counting (problems derived from silos)

Data is increasingly stored as “Lessons learned”. In some situations this has enabled to turn uncertainties into risks. An example relates to the uncertainty surrounding the approval testing. In order to deal with the issue of a failure at this point, the problem is treated as risk, while risk mitigation methods, such as employing tests along the way have been implemented.

*(2) What process do you follow to incorporate uncertainty into cost estimation?*

It is hard to establish a single standard when the scale of operations reaches 14-15 sites, which the case with Organisation A.

The most sophisticated estimating processes are made for software's. These are 3 point estimates, while there are different ways to construct these processes.

It is a fact that Organisation A is not good at estimating costs for functional activities.

The company has reorganized and reallocated the task of costing into a commercial department.

It is necessary to recognise the boundaries of an estimate. The issue arises as different approaches are taken among individuals and more specifically different departments. There is much emphasis on reviews, many iterations help to resolve or reduce issues. It is a structured process.

The difference between competitive and single source bids is diminishing, while the difficulty of winning the contract is harder in single source bids. For instance, in a Naval system, the cost risk breakdown was passed on to the MoD.

#### **Section B: Specific questions: In-service and disposal uncertainty**

*In a project that you have been involved what have the types and sources of uncertainty in different life cycle stages of capability contracts been? (Most interest in the in-service and disposal phases)*

In service assessment relates to the spares and repairs. It is necessary to know how the equipment will work. Traditionally, there have been 4 layers of support. The 1st layer relates to the support that is done at the battle field, whilst the 4th layer relates to the heavily resources sites that enable the repair of equipment. There is a trend to get closer to the 1st layer of support. This brings about a different business model for Organisation A. A range of new uncertainties arise. Examples: Training abroad, availability of people, who owns which facilities? Additionally, it is a question of how long the contract is for? What will the costs of the maintenance be?

The biggest uncertainty relates to the support of the COTS equipment. How can you predict the refresh rate? There is no substantial data to make forecasts in many circumstances. Furthermore, the data is not stored properly. While the cost of the support increases the affordability diminishes.

- Uncertainty- refresh, availability of necessary kit, rate of technology change, how to deal with obsolescence (30 years of spare parts used to be purchased).
- Risk is an issue of unsupportable kit (system or hardware obsolescence)

To think of service uncertainty in a structured manner, the work breakdown structure tends to be considered. So both the work packages and the product breakdown for all the WBS are examined. Example: A certain kit has 5 years of life span; it could be that you need to redesign the whole kit after this period, as the support may become useless due to the significance of this specific kit.

The availability or the supply of data concerning mileage or usage has commonly been an issue, though lately developments in data storage by the Navy have been good. This has helped to improve the support.

Disposal had not traditionally been considered in depth. Though, the growing influence of environmentalists has increased estimations in this area. This was the case in Type 45, in a recent phase review; this project enables air defence capability on sea (ship).

It could be argued that all contracts are capability focused nowadays. It means that projects are measured on more than one metric, while one may reduce the significance of a weakness of another metric. This means that the supplier offers a system, with a system many elements work together to provide a capability, an end capacity to operate. Although, this may reduce the importance of some functions, it is also worth to recognise the role of specific functions such as speed of message tracks in radars. This will still have an important contribution in the capability that is offered.

### **Section C: Follow on questions to the project that ..... selects**

*What standard or process is employed to capture uncertainties?*

*- What is the standard to capture costs?*

Integration of uncertainty follows the cost estimation procedure.

The uncertainty level in a WBS will be influenced by the toughness of the required operation.

Assumptions dictate how the project works. So, you can assign risks to the non-occurrence of such events. Experienced individuals ask what could go wrong. There is no standard procedure for this application, experience is the biggest skill. This process would cover the life cycle.

Examples of risks: issues that arise in integrating systems, the number of subsystems along the supply chain, schedule risk...

All risks are considered in terms of impact on cost, schedule and performance. (i.e. for the breakage of crane) Some risks will be more important than other driven by the 3 parameter mentioned above (i.e. gas manne of an apartment will be more significant than most other risks)

Long lists of risks are considered, those that do not materialise pay for the impact of risks that do occur. In parallel, it is easy to under/over estimate a cost estimate. For each project, it is necessary to examine whether the uncertainty or the risk side dominates.

The common application is to reduce the uncertainty spread.

In manufacturing there are not that many uncertainties. The well known risk relates to the failure of equipment. In the development stage a major uncertainty relates to the departure of an individual from the company. The stage of the life cycle will have a significant impact.

*How do you prioritise the uncertainties?*

A case by case approach is taken to prioritize uncertainties. Comparing uncertainty relates to looking at their connection with the cost and the schedule (is important as in many cases it is the most important parameter that delights customers).

*What are the influences/impacts of these uncertainties on costs?*

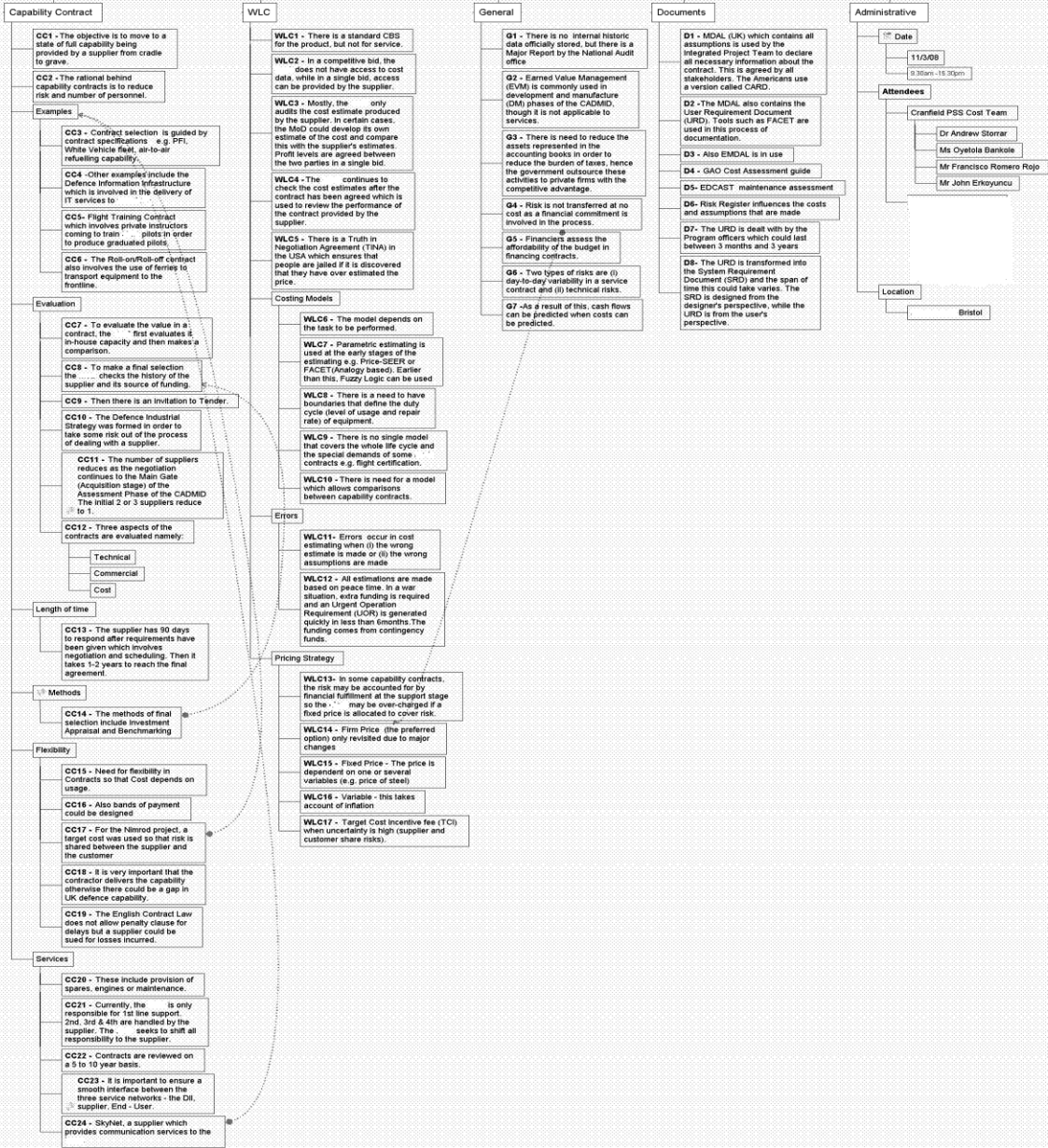
Monte Carlo analysis spreads are derived (preference of minimum) and the confidence of for a price is defined (Half the time is not good enough, as this will cause you to go bankrupt). 80-90% confidence means that 8-9 out of 10 projects will be successful.

There is a standard list of metrics to cover all risks: DAREO - Dependency; Assumptions: if it doesn't happen?; Risks; Exclusion: scope, Opportunity

## **Appendix C      MindMap analysis of interviews**

This section demonstrates a sample MindMap that was developed in collaboration with the 'PSS-Cost' project members to analyse the outcomes from interviews.

PSS Cost Project Introductory Visit To Bristol On 11/3/08



## **Appendix D     Sample industrial report**

This section demonstrates a sample report that was delivered to industry.

### **D.1    Development of a generic set of linkages between cost drivers           and uncertainties**

#### **Abstract**

This report summarises the outcome of the meeting that took place on 29.05.2009 between Cranfield University and Organisation A.

Approved by:

Professor Rajkumar Roy  
Head of Decision Engineering Centre  
Cranfield University

## Glossary of Terms

BoM	Bill of material
CADMID	The Concept, Assessment, Demonstration, Manufacture, In-service, Disposal cycle has been used by the United Kingdom Ministry of Defence (MOD) since 1999, when it was devised as part of the Smart Procurement initiative, since replaced by Smart Acquisition, to deliver equipment capability within agreed performance, cost and time parameters.
CBS	Cost Breakdown Structure
CER	Cost Estimating Relationship
DSR	Demand satisfaction rate
GFX	Government Furnished Asset
KPI	Key Performance Indicator
MPAL	Platform Maintenance Policy
MTBF	Mean time between failure
TRT	Turnaround Around Time
TUPE	Trade Union Protection Employment
WACC	Weighted Average Cost of Capital
WLC/ WLCC	Whole Lifecycle Cost (or Whole Life Cycle Cost), refers to the holistic view of cost end-to-end across the CADMID cycle.

### D.1.1 Executive Summary

This report provides an overview of the attempt by Cranfield University and Organisation A to develop a generic list of linkages between cost drivers and uncertainties across availability oriented contracts. It is envisaged that this will enable to enhance the reliability of cost estimates.

The report categorises the main cost drivers as supply chain, engineering, training, maintenance, performance and business management. Furthermore, each category is further broken-down by considering suitable cost drivers and uncertainties that influence the level of variability. The meeting was attended by 9 members from Organisation A and 2 from Cranfield University.

### D.1.2 Introduction

This report is based on the uncertainty workshop that took place between Cranfield University and Organisation A on 29.05.09. The report feeds-back information that was collected in relation to linking uncertainties to cost drivers. The meeting was organised as follow-on to the previous meeting that took place on 22.05.09. In that meeting a generic list of cost drivers and the realisation of the level of uncertainty for each cost driver was established. The following section lists a generic list of uncertainties for each cost driver in each cost category. The cost categories and cost drivers are used as given from the previous meeting.



### D.1.3 Supply chain:

The main cost drivers considered in supply chain are arising rate, MTBF, purchase cost and repair cost. Furthermore, in the case of MTBF the uncertainties that cause variation in cost are considered to be fleet maturity, mode of failure, equipment operating environment and quality of item. Uncertainties for arising rate, repair cost and purchase cost are represented in Figure 1.

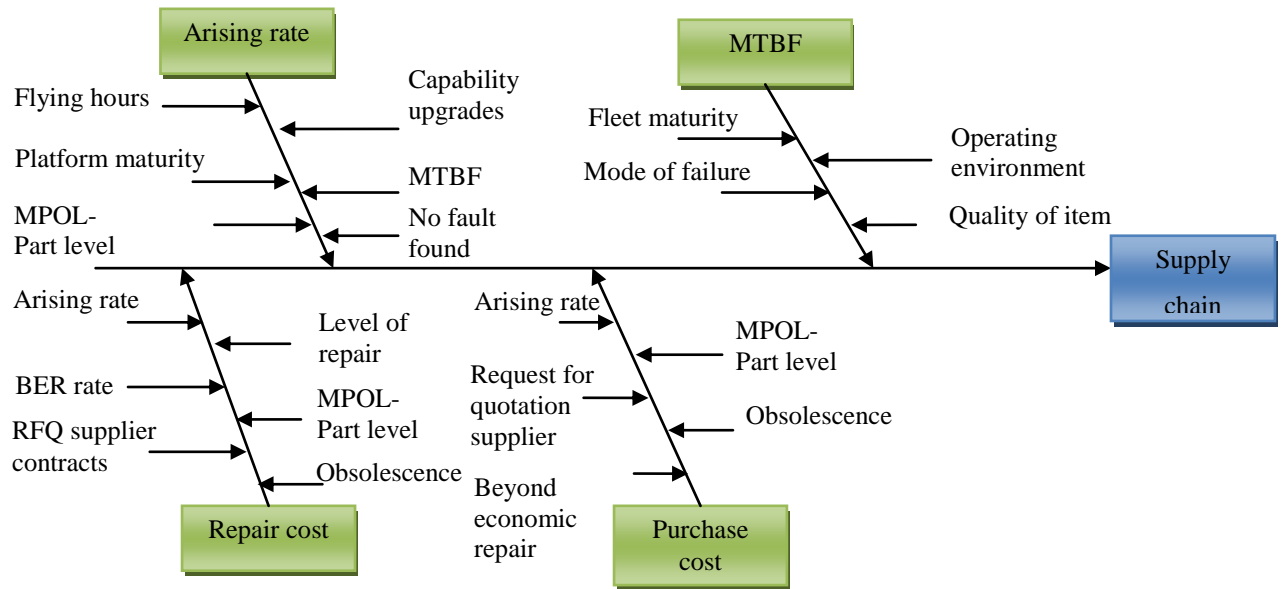


Figure 1. Linking the cost driver associated to 'Supply chain' and relevant uncertainties

### D.1.4 Engineering

The main cost drivers considered in engineering are query response time, query volume and quality of response.

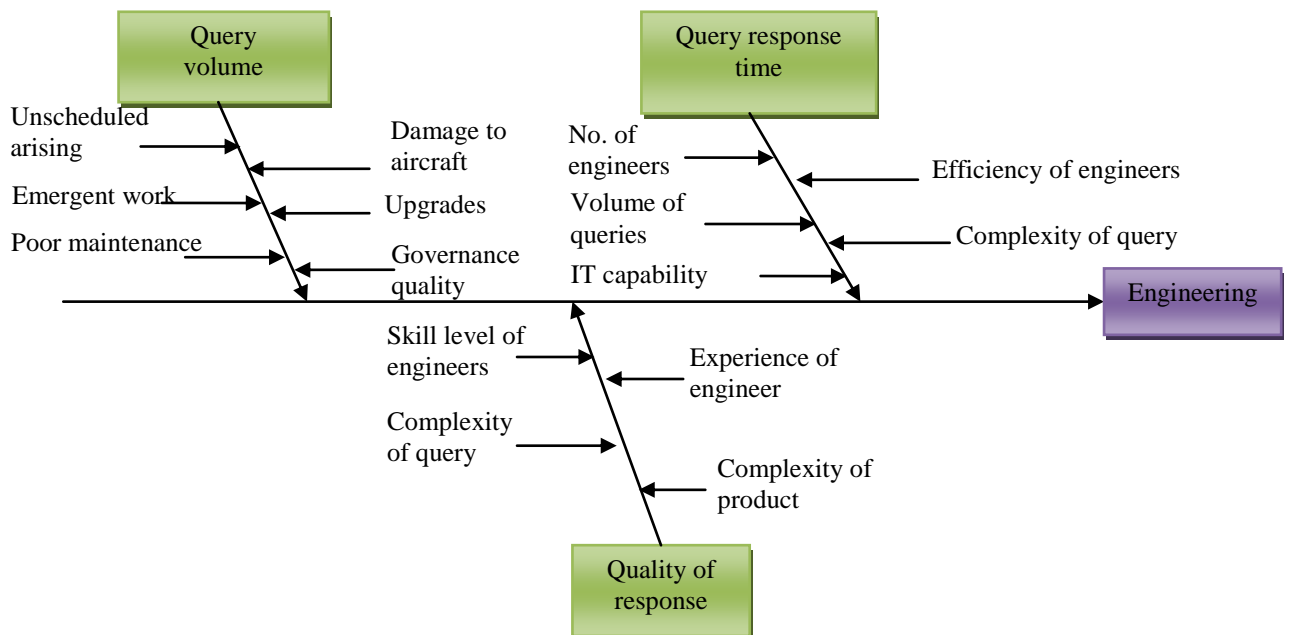


Figure 2. Linking the cost drivers associated to 'Engineering' and relevant uncertainties

In terms of the uncertainties related to the query response time the participants highlighted aspects such as number of engineers, volume of queries, IT capability, efficiency of engineers and the complexity of a given query. Furthermore, the uncertainties for query volume and quality of response are represented in Figure 2. Through validation it was recognised that mission or role play a factor that drives priority in required response time.

### D.1.5 Maintenance

The main cost drivers considered for maintenance are emergent work, GFX supply, labour availability and purchase cost. The uncertainties in emergent work have been considered to be operating environment, maintenance behaviours, operations and MPOL adherence. All elements considered for maintenance are represented in Figure 3.

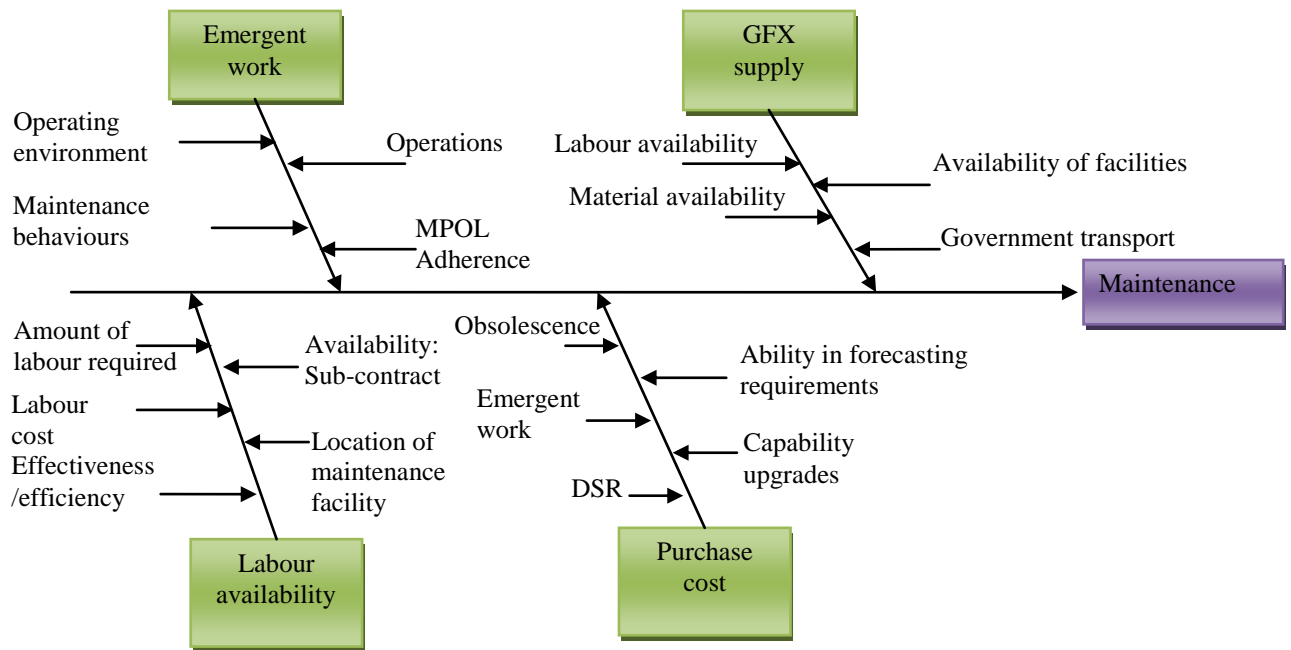


Figure 3. Linking cost drivers associated to 'Maintenance' and relevant uncertainties

### D.1.6 Training

The main cost drivers considered for training are number of students, number of trainers and facilities training. The uncertainties related to the cost driver, number of students, include availability of suitable candidates, requirement-budget, level of re-training and turnover of staff. The uncertainties for all cost drivers are represented in Figure 4.

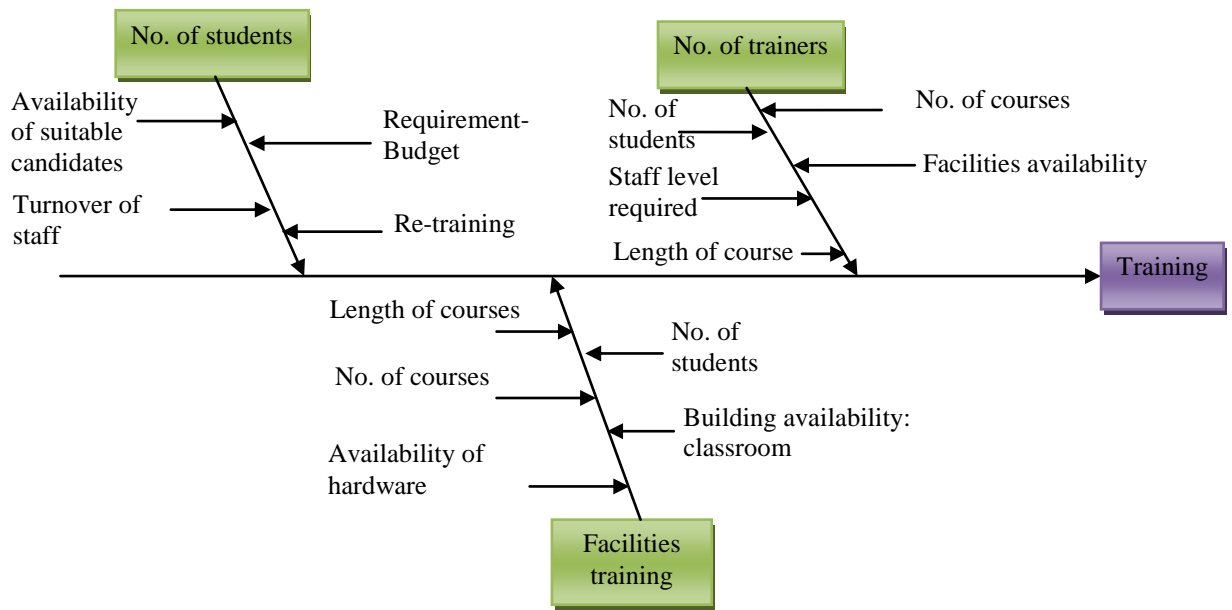


Figure 4. Linking cost drivers associated to 'Training' and relevant uncertainties

### D.1.7 Manage business

The main cost drivers considered for 'manage business' are GFX supply and debt/creditor days. The uncertainties for the debtor/creditor days include the availability of labour, material and facilities. The associated linkage between cost drivers and uncertainties are represented in Figure 5.

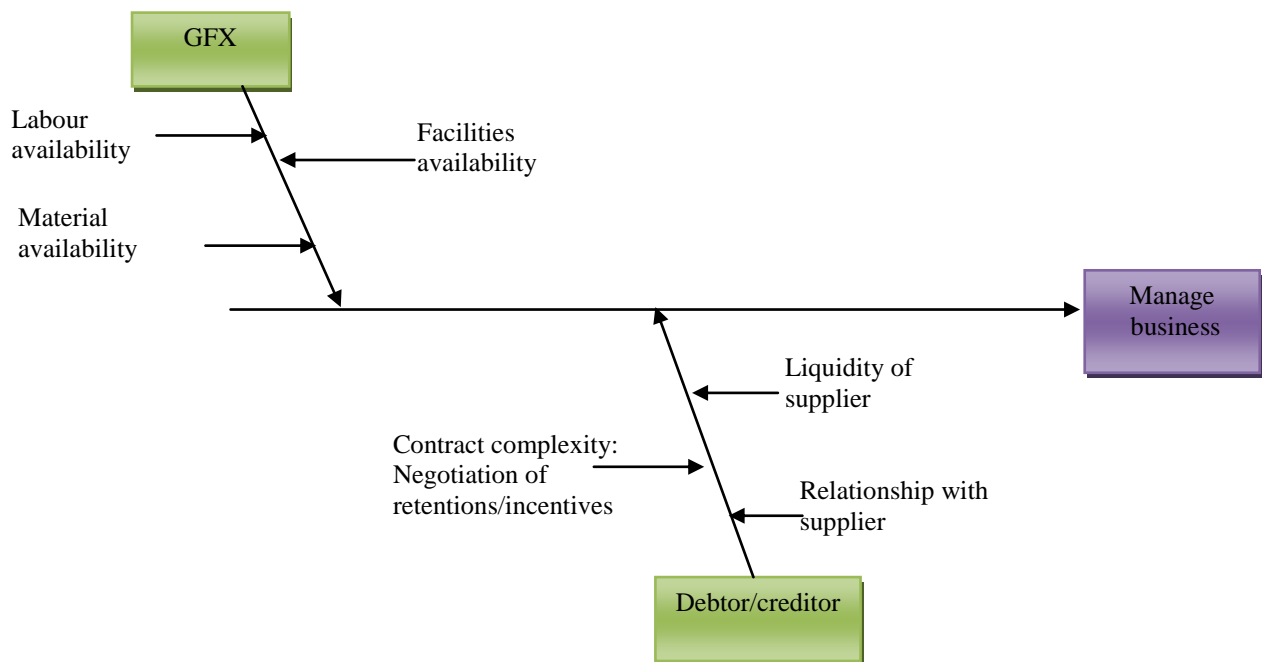


Figure 5. Linking the cost drivers associated to 'Manage Business' and relevant uncertainties

For the naval context it was also suggested to include Supplier Key Performance Indicators (KPIs) in the debtor/creditor line to recognise their potential involvement in many aspects associated to delivering support.

### D.1.8 Performance

The main cost drivers considered for maintenance are emergent work, GFX supply, labour availability and purchase cost. The uncertainties in emergent work have been considered to be operating environment, maintenance behaviours, operations and MPOL adherence. Figure 6, represents the complete of the linkages.

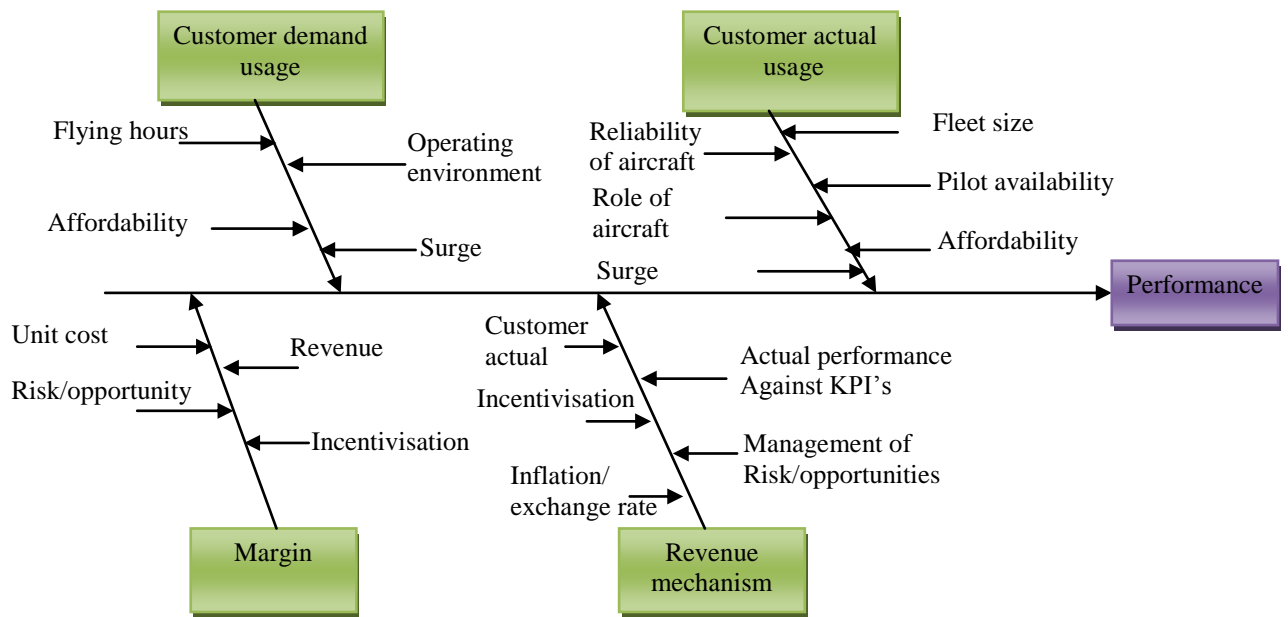


Figure 6. Linking the cost drivers associated to 'Performance' and relevant uncertainties

### D.1.9 Analysis of cost driver-uncertainty linkage

Based on the uncertainties that were suggested for each of the cost drivers an analysis to assess correlation across cost drivers was performed. For each uncertainty related cost drivers are considered to be correlated. For instance, emergent work as an uncertainty influences cost drivers such as query volume and material availability. Furthermore, due to variations across projects it was suggested that it would not be possible to rank or assign values to the level of correlation between the cost drivers.

Table 1. Uncertainties influencing many cost drivers

<b>Uncertainty</b>	<b>Cost driver 1</b>	<b>Cost driver 2</b>	<b>Cost driver 3</b>
Emergent work	Query volume	<b>Material availability</b>	
Query volume	Query response time	Purchase cost	Repair cost
Complexity of query	Query response time	Quality of response	
Aircraft operating Environment	<b>MTBF</b>	<b>Emergent work</b>	Customer demand usage
Flying hours	<b>Arising rate</b>	Customer demand usage	
MPOL	<b>Arising rate</b>	<b>Emergent work</b>	Repair cost
RFQ	Repair cost	Purchase cost	
Obsolescence	Repair cost	Material cost	Purchase cost
Operating Environment	<b>Emergent work</b>	Customer demand usage	<b>MTBF</b>
Affordability	<b>No. of students (training)</b>	<b>Customer actual Usage</b>	Customer demand usage
Capability upgrades	Query volume	<b>Arising rate</b>	Material availability

Table 1 also represented the dual role of some elements that are considered in the table. For instance, material availability has been considered as an uncertainty to other cost drivers and a cost driver within itself.

**Disclaimer:**

All the analysis and conclusions shown in this report are based on the information collected during the interview carried out on 29.05.09 with Organisation A.

## Appendix E Explanation of the types of uncertainties

This section initially presents a description of each of the types and categories of the specified uncertainties. Subsequently, the analysis for the transformed uncertainties is presented.

### E.1.1 Description of categories & types of uncertainty in availability contracts

#### *Explanation of categories:*

- *Commercial uncertainty* considers factors that affect the contractual agreement, which is driven by certain requirements set by the customer. However, industry takes responsibility in defining these requirements based on its capability constraint. Responsibilities are driven by both the customer and industry
- *Affordability uncertainty* considers factors that affect the ability to predict the customers funding for the given granularity of a project. Responsibility is driven by the customer.
- *Performance uncertainty* considers factors that affect industrial achievement in reaching the performance goals (KPIs) for the given project granularity level
- *Training uncertainty* considers factors that affect industrial achievement in reaching customer needs for the delivery of training
- *Operation uncertainty* considers factors that affect industrial achievement in reaching the required level of service and support delivery. It focuses on equipment level activities (i.e. onshore, maintenance) to deliver IPS<sup>2</sup>
- *Engineering uncertainty* considers factors that affect industrial achievement in managing strategic decisions with regards to the future service and support requirements (i.e. offshore, obsolescence management) to deliver IPS<sup>2</sup>

#### *Detailed explanation of the types of uncertainties:*

Commercial		
Uncertainty type	Description	Source
Customer equipment usage	Degree of misuse in equipment usage	Customer
Labour availability	Labour availability rate is considered; this also considers the uncertainty in skill loss over contract duration (labour pool)	OEM
Work share between partners	Driven by dependency on partners, uncertainties that arise from conducting individual work shares	Customer-OEM-Supplier
KPI Specification	Selecting the appropriate KPIs at bidding and how these evolve throughout contract	Customer-OEM
Interest rates	Interest rates affecting expenditure for the project or influencing customers funding	Financial
Environmental impact	Environmental burden arising from pollution and disposal within the project duration	Financial
Relationship with suppliers	Over the contract duration the uncertainty in the relationship with suppliers. This uncertainty has an influence over the flow of materials/skills/cost along the supply network	OEM-Supplier
Warranty scope	Predictability of the warranty scope for the given project	OEM

<b>Relationship with customer</b>	Driven by the progress (in terms of delivered quality and managing customer requirement) of a project resulting in uncertainty over the relationship with the customer	Customer-OEM
<b>Stability of customer requirements</b>	The uncertainty in customer requirements that influence the delivery of a project	Customer
<b>Commodity and energy prices</b>	The uncertainty level in commodity and energy prices during the project duration	Financial
<b>Exchange rates</b>	Uncertainty in exchange rates that influence expenditure and income over the project duration	Financial
<b>Inflation/Deflation</b>	Uncertainty in the inflation/deflation rate	Financial
<b>Material cost</b>	Uncertainty in material costs: includes spares, and consumables (influenced by scarcity)	Financial
<b>Labour rate</b>	Uncertainty in the labour rate	Financial
<b>Labour hours</b>	Level of labour requirement which influences the labour cost	OEM
<b>Labour efficiency</b>	Uncertainty over how labour is utilised in a project	OEM

<b>Affordability</b>		
<b>Uncertainty type</b>	<b>Description</b>	<b>Source</b>
<b>Customer ability to spend</b>	For the given project the uncertainty in customer ability to spend	Customer
<b>Bid success rate</b>	The bid success rate for an organisation influences the setting of the prices. The variation is driven by the experience of employees and skill level. The link between bid success rate and affordability is price	OEM
<b>Project life cycle cost</b>	Driven by the rate of difficulty existing in predicting the whole life cycle costs (driven by complexity or technological newness)	OEM
<b>Economy</b>	Affordability influenced by the uncertainty in the economy, which includes a combination of interest & exchange rates, and inflation.	Financial
<b>Equipment availability</b>	In availability contracts the affordability for customer is driven by the rate of equipment availability that is to be provided. Achievements with equipment availability are not static and vary driven by various factors such as labour quality and efficiency, failure rate and emergent work (requires definition of differences between at war and not)	Customer-OEM
<b>Customer willingness to spend</b>	The variation in the customers' willingness to spend on a particular project	Customer

<b>Performance</b>		
<b>Uncertainty type</b>	<b>Description</b>	<b>Source</b>
<b>IT</b>	IT refers to its role in the infrastructure and in project management tools. The uncertainty is associated to the performance of these aspects driven by the IT capability.	OEM
<b>performance against KPIs</b>	Measures the performance in agreed levels (i.e. for OPDEFs), the question takes a high level view of the KPIs	OEM
<b>Rate of surge</b>	The rate of surge.	OEM

<b>Training</b>		
<b>Uncertainty type</b>	<b>Description</b>	<b>Source</b>
<b>trainee skill level</b>	Given the scenario that the customer does not specify or misspecifies the trainee skill level there is an uncertainty that OEM needs to address. This influences the delivered course in terms of course speed, depth of covered material.	Customer
<b>availability of trainers</b>	The OEM is responsible to provide the trainers for the given training. However, the availability of trainers over project duration is not certain, due to uncertainties in the labour quantity and customer requirements.	OEM
<b>number of students</b>	It may be the case that the customer does not know the number of trainees to be sent. It is also the case that rate of demand in the market is hard to predict.	Customer
<b>facilities availability</b>	This includes the uncertainty the level of course material, computers or software tools, lecture rooms or buildings required.	OEM
<b>courses to be offered</b>	The number of courses that the customer requires is uncertain because of its evolving needs.	Customer
<b>affordability for training</b>	Specifically the affordability of the customer for the training service	
<b>availability of suitable candidates for training</b>	The uncertainty is driven by the ability to find candidates for training	Customer
<b>ability to screen candidates for training</b>	The uncertainty is driven by the ability to assess the candidates that will be trained.	Customer
<b>length of course</b>	Related to the skill level of students and the uncertainty in the demanded length of the training course	Customer
<b>delays in training</b>	The uncertainty in delays may arise due to the customer or the OEM. From the customers perspective, it may relate to sending the trainees later than planned. From the OEM perspective it may involve not making facilities available. The uncertainty relates to the process of the customer and the OEM providing the necessary input to achieve planned training.	Customer-OEM-Supplier
<b>rate of re-training</b>	Re-training refers to those trainees that have not achieved the sufficient level of qualification and provision of additional training for those to reach the required level. The uncertainty relates to the level of re-training required.	OEM

<b>Operation</b>		
<b>Uncertainty type</b>	<b>Description</b>	<b>Source</b>
<b>complexity of equipment</b>	The complexity of equipment effects the requirements for maintenance and spares.	OEM-Supplier
<b>quality of component(s)</b>	Typically certification for bought-in components, which may create uncertainty. This has a knock-on effect on the service delivery.	OEM-Supplier
<b>quality of manufacturing</b>	Includes the uncertainty in the manufacturing quality of the equipment. The uncertainty is driven by the certification of the system assembly.	OEM-Supplier
<b>maintainer performances</b>	This covers the uncertainty in the service delivery due to the varying performance of maintainers.	OEM
<b>equipment utilisation rate</b>	The uncertainty is considered to be driven by equipment operating environment and the uncertainty in the rate of equipment utilisation	Customer
<b>rate of emergent work</b>	The uncertainty in the additional work needed to do prior to actual work (i.e. breaking down an engine to conduct repair)	OEM



<b>supply chain logistics</b>	The uncertainty associated to the timeliness of spares/maintenance logistics from the supply chain	Supplier
<b>OEM logistics</b>	The uncertainty associated to the timeliness of spares/maintenance logistics from internal sources	OEM
<b>rate of repairability</b>	The uncertainty is related to the number of times that equipment is repairable. This affects the level of spares requirements	Customer
<b>mean time between failure data</b>	The uncertainty is in the data that represents the MTBF. As a result interpretation of the MTBF becomes difficult	Customer-OEM
<b>no fault found (NFF) rate</b>	The uncertainty in the NFF rate of occurrence	Customer
<b>location of maintenance</b>	This uncertainty relates to visits to various places that are made to maintain equipment	Customer
<b>calibration of workscope</b>	The rate of change in the required level of service requirements	OEM
<b>availability of maintenance support resources</b>	Availability of resources in order to meet the agreed availability level. However, driven by the variation in the resource usage its availability is uncertain.	OEM
<b>rate of materials</b>	The uncertainty in the rate of materials (i.e. spares) is driven by the requirements that arise in the maintenance process	OEM
<b>turnaround time</b>	There are many factors such as skill level, tools and facilities availability that influences the overall turnaround time. This is an uncertainty that affects the repair costs.	OEM
<b>rate of beyond economical repair</b>	The uncertainty in the rate of beyond economical repair (BER)	OEM
<b>rate of provision of consumables</b>	The uncertainty that is associated to the amount of required consumables	OEM
<b>operating parameters</b>	Uncertainty deriving from the temperature, sand, moisture in the equipments operating environment	Customer
<b>effectiveness maintenance policy part level</b>	Uncertainty deriving from the level of maintainability of the equipment	Customer-OEM
<b>failure rate of hardware</b>	Uncertainty in the failure rate of hardware	OEM
<b>uncertainty level of spare parts storage</b>	Involves the level of spare parts that will be needed to be stored.	OEM
<b>customer equipment utilisation</b>	The uncertainty associated to the degree of equipment usage, which evolves based on customer preferences	Customer
<b>component stress and load</b>	The uncertainty in the stress and load that is applied at the component level	Customer

<b>Engineering</b>		
<b>Uncertainty type</b>	<b>Description</b>	<b>Source</b>
<b>rate of capability upgrades</b>	The requirement of capability upgrades (i.e. enhancing the equipment availability level) is an uncertainty that influences service delivery performance and customer affordability	Customer

<b>rate of system integration issues</b>	The uncertainty that arises from system integration relates to the awareness of the possible mode of failures. These aspects also relate to the customer misuse and the scope of warranty	OEM
<b>maintaining design rights</b>	Over an equipments life cycle, the design rights can get transferred to other support providers. The uncertainty is embedded in who holds the design rights.	Customer -OEM
<b>cost of licensing and certification</b>	The uncertainty the cost of licensing and certification covers a number of areas including: EMC/ Tempest/Security/Safety/Airworthiness/Lloyds etc	Customer -OEM
<b>rate of rework</b>	It involves any kind of rework including design or service delivered. The uncertainty is associated with the level of certainty in predicting the rate of rework	OEM
<b>failure rate for software</b>	The level of uncertainty in the failure rate for software	OEM
<b>rate of severity of obsolescence</b>	The certainty in costs that arise from obsolescence is assessed. This is aligned with the ability to determine the severity of the likely obsolescence issues. The question takes a broad view of obsolescence, without distinguishing across the many types of obsolescence.	OEM- Supplier- OEM
<b>cost estimating data reliability or quality</b>	Issues such as reliability and quality of data that creates uncertainty in the cost estimation process.	OEM
<b>effectiveness of management of risk and opportunities</b>	Uncertainty concerning the elements that are covered in the risk and opportunities management process.	OEM

### E.1.2 Sample analysis of transformed uncertainties

Table 1 demonstrates an example for the detailed analysis that was considered for a transformed uncertainty, where the example is “Failure rate for hardware”.

<b>Shifting factors</b>	<b>Uncertainty: Failure rate for hardware</b>
<b>Responsibility (Risk sharing)</b>	<p><b>Traditional:</b> The customer is responsible of the implications of the failure rate, where it contacts the solution provider only if it is unable to manage the failure in terms of spares requirement and resources (knowledge). The interaction between the solution provider and the supplier is largely based on an ad-hoc basis. Inadequate failure predictions and lack of communication with solution provider may cause inefficient allocation of responsibilities.</p> <p><b>New scenario:</b> Irrespective of the failure rate for hardware, (given specified boundaries) the solution provider is responsible of achieving performance requirements (availability). This means that the management of the implications of failures is driven by solution provider’s responsibility. With the increasing responsibilities the solution provider further collaborates with suppliers</p>
<b>Time (At which decisions are made)</b>	<p><b>Traditional:</b> The time at which the failure rate is considered depends on the customers’ pro-activeness. It may be considered in an ad-hoc manner during the service delivery or predicted prior to the bid agreement. The solution provider is typically expected to respond to ad-hoc requirements that arise driven by the failure rate. As time passes it becomes possible to understand the equipment performance, however this information is constrained to the customer.</p> <p><b>New scenario:</b> Requires the solution provider to predict the failure rate that is realistic to achieve the expected costs/profits for the customer requirements in terms of spares and resources during bidding. The importance of the assessment of failure grows due to the financial implications to the complete supply</p>

	chain. Also, the prediction needs to be continuous throughout the contract duration in order to be able to manage the implications of failures.
<b>Information (Source and flow)</b>	<p><b>Traditional:</b> The information regarding equipment usage becomes irrelevant to the solution provider and suppliers as they are not responsible to guarantee spares delivery and operate on an ad-hoc basis. The information required is about what the demand is (e.g. Spares requirement) and information flow does not assist to manage future demand.</p> <p><b>New scenario:</b> There is an increase in the need for sharing information across the supply chain. With the scenario that the customer is still responsible of using the equipment, the flow of information is driven by the customer regarding various aspects related to the equipment performance and usage conditions. This information is used by the solution provider and suppliers to meet the demand. The provided information is used to manage the service delivery in a structured manner.</p>
<b>Supply chain integration (Dependency and alliance)</b>	<p><b>Traditional:</b> The customer only gets in touch with the solution provider if it can not manage the service requirement by it self. This means that it builds a certain level of operational capability to self-sustain the desired equipment usage. The solution provider takes a similar approach where it only asks for support from the suppliers if it is outside of its capability. Thus, across the supply chain there is lack of integration.</p> <p><b>New scenario:</b> In order to achieve the customer performance requirements collaboration between the supply network occurs. With the information flow assisting in deciding the tasks (e.g. deliver spares) that the solution provider is to undergo. The spares requirements raised by the customer are decided in collaboration with the solution provider. It may also be the case that the solution provider decides the requirements and in collaboration with the suppliers it works to meet the performance.</p>
<b>Capability (e.g. Knowledge)</b>	<p><b>Traditional:</b> The capability for the solution provider is in relation to reacting to support requirements raised by the customer. This requires capabilities such as spares storage.</p> <p><b>New scenario:</b> The solution provider requires enhanced capability to predict failures in order to achieve performance requirements. Thus, areas such as health monitoring has become important.</p>
<b>Implications on stakeholders for the new scenario</b>	<p><b>Customer:</b> Failure rate for hardware is no longer the responsibility of the customer. When preparing the budget for a new project the customer needs to consider the failure rate, in order to communicate the expected cost level. The customer becomes an important source of information for the supply network, and has to manage the flow of information in order to achieve the performance required. The capability of the customer shifts from managing processes to overcome the impact of failure rate to sharing information across the supply chain.</p> <p><b>Solution provider:</b> Failure rate stops being a source of revenue, as the customer pays for the outcome of using the equipment or having the equipment readily available for use when required. As the responsibility moves to the solution provider it becomes essential to have suitable processes to fulfil demand. These processes involve planning (for failure), and delegation across the supply chain (to manage impact). A pro-active approach becomes necessary to predict the performance of the equipment.</p> <p><b>Supplier:</b> The suppliers become more integrated to the supply chain as they become part of the process of achieving customer requirements.</p>

# Appendix F      User Manual of the Uncertainty Tool for Assessment and Simulation of Cost

This section presents the User Manual that has been delivered to industrial collaborators concerning the developed Uncertainty Tool for Assessment and Simulation of Cost.

## Abstract

This User Manual, produced by the PSS-Cost Project at Cranfield University, provides support concerning the context and the guidelines to use the Uncertainty Tool for Assessment and Simulation of Cost. The tool has been developed due to the challenges that are faced with the transfer of uncertainties from the customer to the prime contractor. The focus of the tool is to reflect the influence of uncertainty in cost estimation at the bidding stage of availability contracts. The key features of the presented tool include uncertainty identification, prioritisation, management, range definition, turning a single point estimate into three and decision making through Monte Carlo and Agent Based Simulation.

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## Document History

Version	Date	Comments
1	07/06/10	Initial release by Cranfield University

## Glossary of Terms

CBS	Cost breakdown structure
CADMID	The Concept, Assessment, Demonstration, Manufacture, In-service, Disposal cycle has been used by the United Kingdom Ministry of Defence (MOD) since 1999, when it was devised as part of the Smart Procurement initiative, since replaced by Smart Acquisition, to deliver equipment capability within agreed performance, cost, and time parameters.
CER	Cost estimating relationship
CfA	Contracting for Availability
LRU	Line replaceable unit
OEM	Original equipment manufacturer
PSS	Product-Service Systems
WBS	Work breakdown structure
WLC/ WLCC	Whole Lifecycle Cost (or Whole Life Cycle Cost), refers to the holistic view of cost end-to-end across the CADMID cycle.

### F.1.1 Overview of the Uncertainty Tool for Assessment and Simulation of Cost

The U-TASC has been classified into three phases, as represented in Figure 1. This User Manual follows this architecture to cover the features of the tool.

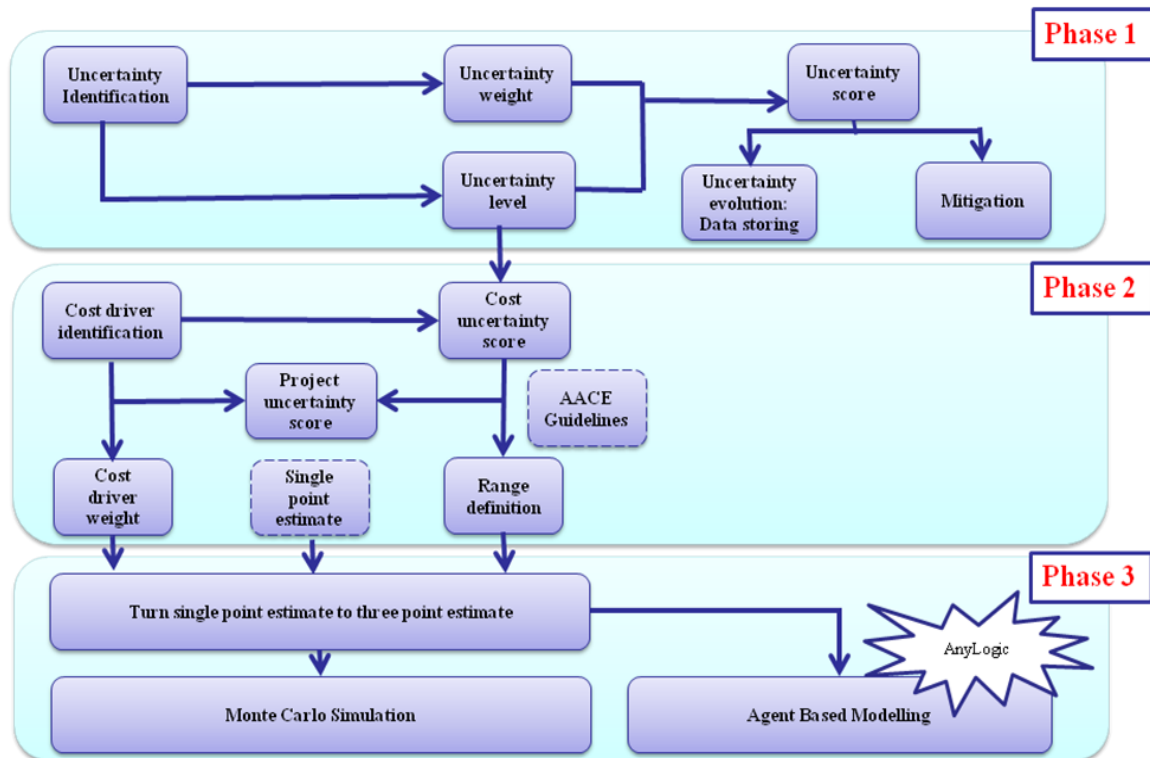


Figure 1. Overview of the Uncertainty Tool for Assessment and Simulation of Cost

Phase 1 focuses on uncertainty, where issues such as identification, prioritisation and management are addressed. Phase 2 concentrates on capturing the influence of uncertainty on cost. This refers to defining the degree of contribution of the specific sources of variation in the cost drivers. Phase 3 focuses on representing the influence of uncertainty through simulation yielding distributions to be used during the bidding. Two approaches are considered including Monte Carlo Simulation and Agent Based Modelling.

In the tool there are introductory explanations concerning how to use the tool and various key concepts that are considered in the software tool. These are covered in the sheets: “Tool Description” and “Uncertainty Ranking Guide”.

- 1 The initial sheet that requires the user to input information is “Broad-Info”, where a broad level of information is collected regarding the project (e.g. user name, project name and system/ work breakdown class, etc.), as shown in the snapshot representing this sheet in Figure 2. The purpose of the collected data (e.g. “Date of tool usage”, “Project Phase”, “User Name”) is to enable a structured approach to retrieve information that is gathered from the following sheets.

**Broad Questions About Project Characteristics**

User Name	Project Phase	Date of tool use
1		25-Mar-2010 6:00 PM
2		
3		

Project Name: \_\_\_\_\_

System or Work breakdown class: \_\_\_\_\_

Type of platform: \_\_\_\_\_

Project life cycle (Year): \_\_\_\_\_

Categories of Uncertainties	Relevance	GO TO SHEET
1 Uncertainty level in commercial for a project at bidding stage	<input type="checkbox"/>	Input-Commercial
2 Uncertainty level in affordability for a project at bidding stage	<input type="checkbox"/>	Input-Affordability
3 Uncertainty level in performance for a project at bidding stage	<input type="checkbox"/>	Input-Performance
4 Uncertainty level in training for a project at bidding stage	<input type="checkbox"/>	Input-Training
5 Uncertainty level in operation for a project at bidding stage	<input type="checkbox"/>	Input-Operation
6 Uncertainty level in engineering for a project at bidding stage	<input type="checkbox"/>	Input-Engineering

Figure 2. Initial input to the Software Tool: Broad Information

- 2 The relevance of the defined categories of uncertainties that have been considered in the Software tool are assessed. This is requested through tick boxes, which enables to ignore the detailed list of uncertainties within each of the categories.
- 3 The arrows represented at the top of the sheet enable to move on to the previous and following sheets. Additionally, to assist the user to go to relevant sheets buttons are positioned on the right hand side of each sheet. It is also possible to go to the required sheets by using the buttons situated beside each category of uncertainty. The sequence of the input does not affect the analysis.

This User Manual is structured based on the key features of the U-TASC. For each of the sections the conceptual background and steps for the implementation are explained. Section 2 focuses on the identification and importance assessment of uncertainty. Section 3 explains the way in which the tool prioritises the uncertainties. Section 4 defines the approach to uncertainty management. Section 5 concentrates on the assessment of the evolution of uncertainty, which refers to understanding the changes in uncertainty in terms of the importance of the type and the level of uncertainty over time. Section 6 begins by defining the relevant cost drivers. Subsequently the considered link between cost and uncertainty is explained, which sets the basis for the range definition for the cost drivers. Section 7 explains the process of turning a single point estimate into a three point estimate. Section 8 concentrates on the Monte Carlo simulation that is conducted within the tool. Section 9 defines the calculation of the maturity indicator, which is based on the uncertainty level. Section 10 focuses on an Agent Based Model that takes input from the presented software tool and the model runs through AnyLogic. The following sections provide explanation of the potential development of the tool, summary of the manual, future reading suggestions and in appendix the terms that are considered in the tool are defined.

## **F.1.2 Uncertainty Identification and Importance Assessment**

### ***Conceptual Background***

The section focuses on the conceptual background to the identification and importance assessment of the uncertainties that are considered in the software tool. Through interaction with industrial partners a list of uncertainties that are likely to be experienced in an availability type contract has been established. For this reason the focus is on the most commonly offered services: maintenance, spares and training. Initially the types of uncertainties were classified into six categories:

- Commercial uncertainty refers to the list of uncertainties that arise from contractual issues
- Affordability uncertainty, considers the customers ability to fund required operations
- Performance relates to the uncertainty that arises in achieving the key performance indicators
- Training focuses on the uncertainties that arise in delivering this service
- Operation focuses on equipment level activities (e.g. onshore) to deliver in-service support
- Engineering focuses on managerial input at a strategic level (e.g. offshore) from engineers to deliver in-service support

Once the relevant uncertainties are established to be able to understand the level of uncertainty the Numeral, Unit, Spread, Assessment and Pedigree approach (NUSAP Pedigree Matrix) is applied, which classifies uncertainty into three dimensions.

- Basis of estimate. Typically refers to the degree to which direct observations are used to estimate the variable. The focus of this measure is the level of data that is available to be able to make a cost estimate.
- Rigor in assessment. It refers specifically to the methods used to collect, improve, and analyse the data that is used to make cost estimation.
- Level of validation. This metric refers to the degree to which efforts have been made to cross-check the data against independent sources.

For each of these criteria a scoring mechanism is put in place where a definition for four scores is provided in each of the scoring sheets. The user is allowed to pick a score from one to seven, where description of the scores is provided in Figure 3.



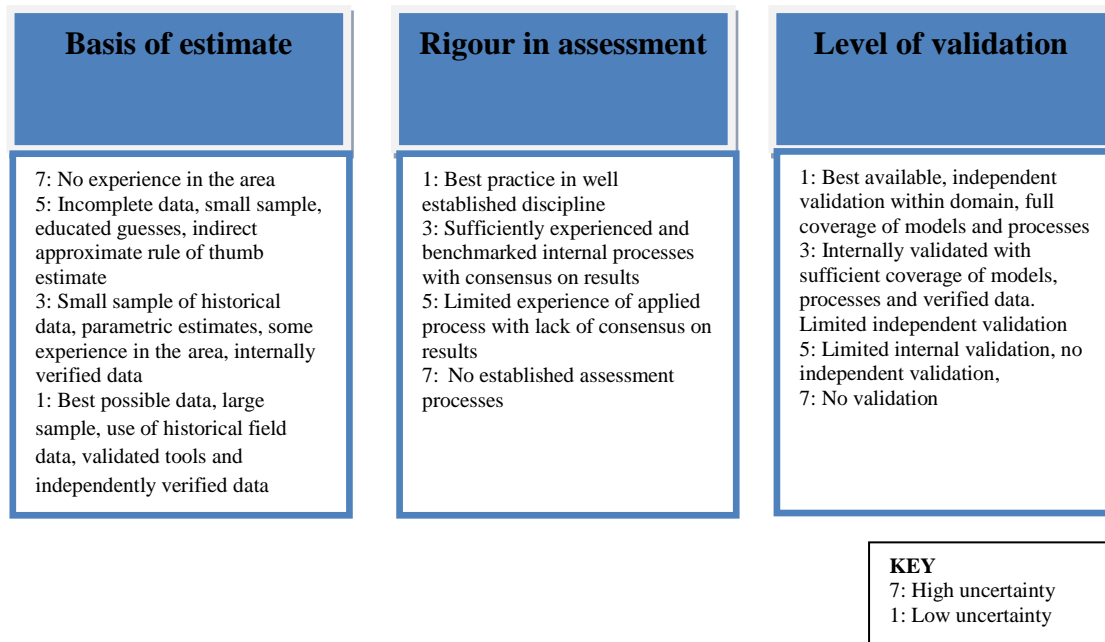


Figure 3. Numeral, Unit, Spread, Assessment and Pedigree Approach: Uncertainty Assessment

Once the level of uncertainty is established the tool moves on to understand the importance or level of the relevance of the uncertainty to the considered project. For this purpose the analytic hierarchy process (AHP) is implemented. AHP is a pairwise comparison technique which enables to compare across different elements. Some of the main approaches in AHP include the weighted sum method and the weighted product method. The weighted sum method, which is one of the earlier approaches, evaluates each alternative with respect to each criterion and then multiplies that evaluation by the importance of the criterion. This product is summed over all the criteria for the particular alternative to generate the rank of the alternative. On the other hand, the weighted-product method compares each alternative by multiplying a number of ratios, driven by the involved criteria. The comparison of the alternatives  $A_1$  and  $A_2$  is represented in Equation (1).

$$R(A_1 / A_2) = \prod_{j=1}^N (a_{1j} / a_{2j})^{w_j} \quad (1)$$

where  $N$  is the number of criteria,  $a_{ij}$  is the actual value of the  $i$ th alternative in terms of the  $j$ th criterion and  $w_j$  is the weight of the  $j$ th criterion. Thus, in the tool the user is requested to input a score regarding the relevance of the given uncertainty level for the project, where the scores are defined in Figure 4.

#### Pairwise Comparison Scores

1. Minimally significant/relevant; 2. Minimally to moderately significant/relevant; 3. Moderately significant/relevant; 4. Moderately to strongly significant/relevant; 5. Strongly significant/relevant; 6. Strongly to very strongly significant/relevant; 7. Very strongly significant/relevant; 8. Very to extremely strongly significant/relevant; 9. Extremely significant/relevant

Figure 4. Scores used in the Analytic Hierarchy Process

**Implementation**

- 4 Guidance concerning scoring of the level of uncertainties within each category is provided.
- 5 The tool assesses the level of input in order to recommend whether sufficient information has been provided. Thus, if the user specifies that the uncertainty is relevant and that it is possible to make an assessment of the uncertainty, then all three criteria needs to be scored, in order for the uncertainty to be properly considered in the outputs.

The focus for this sheet is uncertainties that relate to contractual performance. This section requires inputs/scoring in "Basis of estimate", "Rigour in assessment", "Level of validation" and to assign a weight for the significance of the uncertainty on the project. Explanation of the scoring for each of the uncertainty metrics is provided below. The user needs to define whether it is possible to assess the uncertainty by using the tick box. Furthermore, if it is possible to assess the uncertainty all three criteria need to be filled.

**Uncertainty Ranking**

Best   Typical   Poor   Worst

1   3   5   7

**Basis of Estimate**

- 7: No experience in the area
- 5: Incomplete data, small sample, educated guesses, indirect approximate rule of thumb estimate
- 3: Small sample of historical data, parametric estimates, some experience in the area, internally verified data
- 1: Best possible data, large sample, use of historical field data, validated tools and independently verified data

**Rigour in Assessment**

- 7: No established assessment processes
- 5: Limited experience of applied process with lack of consensus on results
- 3: Sufficiently experienced and benchmarked internal processes with consensus on results
- 1: Best practice in well established discipline

**Level of Validation**

- 7: No validation
- 5: Limited internal validation, no independent validation
- 3: Internally validated with sufficient coverage of models, processes and verified data. Limited independent validation
- 1: Best available, independent validation within domain, full coverage of models and processes

Commercial	Source	Relevance	Ability to fill	Basis of estimate	Rigour in assessment	Level of validation	Accuracy of input	Score Justification
1 Uncertainty in customer equipment usage	Operational	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		7	7	False	
2 Uncertainty in material cost	Market-Operational	<input type="checkbox"/>	<input checked="" type="checkbox"/>		7	7		
3 Uncertainty in the work share between partners	Operational	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	3	5	3		Score Justification
4 Uncertainty in the level of relationship with supplier	Operational	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	1	1	3		
5 Uncertainty in the level of relationship with customer	Operational	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	3	5	3		

Figure 5. Input to the Software Tool: Defining the Uncertainty Level

- 6 The button takes the user to the score justification sheet, where the user is facilitated to justify the scores that it has considered for each type of uncertainty within each uncertainty category. This enables to understand the shift in the reasoning for the uncertainty scores.

Commercial	Source	Relevance	Ability to fill	Basis of estimate	Rigour in assessment	Level of validation	Accuracy of input	Score	Justification
1	Uncertainty in customer equipment usage	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Operational	7	7	False	7	Score Justification
2	Uncertainty in material cost	<input type="checkbox"/>	<input checked="" type="checkbox"/>	Market-Operational	7	7		7	Score Justification
3	Uncertainty in the work share between partners	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Operational	5	3		5	
4	Uncertainty in the level of relationship with supplier	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Operational	1			1	
5	Uncertainty in the level of relationship with customer	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Operational	5			5	
6	Uncertainty in KPI specification	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		3			3	
7	Uncertainty in the scope of warranty	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		3			3	
8	Uncertainty in environmental impact	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>						
9	Uncertainty in stability of customer	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>						
10	Interest rates	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>						
11	Uncertainty in the commodity and	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>						
12	Uncertainty in exchange rates	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>						
13	Uncertainty in inflation rate	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>						
14	Uncertainty in the rate of labour availa	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>					5	
15	Uncertainty in labour hours	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>					5	
16	Uncertainty in labour rate	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>					3	
17	Uncertainty in the labour efficiency	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Operational				5	

Commercial	Source	Relevance	Ability to fill	Basis of estimate	Rigour in assessment	Level of validation	Accuracy of input	Score	Justification
1		<input type="checkbox"/>	<input type="checkbox"/>						Score Justification
2		<input type="checkbox"/>	<input type="checkbox"/>						
3		<input type="checkbox"/>	<input type="checkbox"/>						
4		<input type="checkbox"/>	<input type="checkbox"/>						
5		<input type="checkbox"/>	<input type="checkbox"/>						
6		<input type="checkbox"/>	<input type="checkbox"/>						
7		<input type="checkbox"/>	<input type="checkbox"/>						

Figure 6 Input to the Software Tool: Broad Information

Figure 6 illustrates the specific inputs that are required in order to identify uncertainty and to define the uncertainty level. The figure only shows the commercial uncertainty category, while the other categories also follow the same process of input. The first and second inputs, through tick boxes, evaluate the relevance of the uncertainty to the project and the ability to assess (considering the case that due to lack of information it may not be clear to what degree there is uncertainty) the particular uncertainties. Subsequently, if the uncertainty is relevant and it is possible to assess it, then the user is requested to input a score for each of the criteria's. If an uncertainty is considered to be relevant, but it is not possible to make an assessment of the uncertainty, then the uncertainty for that particular line is considered to be the highest possible value (7 as a score). Figure 7 demonstrates the use of buttons in the tool.



The user has the option of including additional uncertainties for the identification and prioritisation assessments by following the same input procedure that has been defined.

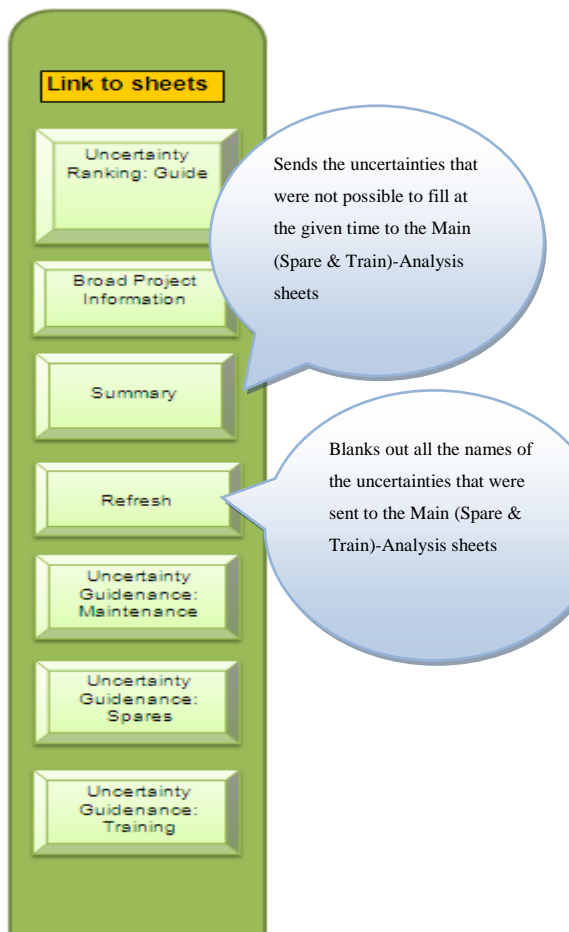


Figure 7. Buttons: Navigation and further uncertainty analysis

Link to other sheets and further analysis is assisted from the right hand side of each sheet. A Macro, embedded in the “Summary” button, is used to store those uncertainties that were relevant but could not be considered due to the lack of maturity of the given project. The text describing the type of uncertainty is sent to the “Main (Spare & Train)-Analysis” sheets. This way it is possible to observe the shift in the uncertainties, which can be assessed over time. On the other hand the “Refresh” button enables to remove those uncertainties from the “Main (Spare & Train)-Analysis” sheets. The other buttons enable to go to specific sheets (e.g. “Uncertainty Guidance: Maintenance” defines the prioritisation of uncertainties).

Figure 8 defines the process of justifying the input scores concerning the uncertainties. The complete list of the types and categories of uncertainties are provided. This involves writing information about the specified score, name of user, date, and reasons for the selected score. This enables the tool to identify stakeholders responsible of decision making and also for future use the tool becomes less dependent on former users.

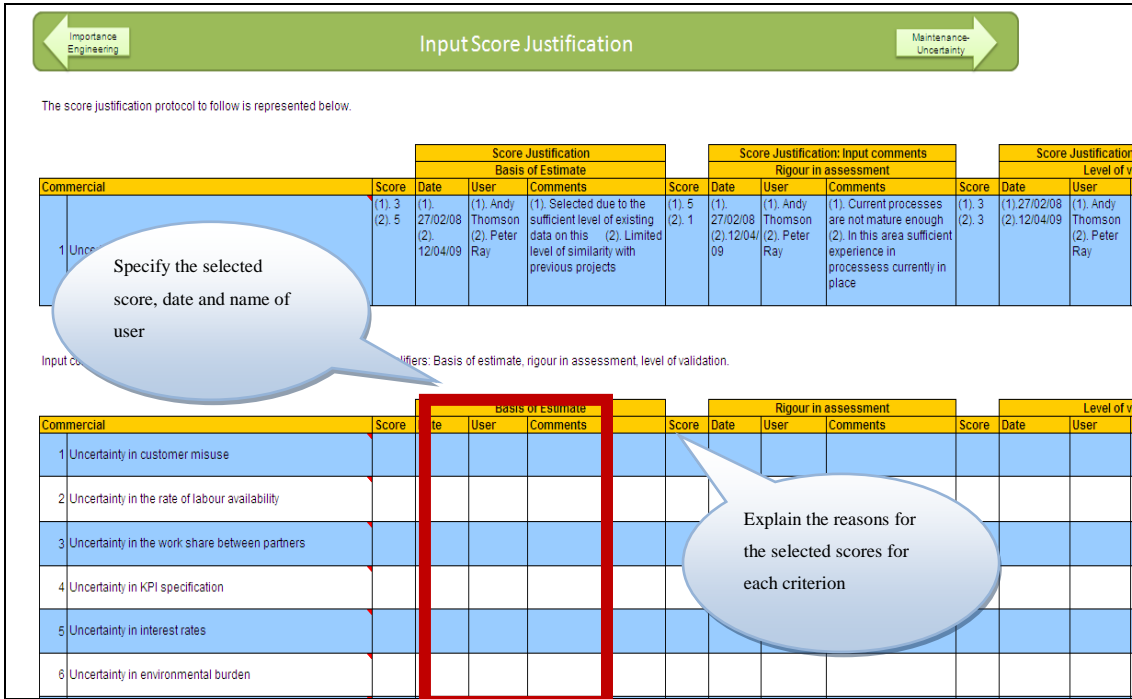


Figure 101. Input to the Software Tool: Score justification

Figure 9, presents the uncertainty importance assessment process. The only input requested from the user is to score the level of relevance and significance of the uncertainty to the project.

- 9 Represents the output from the Analytic Hierarchy Process assessment for the comparison of uncertainties. A pairwise comparison is applied to compare the significance of each uncertainty.
- 10 Represents normalised scores for the percentage significance of uncertainties that have been calculated. The normalised scores are calculated by considering the expected average score and any uncertainty significance level above that is considered to be 100% important. The scores below this level are compared to the average by capturing the percentage contribution.
- 11 The input scores are assessed in the AHP, where recommendations concerning the considered inputs is provided.
- 12 Presents the guidance with the scores to define the importance/relevance of the uncertainties.

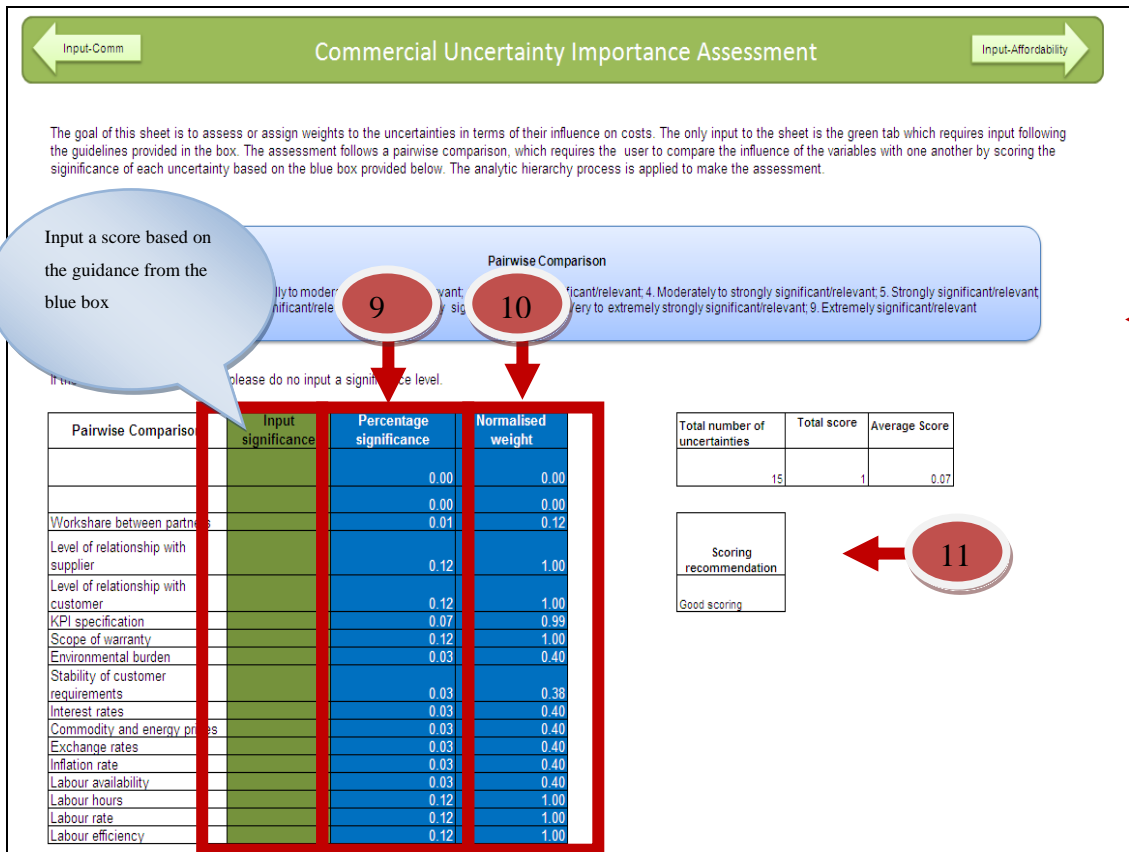


Figure 102. Input: Uncertainty importance assessment

Figure 10 demonstrates the calculation of the AHP, where there is flexibility in the calculation based on the relevance of the uncertainty to the project. Thus, if an uncertainty is defined to be irrelevant then it is not considered in the AHP calculations.

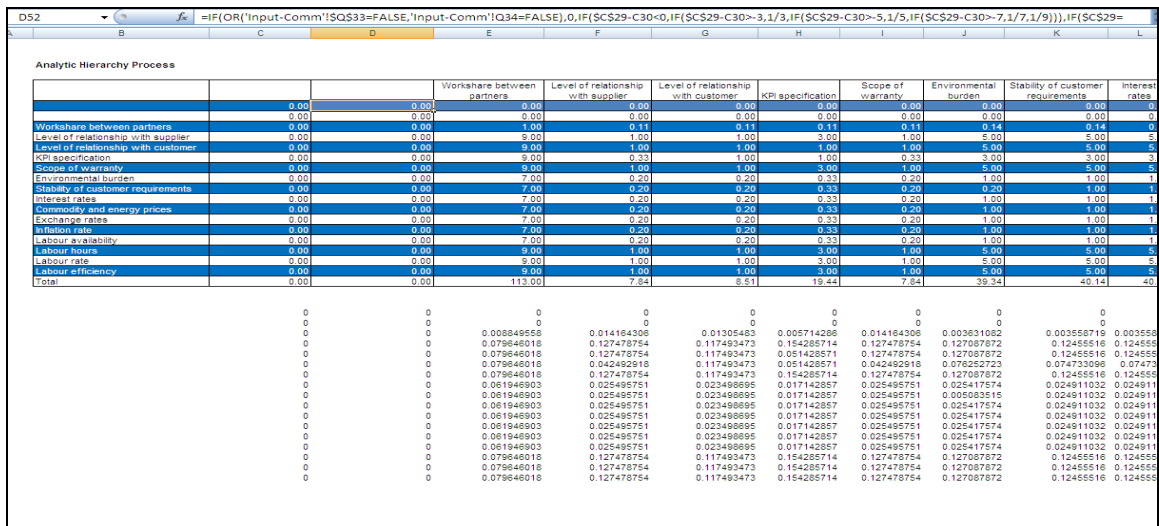


Figure 10. Application of the analytic hierarchy process for uncertainty types

### F.1.3 Uncertainty Prioritisation

#### Conceptual Background

Two aspects are considered for the uncertainty prioritisation. Firstly, results from the NUSAP Pedigree Matrix approach are considered, where the average of the three qualifiers is used. The second aspect that is considered for the prioritisation is the importance assessment through the Analytic Hierarchy Process (AHP). By multiplying the scores for these two aspects an uncertainty score is calculated to be used in the prioritisation. As a result uncertainties get classified into high, medium and low level using a traffic light system for services including maintenance, spares, and training. It is worth noting that the same procedure for uncertainty prioritisation is followed for all these services.

#### Implementation

Figure 11 depicts the first output of the software tool by collating information that is collected up to this part of the tool.

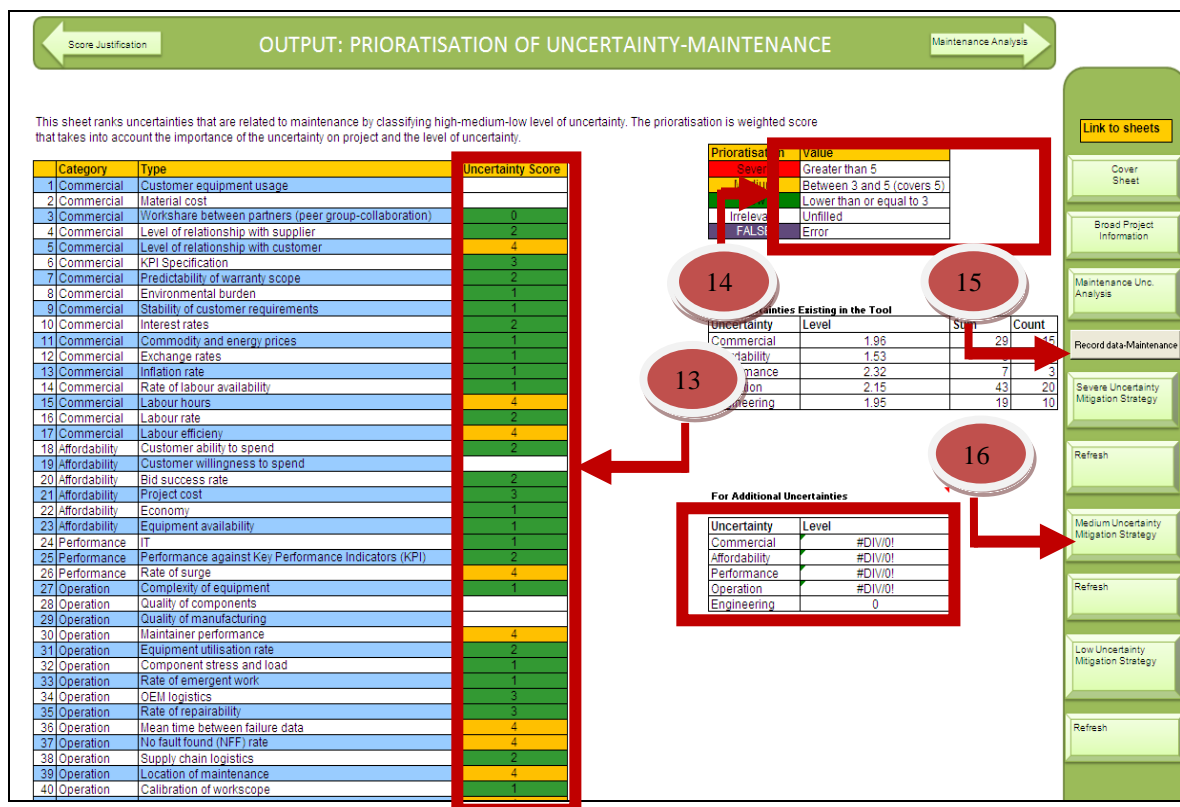


Figure 11. Output: Prioritisation of Uncertainty

13 The full list of uncertainties that is considered in the software tool is provided. This sheet summarises the input from the previous sheets based on the uncertainty level and the uncertainty importance through the uncertainty score.

- 14 The type of uncertainty is deemed red (hi uncertainty) if the average of the three criteria is greater than five. The type of uncertainty is orange (medium uncertainty) if the average is between three and five (including five). And green (low uncertainty) if the average is lower than or equal to three. This enables to direct the focus into uncertainties that need attention.
- 15 The “Record data” button enables to store data about the average uncertainty score for each category of uncertainty and for each of the services offered. This enables to observe the evolution of uncertainty.
- 16 The uncertainty mitigation buttons are used to allocate the uncertainties based on hi, medium and low levels to the uncertainty mitigation strategies. Along with this the “Refresh” buttons help to remove the uncertainties that are allocated into the uncertainty management sheets.

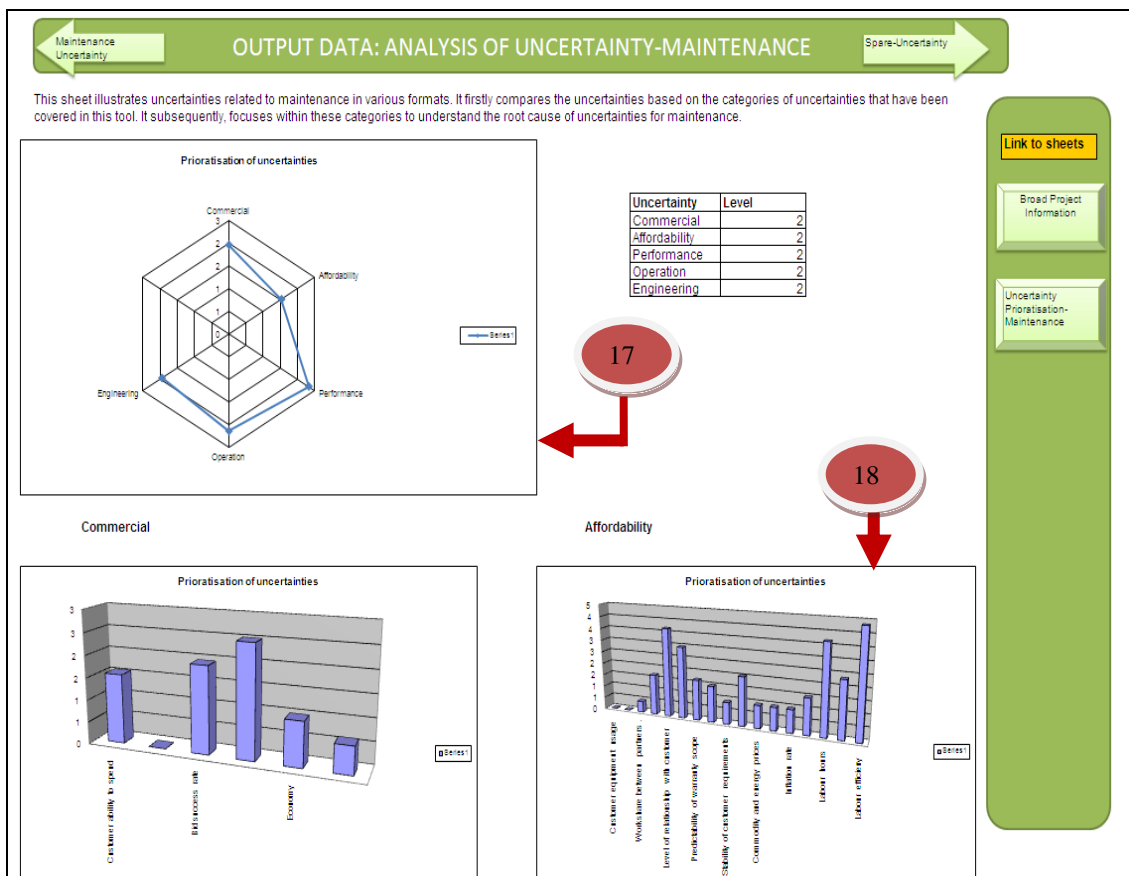


Figure 12. Output: Graphical illustration of prioritised uncertainty

- 17 The average of the uncertainty scores for each category is represented through a spider diagram.
- 18 For each category of uncertainty the uncertainty scores are represented, which enables to realise the key uncertainties within each category.







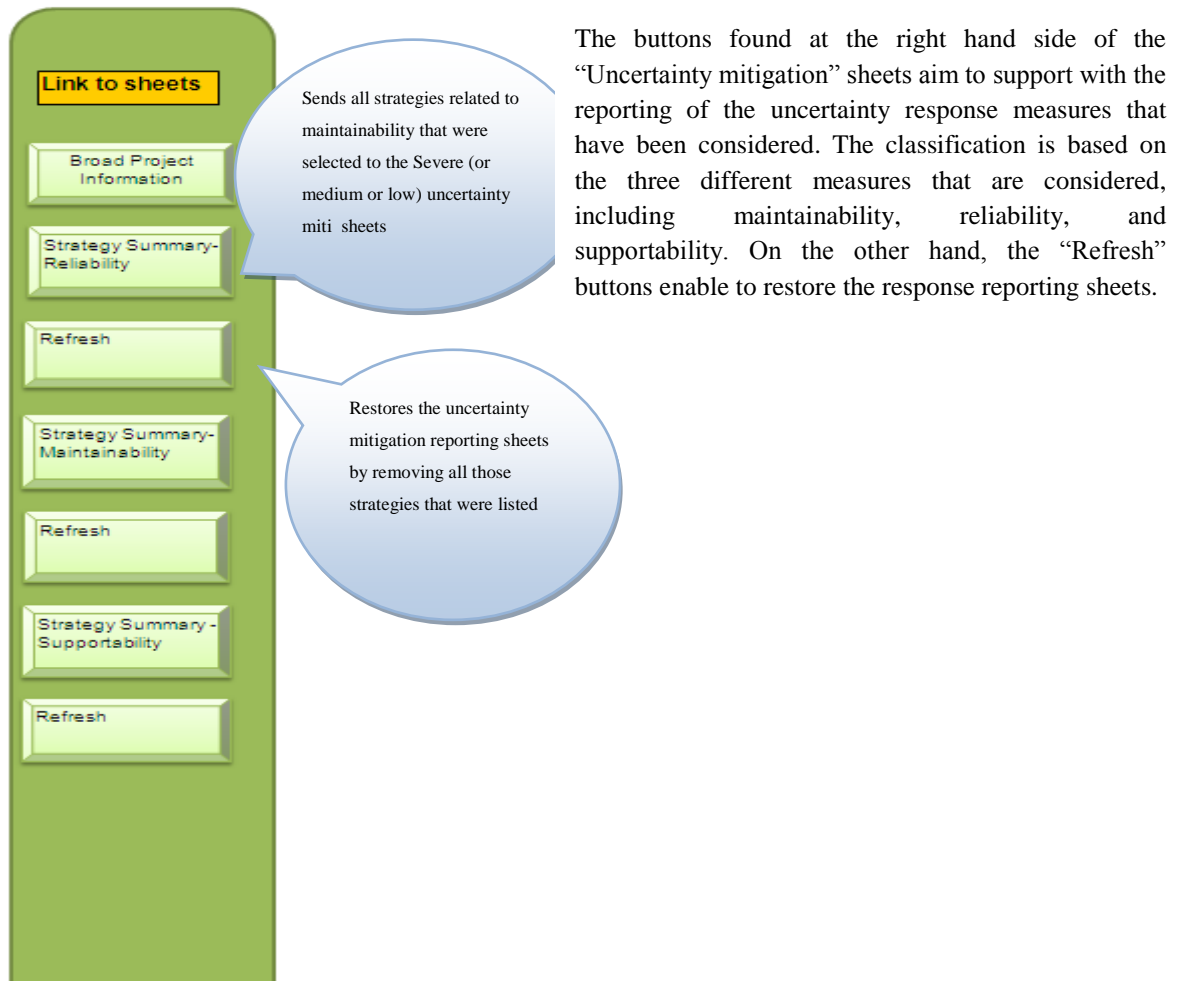


Figure 15. Buttons: Navigation and ability to report the uncertainty management strategies

21 The selected responses are brought together as a report to guide the user with suitable measures for the uncertainties. The reporting depicted in Figure 16, follows the same process for the medium and low levels of uncertainty.

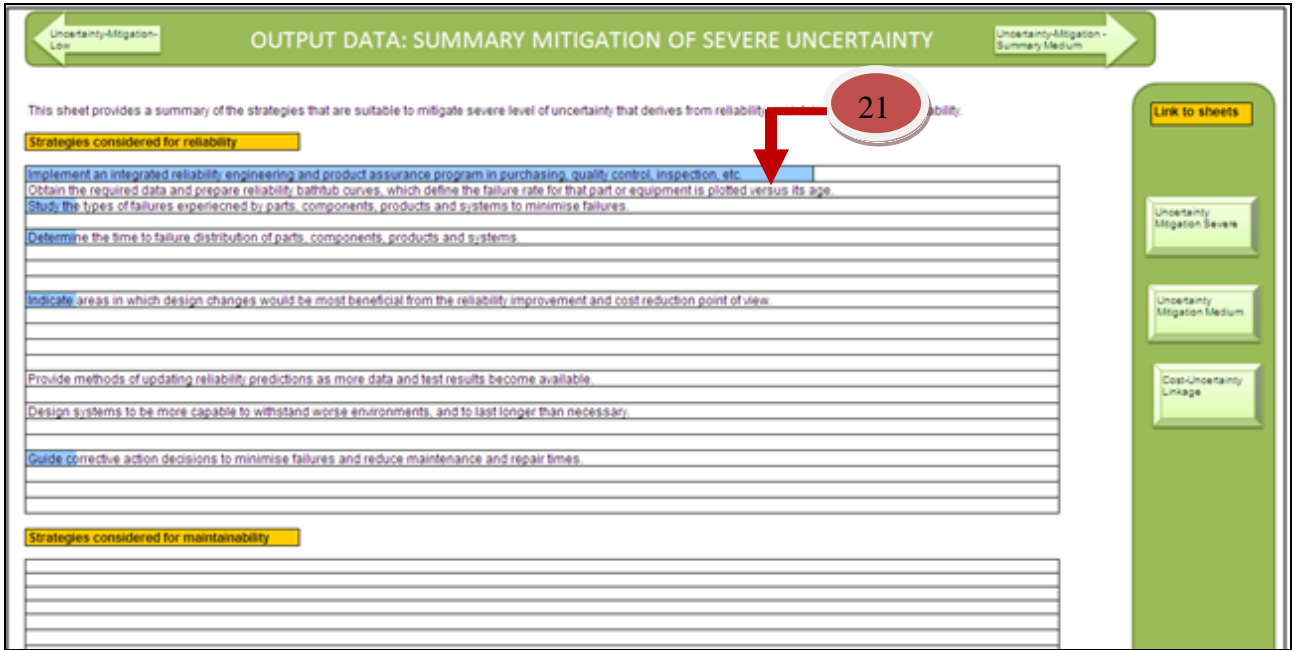


Figure 16. Output: Reporting the uncertainty management strategies adopted for the project

## F.1.5 Uncertainty Evolution Assessment

### *Conceptual Background*

The uncertainty scores, calculated based on the uncertainty level and the importance/relevance of uncertainty, is stored in the tool. This enables to observe the evolution of uncertainty over time.

### *Implementation*

The data storing procedure follows for the spares and training services.

- 22 In the data storage sheet the average score for each category of uncertainty is stored. However, the user needs to input the date of the input. As a result the deviation over time is graphically represented on the right hand side of the sheet.

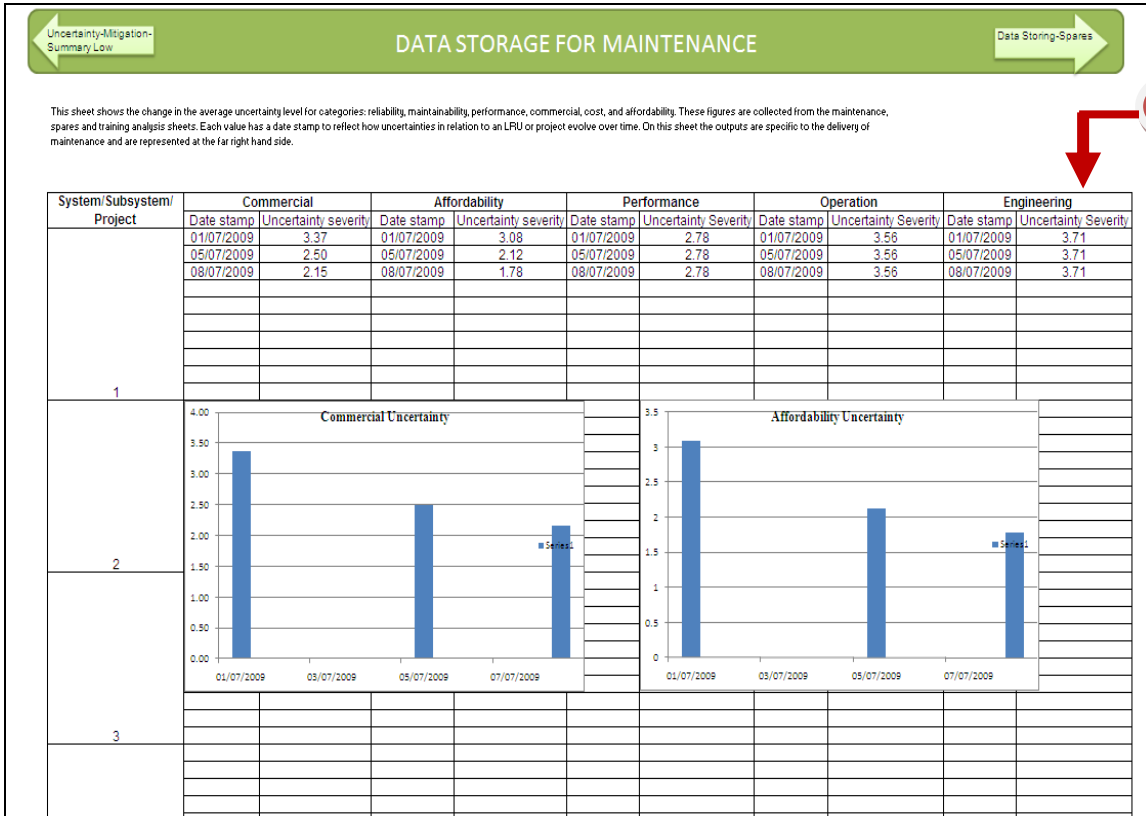


Figure 17. Output: Representing the evolution of uncertainties

### F.1.6 Range Definition for Cost Drivers

#### Conceptual Background

The feature of the tool to define a cost range for cost drivers is achieved by (1) establishing cost drivers, (2) defining the causes of variation in cost drivers through specific uncertainties, and (3) the AACE (1997) guidelines, which based on the level of project definition enables to define a suitable range:

Beginning from this phase onwards the link between cost drivers and uncertainties is considered. In the tool, these are contained in the “Cost drivers” sheet. Initially, the user is requested to define cost drivers that are relevant to the project. A total of 19 cost drivers have been considered in the tool. This list was developed through workshops that took place in the air and naval domains. Subsequent to the workshops, validation of the list with various partners of the project took place. This also enabled to refine the list.

- Failure rate
- Turnaround time
- Line replaceable unit (LRU) cost
- Transport cost
- Packaging cost
- Repair cost

- Demand rate (spares)
- Storage
- Emergent work
- GFX Supply
- Material availability
- Labour availability
- Customer demand usage (e.g. fleet time and harbour)
- Customer actual usage (e.g. fleet time)
- No fault found (NFF) cost
- Beyond economical repair (BER) cost
- Number of students
- Number of trainers
- Facilities for training

For each cost driver specific types of uncertainties are associated with the goal of determining the variation in cost drivers. This means that all the uncertainties that were assessed up to this point of the tool are linked to the cost drivers. For example, for the cost driver of failure rate the source of variation is considered to be:

- Uncertainty in customer equipment usage
- Uncertainty in the level of relationship with the customer
- Uncertainty in the rate of surge
- Uncertainty in the quality of components
- Uncertainty in equipment utilisation rate
- Uncertainty in the operating parameters
- Uncertainty in the failure rate of hardware
- Uncertainty in the rate of capability upgrades
- Uncertainty in the rate of system integration issues
- Uncertainty in the failure rate for software

The uncertainty level, which is the average of the pre-defined three criteria's for each of these uncertainties, is used to define an uncertainty score for the cost drivers. This is considered as the average of the associated uncertainties.

The tool adopts guidelines provided by AACE (1997) to specify appropriate ranges based on the uncertainty levels in the cost drivers, as represented in Table 1. The guideline specifies that there are many characteristics that can be used to categorise cost estimate types. The most significant of these are degree of project definition, end usage of the estimate, estimating methodology, and the effort and time needed to prepare the estimate (AACE, 1997). For the classification of the cost uncertainties, the tool

adopts the considerations for the degree of project definition. This characteristic is based upon percent complete of project definition (roughly corresponding to percent complete of engineering). The level of project definition defines maturity or the extent and types of input information that is available to the estimating process. The tool considers these from the perspective of uncertainty, where the cost uncertainty score represents the level of project definition.

Table 1. Range specification based on uncertainty level of project definition

<b>Estimate class</b>	<b>Level of project definition</b>	<b>Methodology</b>	<b>Lower uncertainty value</b>	<b>Upper uncertainty value</b>	<b>Range-Minimum</b>	<b>Range-Maximum</b>
<b>Class 1</b>	50% to 100%	Deterministic	0	0.3	-10	15
<b>Class 2</b>	30% to 70%	Primarily deterministic	0.3	0.5	-15	20
<b>Class 3</b>	10% to 40%	Mixed but primarily stochastic	0.5	0.7	-20	30
<b>Class 4</b>	1% to 15 %	Primarily stochastic	0.7	0.9	-30	50
<b>Class 5</b>	0% to 2%	Stochastic or judgment	0.9	1	-50	100

The level of project definition is considered in 5 classes. A Class 5 estimate is based upon the lowest level of project definition (e.g. highest uncertainty), and a Class 1 estimate is closest to full project definition and maturity. This arbitrary “countdown” approach considers that estimating is a process whereby successive estimates are prepared until a final estimate closes the process.

***Implementation***

For the range definition the tool at this point requires the user to select those cost drivers that are relevant to the project. This is requested from the user through tick boxes as shown in Figure 18.

Data Storing-  
Training
SELECTION OF COST DRIVERS
Cost Uncertainty  
Linkage

The user is requested to tick the cost drivers that are relevant to the considered project.

Cost Drivers		
1	Failure rate	<input checked="" type="checkbox"/>
2	Turnaround time	<input checked="" type="checkbox"/>
3	LRU cost	<input checked="" type="checkbox"/>
4	Transport cost	<input checked="" type="checkbox"/>
5	Packaging cost	<input checked="" type="checkbox"/>
6	Repair cost	<input checked="" type="checkbox"/>
7	Demand rate (spares)	<input checked="" type="checkbox"/>
8	Storage cost	<input checked="" type="checkbox"/>
9	Emergent work	<input checked="" type="checkbox"/>
10	GFX Supply	<input checked="" type="checkbox"/>
11	Material availability	<input checked="" type="checkbox"/>
12	Labour availability	<input checked="" type="checkbox"/>
13	Customer demand usage (i.e. fleet time and harbour)	<input checked="" type="checkbox"/>
14	Customer actual usage (i.e. fleet time)	<input checked="" type="checkbox"/>
15	No fault found (NFF) cost	<input checked="" type="checkbox"/>
16	Beyond economical repair (BER) COST	<input checked="" type="checkbox"/>
17	No. of students	<input checked="" type="checkbox"/>
18	No. of trainers	<input checked="" type="checkbox"/>
19	Facilities for training	<input checked="" type="checkbox"/>

Tick boxes to select the cost driver(s) that are relevant to the project

Figure 18. Input: Select the cost drivers that are relevant

Figure 19 represents the “Linkage” sheet where the uncertainties and cost drivers are considered together. The sheet does not require any input from the user.

- 23
 On the left hand side of the matrix, all the uncertainties that have been considered to be relevant from the Input sheets are listed. Thus, if an uncertainty was considered to be irrelevant, then the cell becomes blank.
- 24
 The horizontal axis of the matrix represents the cost drivers that have been considered to relevant to the project. If a cost driver is specified to be irrelevant then the cell becomes blank. The yellow cells reflect that the particular uncertainty influences a cost driver to the
- 25
 degree that was specified in the Input sheets for each category of uncertainty. Thus, if the uncertainty and the cost driver are defined to be relevant then the yellow cell takes the average of the pre-defined three criteria’s. The user has the flexibility to define further relationships if necessary.



LINKING UNCERTAINTIES AND COST DRIVERS											
Uncertainty	Cost Driver										
	Failure rate	Spares and around time	LRU cost	Transport cost	Packaging cost	Repair cost	Demand rate (spares)	Storage	Emergent work	GFX supply	Material availability
Uncertainty in customer equipment usage	5.7	5.7			5.7	5.7	5.7		5.7		
Uncertainty in the work share between partners		3.7									3.7
Uncertainty in KPI specification		1.7									1.7
Uncertainty in environmental impact											
Uncertainty in the level of relationship with supplier		3.0	3.0							3.0	
Uncertainty in the scope of warranty											
Uncertainty in the level of relationship with customer	3.7	3.7								3.7	
Uncertainty in stability of customer requirements		2.3		2.3							
Interest rates			5.0	5.0	5.0	5.0					5.0
Uncertainty in the commodity and energy prices			2.3	2.3							
Uncertainty in exchange rates			2.3	2.3							
Uncertainty in inflation rate			2.3	2.3		2.3					
Uncertainty in material cost						2.3					3.7
Uncertainty in labour hours						3.7					
Uncertainty in labour rate						2.3					
Uncertainty in the labour efficiency		4.3			4.3	4.3					
Uncertainty in the bid success rate											
Uncertainty in project life costs											
Uncertainty in economy			1.0								
Uncertainty in equipment availability			3.0								3.0
Uncertainty in IT		3						3			3
Uncertainty in performance against key performance indicators		3.0									3.0
Uncertainty in the rate of surge	3.7										

Figure.19. Linking uncertainties and cost drivers

Figure 20 illustrates the output from the cost and uncertainty linkage as represented on “Linkage” sheet.

- 26 The average of the yellow cells, which represent the cost-uncertainty linkage, constitutes the cost uncertainty score. The average value is then divided by 7, which is the possible highest value from the input.
- 27 The AACE (1997) guidelines are used to define the class that the uncertainty score fits into, as shown in Table 1. This class represents the maturity level for that cost driver.
- 28 Based on the calculated class the suitable minimum range is specified using the AACE (1997) guidelines, which is shown in Table 1. This is represented as a percentage value (e.g. 15% reduction of cost from the most likely value).

Uncertainty in the efficiency of engineering effort		5.7				5.7	5.7				
Uncertainty in the failure rate for software	3.7	3.7		3.7	3.7	3.7				3.7	
Uncertainty in the level of obsolescence											
Uncertainty in the cost estimating data reliability or quality											
Uncertainty in effectiveness of management of threats and opportunities											
Uncertainty Influence	0.53	0.51	0.46	0.48	0.51	0.52	0.49	0.52	0.51	0.49	0.51
Distribution Guidance	3	3	2	2	3	3	3	3	3	3	2
Range-Minimum	-20	-20	-15	-15	-15	-20	-20	-20	-20	-20	-15
Range-Maximum	30	30	20	20	20	30	30	30	30	30	20
Suitable Distribution	Triangular	Weibull	Weibull	Triangular	Weibull	Lognormal	Lognormal	Triangular	Weibull	Triangular	

Distribution	Requirements
Normal	Mean, Standard Deviation
Weibull	Scale, Shape
Exponential	Mean, Standard Deviation, Kurtosis, Skewness
Uniform	Expectation a and b
Triangular	Minimum, Most likely, Maximum

Rigour for distribution guidance (AACE Guidelines)				
No.	Lower value	Upper value	Range-Minimum	Range-Maximum
1	0	0.3	-10	15
2	0.3	0.5	-15	20
3	0.5	0.7	-20	30
4	0.7	0.9	-30	50
5	0.9	1	-50	100

Figure 20. Output: Assigning an uncertainty score for the cost drivers and suggesting the minimum and maximum ranges

- 29 Based on the calculated class the suitable maximum range is specified using the AACE (1997) guidelines, which is shown in Table 1. This is represented as a percentage value (20% increase of cost from the most likely value).
- 30 Suggestions with regards to representation of each cost driver through a probability distribution are specified based on literature review and recommendations from subject matter experts.
- 31 Table 1 is represented in the “Linkage” sheet in order to notify the user of the basis of the suggested ranges.

Figure 21 shows the output for the cost uncertainty linkage graphically.

- 32 Collates the list of the cost drivers and the suggested range considerations.
- 33 Considers each cost driver, by defining how much uncertainty originates from each of the uncertainties that have been associated to that particular cost driver.

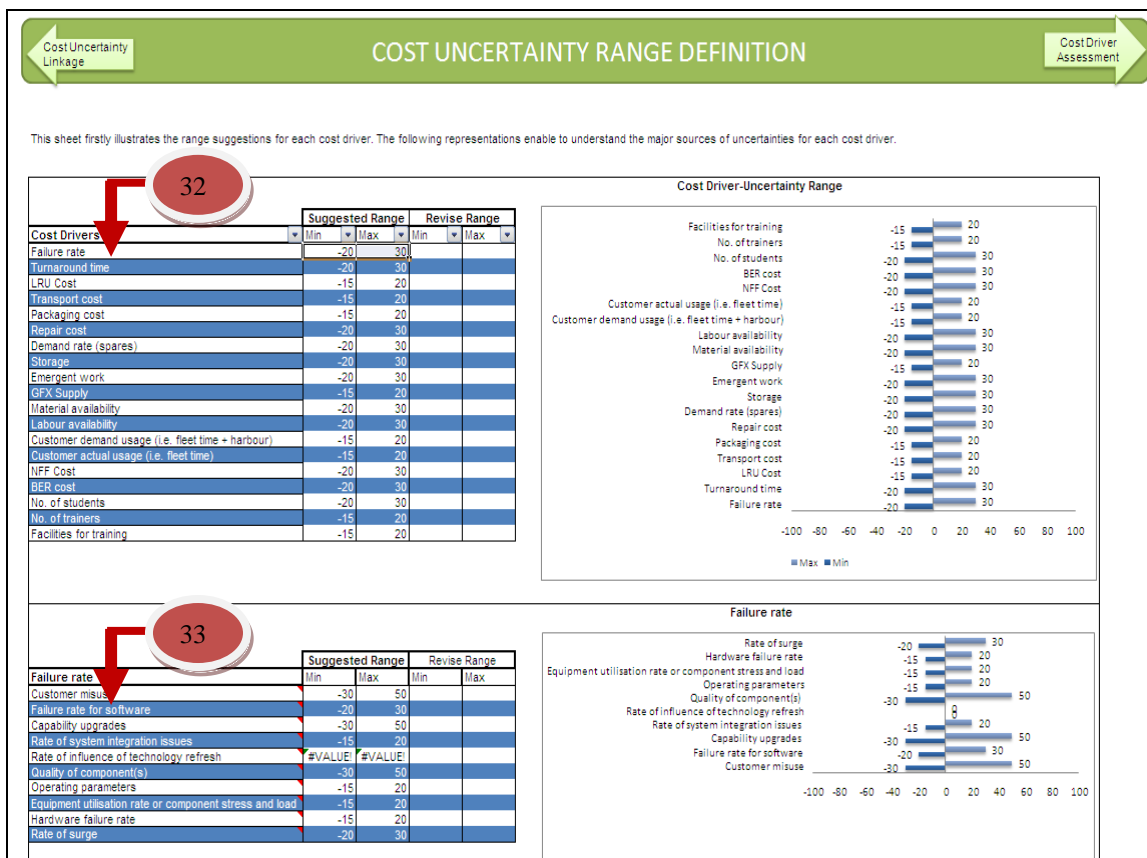


Figure 21. Output: Representation of the suggested ranges for the cost drives and description of the major sources of uncertainty for each cost driver

### F.1.7 Turning a Single Point Estimate into Three

#### Conceptual Background

This phase combines the information that is calculated in the “Linkage” sheet, including the minimum and maximum range suggestions, with actual cost considerations. For this reason, two levels of granularity are defined where initially it is assumed that due to the lack of project maturity cost estimates for each cost driver has not yet been calculated. For this scenario the analytic hierarchy process is applied in order to define the percentage significance of each cost driver over the total cost. This in turn, gets used to allocate the cost estimate at the project or system/sub-system level that is inputted based on calculations from an alternative source. At the second level of granularity the user inputs the cost estimate for each of the cost drivers, which in turn the maximum and minimum cost figures are calculated using the range suggestions.

#### Implementation

If the user specifies that a cost estimate has not been calculated for each cost driver, then the user is requested to input information about the relevance/significance of each cost driver with regards to total cost. For this purpose a number needs to be selected following the guidance provided in the blue box in Figure 22.

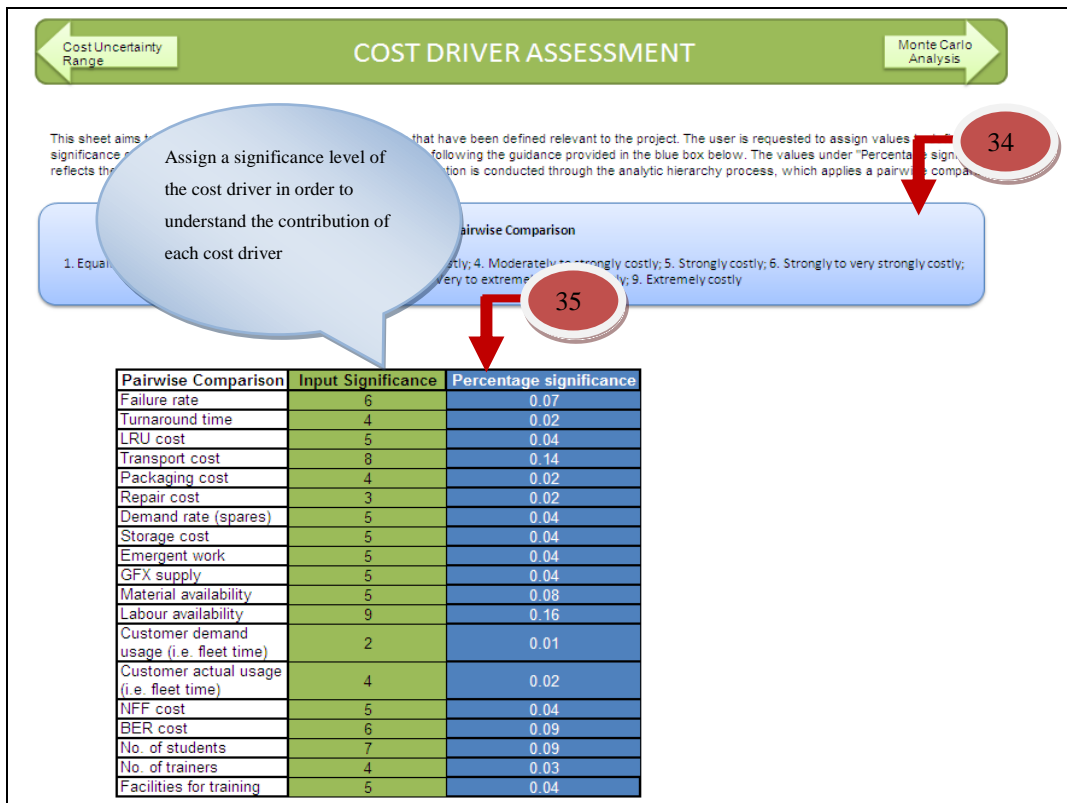


Figure 22. Input: Assign a score based on the contribution of the cost driver to overall cost

34

Represents the guidance concerning how to score the significance/relevance of each cost driver.

35

Represents the output (% contribution) from the AHP.

Figure 23 illustrates the implementation of the AHP in the tool for the comparison of the cost drivers. The tool conducts the analysis based on the input that has been explained for Figure 20.

Analytical Hierarchy Process																
	Failure rate	Turnaround time	LRU cost	Transport cost	Packaging cost	Repair cost	Demand rate (spares)	Storage cost	Emergent work	GFX supply	Material availability	Labour availability	Customer demand usage (i.e. fleet time)	Customer actual usage (i.e. fleet time)	NFF cost	BER cost
Failure rate	1.00	3.00	3.00	0.33	3.00	5.00	3.00	3.00	3.00	3.00	3.00	0.20	5.00	3.00	3.00	1.00
Turnaround time	0.33	1.00	0.33	0.20	1.00	3.00	0.33	0.33	0.33	0.33	0.33	0.14	3.00	1.00	0.33	0.33
LRU cost	0.33	3.00	1.00	0.20	3.00	3.00	1.00	1.00	1.00	1.00	1.00	0.20	5.00	3.00	1.00	0.33
Transport cost	3.00	5.00	5.00	1.00	5.00	7.00	5.00	5.00	5.00	5.00	5.00	0.33	7.00	5.00	5.00	3.00
Packaging cost	0.33	1.00	0.33	0.20	1.00	0.33	0.33	0.33	0.33	0.33	0.33	0.14	3.00	1.00	0.33	0.33
Repair cost	0.20	0.33	0.33	0.14	3.00	1.00	1.00	0.33	0.33	0.33	0.33	0.14	3.00	0.33	0.33	0.20
Demand rate (spares)	0.33	3.00	1.00	0.20	3.00	1.00	1.00	1.00	1.00	1.00	1.00	0.20	5.00	3.00	1.00	1.00
Storage cost	0.33	3.00	1.00	0.20	3.00	3.00	1.00	1.00	1.00	1.00	1.00	0.20	5.00	3.00	1.00	0.33
Emergent work	0.33	3.00	1.00	0.20	3.00	3.00	1.00	1.00	1.00	1.00	1.00	0.20	5.00	3.00	1.00	0.33
GFX supply	0.33	3.00	1.00	0.20	3.00	3.00	1.00	1.00	1.00	1.00	1.00	0.20	5.00	3.00	1.00	0.33
Material availability	0.33	3.00	1.00	0.20	3.00	3.00	1.00	1.00	1.00	5.00	1.00	0.20	5.00	3.00	1.00	0.33
Labour availability	5.00	7.00	5.00	3.00	7.00	7.00	5.00	5.00	5.00	5.00	0.11	1.00	3.00	7.00	5.00	5.00
Customer demand usage (i.e. fleet time)																
Customer actual usage (i.e. fleet time)	0.20	0.33	0.20	0.14	0.33	0.33	0.20	0.20	0.20	0.20	0.20	0.20	1.00	0.33	0.20	0.20
NFF cost	0.33	1.00	0.33	0.20	1.00	3.00	0.33	0.33	0.33	0.33	0.33	0.14	3.00	1.00	0.33	0.33
BER cost	0.33	3.00	1.00	0.20	3.00	3.00	1.00	1.00	1.00	1.00	1.00	0.20	5.00	3.00	1.00	0.33
No. of students	1.00	3.00	3.00	0.33	3.00	5.00	3.00	3.00	3.00	3.00	3.00	0.20	5.00	3.00	3.00	1.00
No. of trainers	3.00	5.00	3.00	0.33	5.00	5.00	3.00	3.00	3.00	3.00	3.00	0.33	7.00	5.00	3.00	0.20
Facilities for training	0.33	1.00	0.33	0.20	1.00	3.00	0.33	0.33	0.33	0.33	0.33	0.14	3.00	1.00	0.33	0.33
Total	17.40	51.67	28.87	7.69	54.33	61.67	29.53	28.87	28.87	32.87	23.18	13.51	83.00	28.87	28.87	15.27

0.057471254	0.056064516	0.103926097	0.043370508	0.05521472	0.0811	0.10158	0.1039261	0.103926	0.091278	0.1294343	0.0147992	0.060240964	0.1039261	0.1039	0.0655
0.019157088	0.019354839	0.019547344	0.026022305	0.01840491	0.0486	0.01129	0.0195473	0.019547	0.010142	0.0143816	0.0105708	0.036144578	0.03464203	0.0195	0.0218
0.019157088	0.096	0.034642032	0.026022305	0.05521472	0.0486	0.03386	0.034642	0.034642	0.030426	0.0431448	0.0147992	0.060240964	0.1039261	0.0346	0.0218
0.172413793	0.096774194	0.173210162	0.130110524	0.09202454	0.1135	0.1633	0.1732102	0.17321	0.15213	0.2167239	0.0246653	0.084337349	0.17321016	0.1732	0.1965
0.019157088	0.019354839	0.019547344	0.026022305	0.01840491	0.0054	0.01129	0.0195473	0.019547	0.010142	0.0143816	0.0105708	0.036144578	0.03464203	0.0195	0.0218
0.011494253	0.006	0.019547344	0.019587361	0.05521472	0.0162	0.03386	0.0195473	0.019547	0.010142	0.0143816	0.0105708	0.036144578	0.01954734	0.0195	0.0131
0.019157088	0.056064516	0.034642032	0.026022305	0.05521472	0.0162	0.03386	0.034642	0.034642	0.030426	0.0431448	0.0147992	0.060240964	0.1039261	0.0346	0.0655
0.019157088	0.056064516	0.034642032	0.026022305	0.05521472	0.0486	0.03386	0.034642	0.034642	0.030426	0.0431448	0.0147992	0.060240964	0.1039261	0.0346	0.0218
0.019157088	0.056064516	0.034642032	0.026022305	0.05521472	0.0486	0.03386	0.034642	0.034642	0.030426	0.0431448	0.0147992	0.060240964	0.1039261	0.0346	0.0218
0.019157088	0.056064516	0.034642032	0.026022305	0.05521472	0.0486	0.03386	0.034642	0.034642	0.030426	0.0431448	0.0147992	0.060240964	0.1039261	0.0346	0.0218
0.019157088	0.056064516	0.034642032	0.026022305	0.05521472	0.0486	0.03386	0.034642	0.034642	0.030426	0.0431448	0.0147992	0.060240964	0.1039261	0.0346	0.0218
0.287356322	0.125493871	0.173210162	0.390334572	0.12883436	0.1135	0.1633	0.1732102	0.17321	0.15213	0.0047939	0.0739958	0.036144578	0.24248423	0.1732	0.3275
0.011494253	0.006	0.006828406	0.019587361	0.00612497	0.0054	0.00677	0.0068284	0.006828	0.006085	0.008629	0.0246653	0.012048193	0.01954734	0.0069	0.0131

Figure 23. Analysis of cost driver contribution to cost through the analytic hierarchy process

Figure 24, depicts the “Monte Carlo” sheet, where the required information for the simulation is calculated, including the minimum and maximum cost values. For this purpose the user is requested to specify the level of information that is available concerning the single point estimates. This refers to the preference of a single point estimate at the project level or for each of the relevant cost drivers through the tick box option. Thus, if the user would like to input a cost estimate value at the system level, then the tick box needs to be left blank, and a single point estimate that is generated from an alternative source needs to be inputted to the first green cell. On the other hand, if a cost estimate for each of the cost drivers is available, then the tick box needs to be ticked and a cost estimate for each of the cost drivers needs to be inputted to the green cells, which are positioned above the maximum and minimum cost values.

36

The name of the cost driver that was defined to be relevant to the project is allocated across this row.



specify the percentile value of interest, in order to capture that specific cost value, which is calculated for each of the represented cost drivers. The percentile value refers to the confidence level.

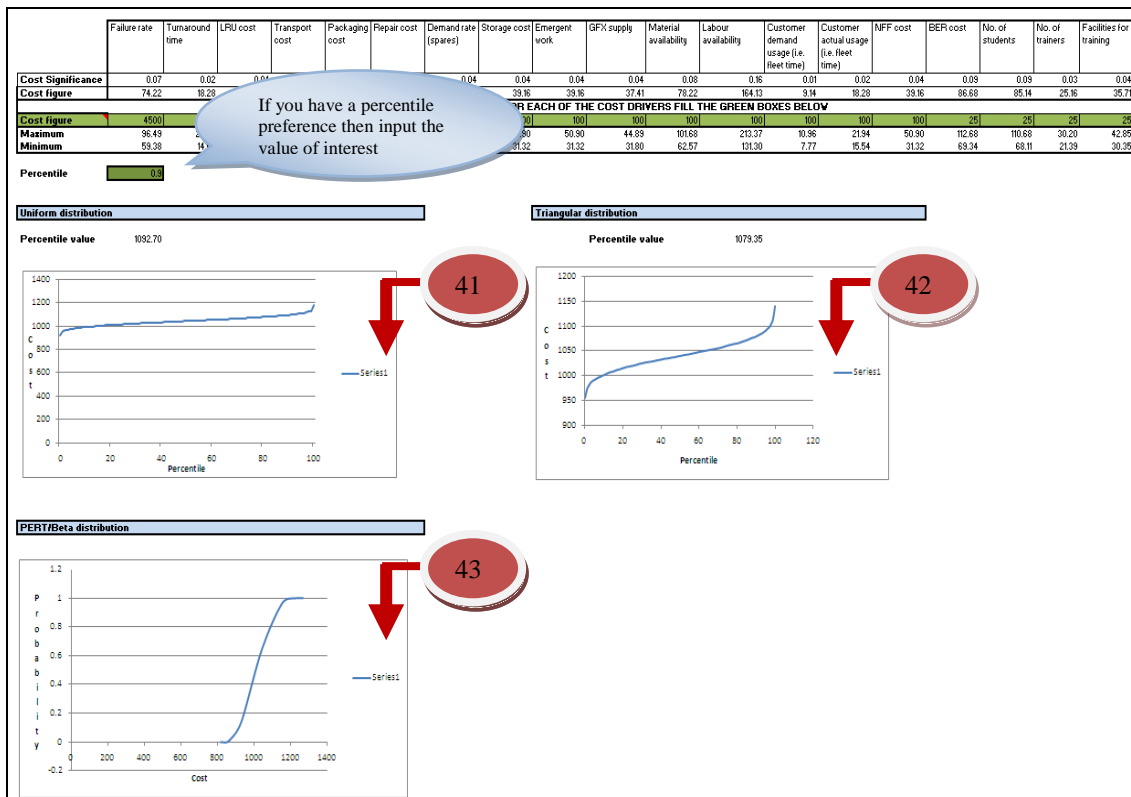


Figure 25. Output: Representation of Monte Carlo Simulation through distributions

- 41 The representation of the uniform distribution.
- 42 The representation of the triangular distribution.
- 43 The representation of the PERT/Beta distribution.

Figure 26, 27 and 28 respectively illustrate the calculation of the uniform, triangular and PERT/Beta distributions in the tool. The tool conducts these analyses through in-built algorithms, where the flexibility in terms of the relevance of the cost drivers is also considered.



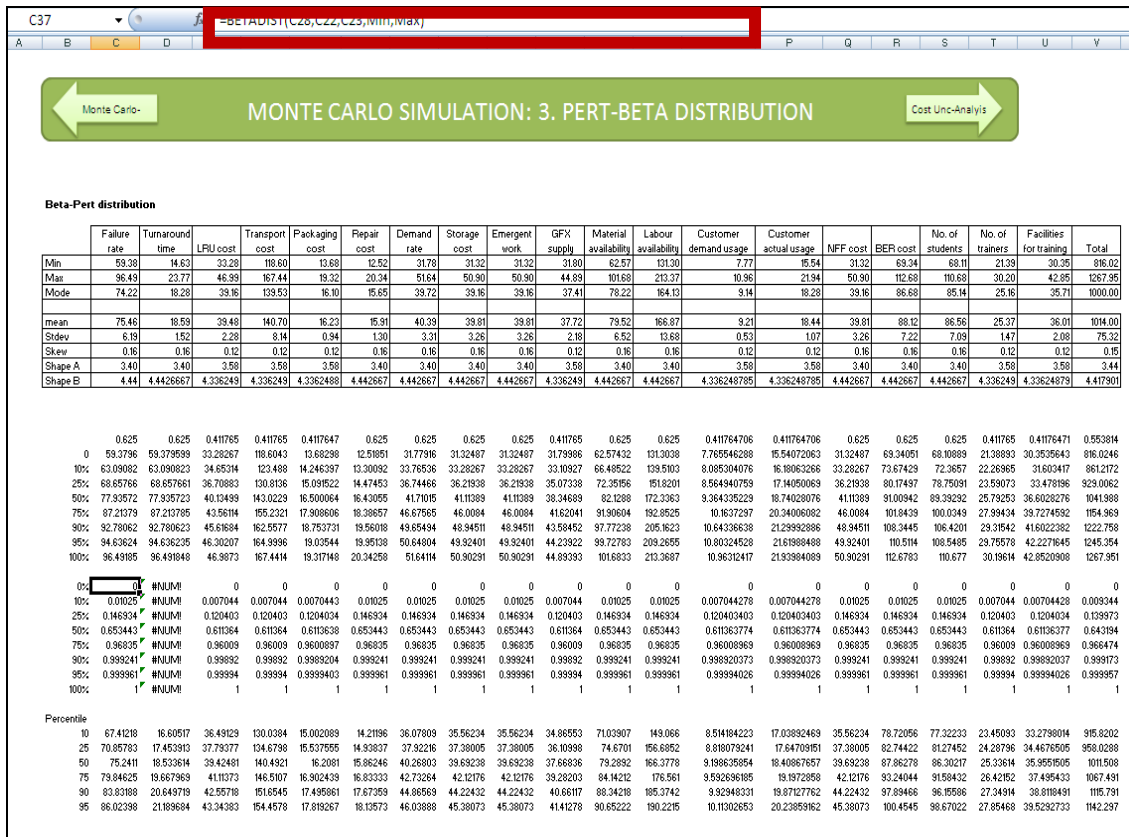


Figure 28. Calculation of the Pert-Beta distribution

### F.1.9 Project Level Uncertainty Analysis

#### Conceptual Background

This phase is concerned about the variation of the maturity level of the project in terms of uncertainty over time. For this purpose the uncertainty score for each cost driver and the significance of each cost driver is considered. There is no additional input required from the user for this analysis. As an output the user can communicate its position over time with the customer and suppliers.

- 44 Represents the maturity indicator, where the cost uncertainty score for each cost driver is multiplied with the significance output from the AHP analysis for the cost drivers. The colour of the cell varies depending on the deviation in the maturity score of the project (Hi, medium and low).
- 45 The use of the button enables to store the score of the maturity indicator level.
- 46 The stored information about the maturity indicator is graphically represented to illustrate the shift over time.

#### Implementation

Figure 29 illustrates the project maturity indicator calculation sheet.



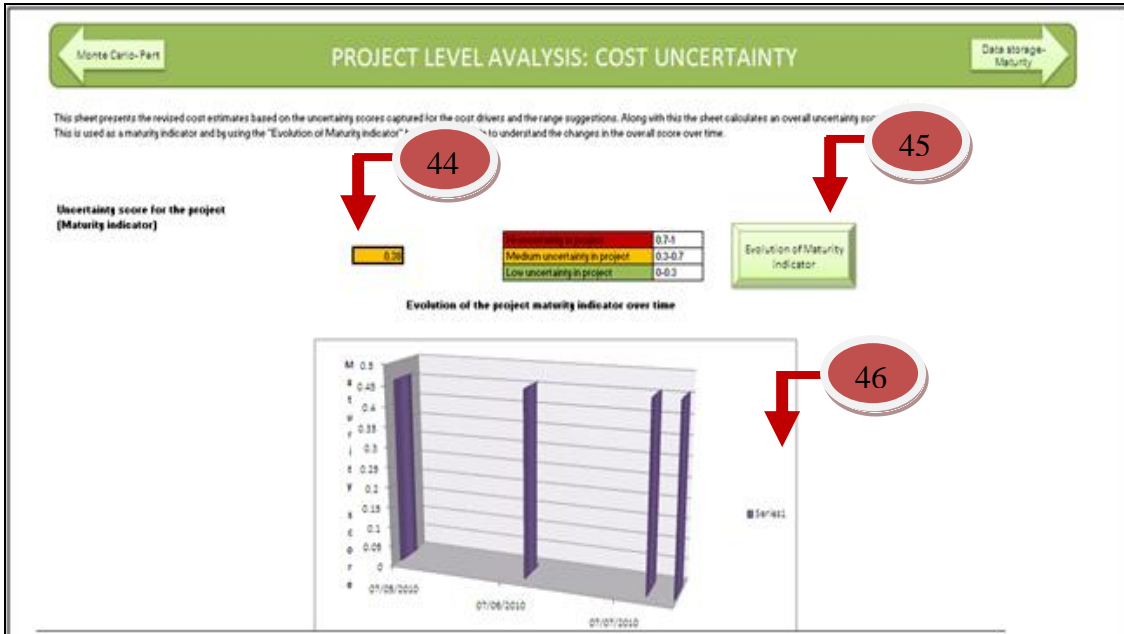


Figure 29. Output: Project maturity indicator

Figure 30 depicts the process of storing data concerning the maturity indicator level, where a specific sheet is allocated for this purpose: "Data-Store-Proj-Matur". The date of the calculation needs to be specified by the user.

47 By pressing the button that is provided on the "Cost-Unc-Analy" sheet, the maturity indicator score is stored in these cells.

**DATA STORE: PROJECT MATURITY LEVEL**

Agent based model-input

Input the date of the calculation of the maturity indicator

47

Input No.	Date stamp	Project maturity score	Comments to explain the score
1	07/05/2010	0.45956248	
2	12/06/2010	0.45956248	
3	14/07/2010	0.45956248	
4	21/07/2010	0.45956248	
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			
21			

Figure.30. Data storage for the Maturity indicator

## F.1.10 Future Expectation of Uncertainty

### *Conceptual Background*

This phase aims to represent the variation in the influence of uncertainty on cost over time through cumulative probability distributions. For this purpose the user queried about the expected changes in the degree of uncertainty over:

- The upcoming year
- Between 1 to 2 years
- Between 2 to 5 years
- Over 5 years

The cost uncertainty score that was calculated in the “Linkage” sheet is used as the benchmark and the user is requested to define the expected change in the uncertainty level as a percentage (e.g. -10% refers to a reduction of 10 percent; 10% refers to an increase of 10 percent). To be able to generate the distributions, the user needs to input the expected variation in uncertainty in the “Future-Unc” sheet for all the suggested time frames.

### *Implementation*

Figure 31 illustrates the inputs for the assessment of the future changes in the cost uncertainties.



There are four time frames to consider, while the cost uncertainty score representing the current view of uncertainty shown in order to assist the user in defining the level of change in the uncertainty



The defined reduction in uncertainty is reflected in the cost uncertainty score, which is subsequently checked in the AACE guidelines (1997) similar to the process explained in Section 6. As a result, potentially a new range suggestion may be made.



Once the minimum and maximum range is calculated the minimum, maximum and most likely cost estimates are represented for each of the four time frames.

The uniform and triangular distributions are calculated using the same process as defined in Section 8, using the information that is generated in the “Future-Unc” sheet. The outcome from the percentile assessment is represented in the “Monte Carlo” sheet in order to compare the cost distributions over time.

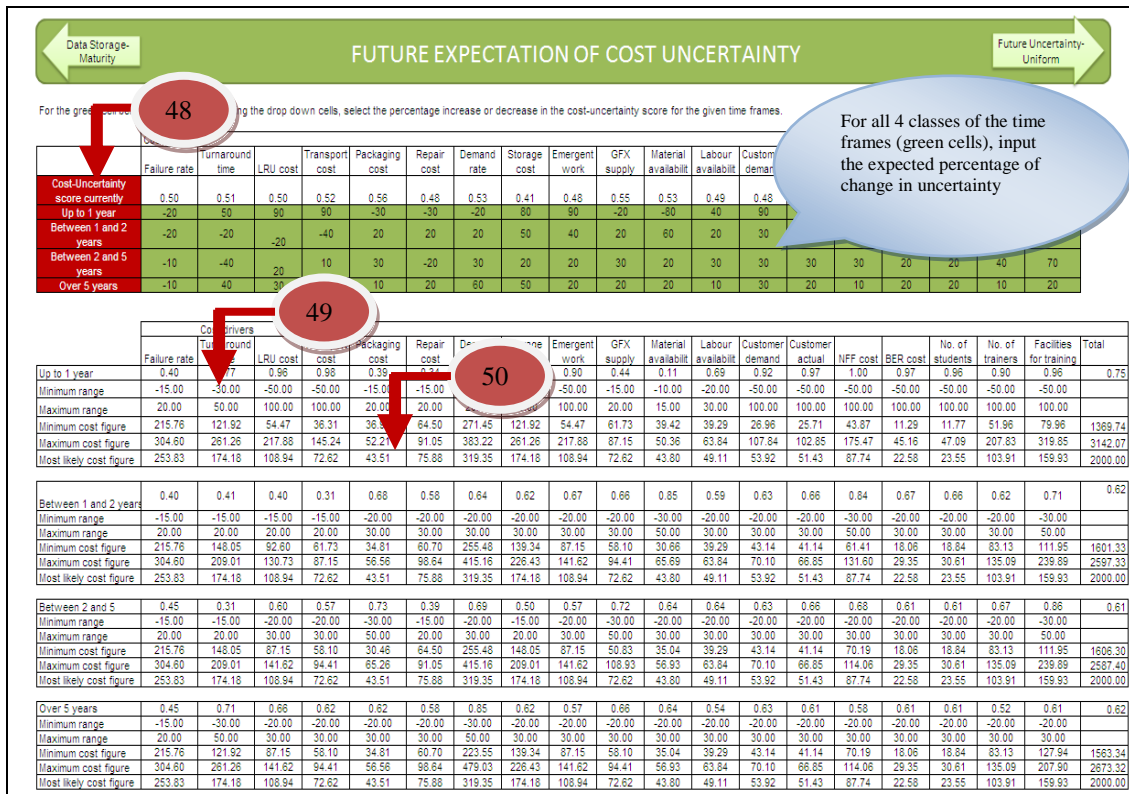


Figure 31. Future expectation of cost uncertainty

Table 2 provides a summary of the input requirements in U-TASC.

Table 3. Input structure to the Uncertainty tool

Input	Sheet
Define relevance of the uncertainty category and this affects the relevant categories	Broad Info
If applicable tick the “relevance” and “ability to fill” for each uncertainty in each category	Input Uncertainty (Commercial, Affordability, Performance, Training, Operation, Engineering)
Score the uncertainty level using the drop down scoring option (1-7)	Input Uncertainty (Commercial, Affordability, Performance, Training, Operation, Engineering)
If you wish to store data about the uncertainty scores click the button on the right hand side	Main-Unc, Spare-Unc and Train-Unc
If you wish you can write the reasons for the uncertainty scores but this will not be necessary for the validation	Score justification
Define the relevance/significance of the uncertainty using the analytic hierarchy process (1-9 scoring)	Importance Uncertainty
Select the suitable uncertainty mitigation strategies	Uncertainty Mitigation
Select the relevant cost drivers by ticking relevant options	Cost driver sheet
Define the significance of each cost driver only if you do not have an estimate for each of the cost drivers	Cost-driver AHP
Input a single point estimate or an estimate for each of the cost drivers	Monte Carlo sheet

# Appendix G Further information on the Agent Based Model

## G.1.1 Supplier architecture

Figure 1 provides an illustration of the contents/variables of the spares supplier.

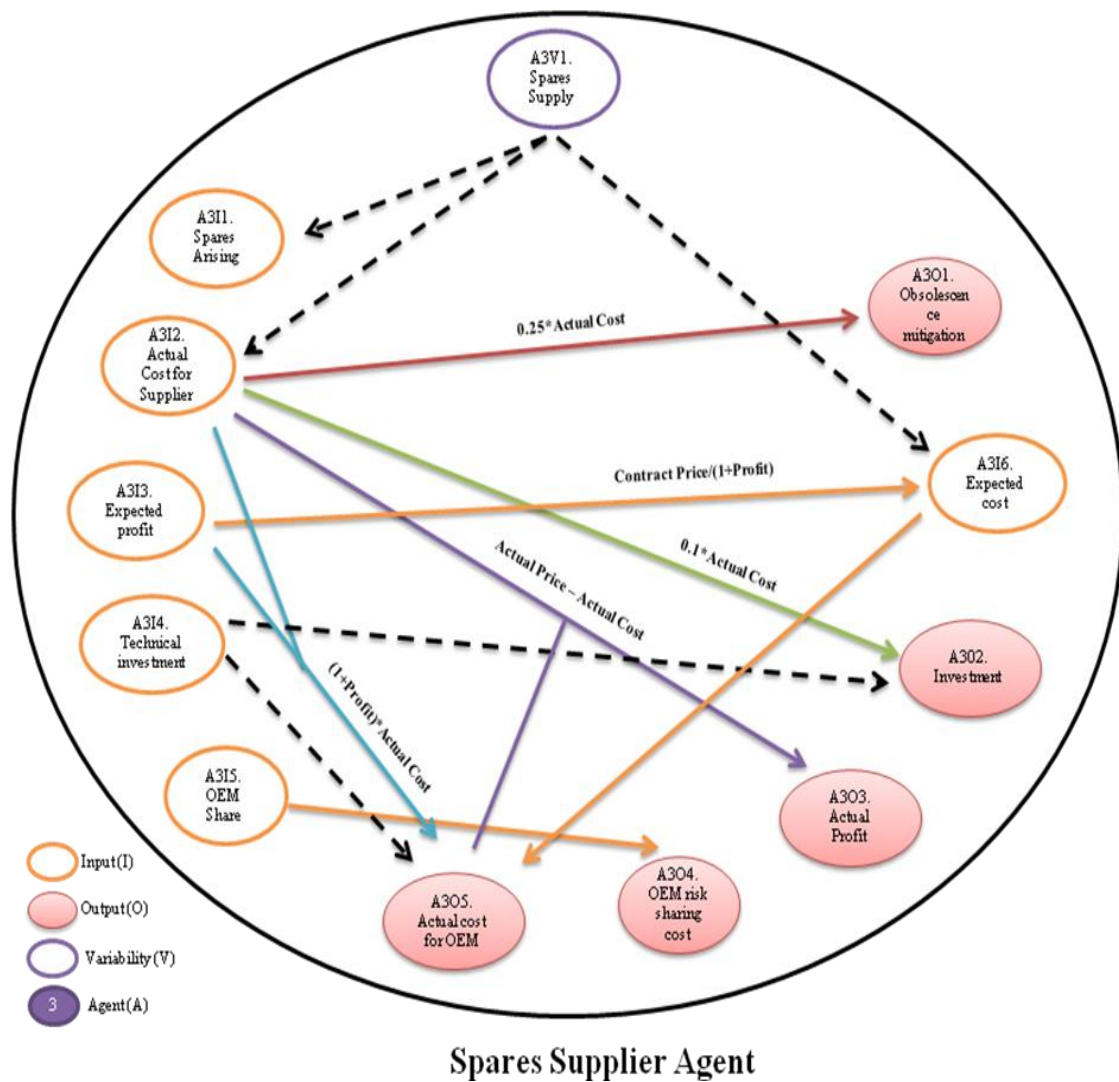


Figure 1 Overview of the interaction between the variables within the spares supplier

Figure 2 provides an illustration of the contents of the resource supplier.

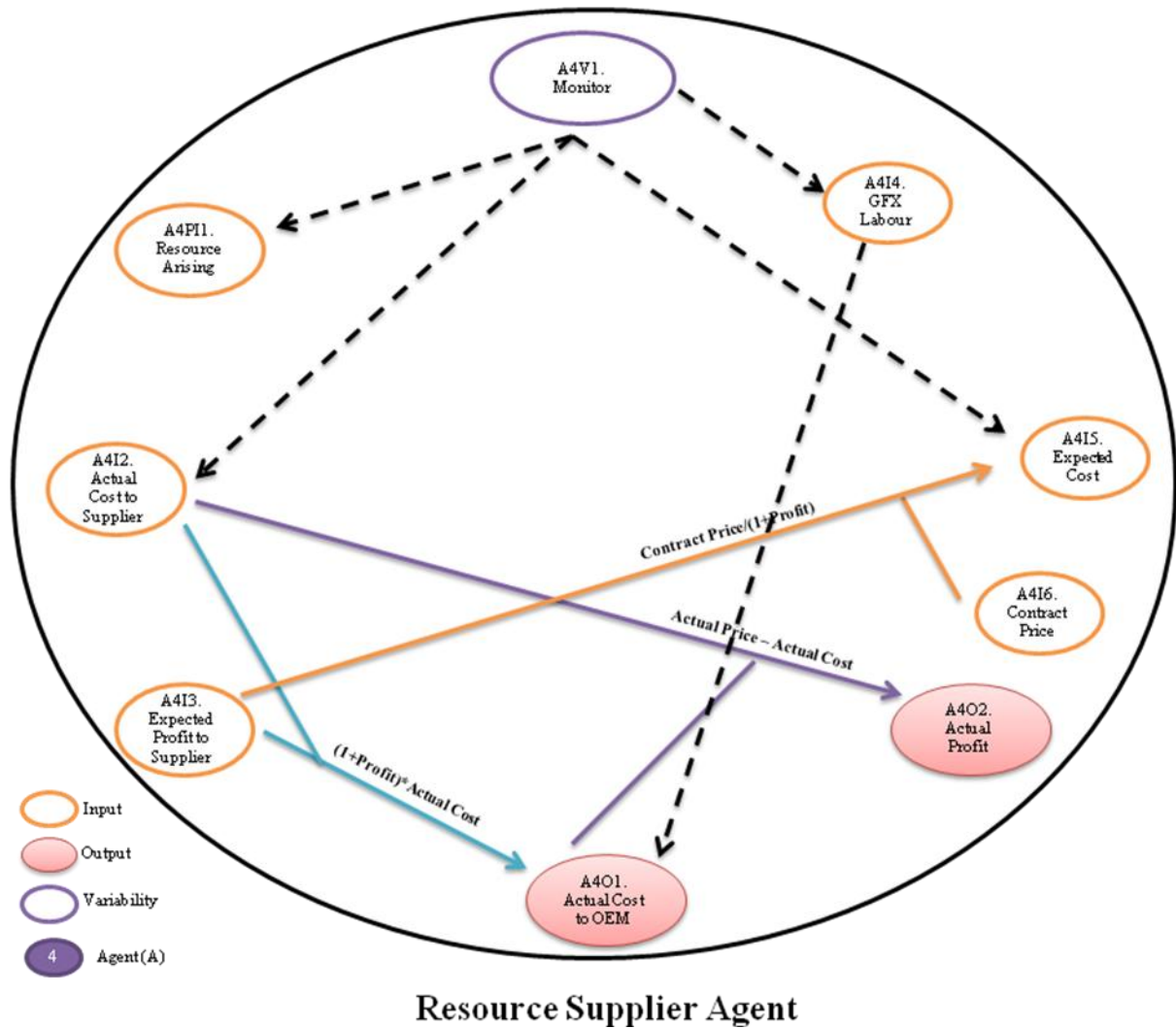


Figure 2 Overview of the interaction between the variables within the spares supplier

Figure 3, illustrates the way in which data explicitly for the agent based model is collected in the Excel based tool. The collected information is sent to AnyLogic through an intermediary excel file, which collects all the information that is to be used. In Figure 4, a snapshot of the solution provider agent is provided.

**Data Storage-Maturity**

## COST UNCERTAINTY ANALYSIS : 2. INPUT TO AGENT BASED MODEL

This sheet requires the user to input data regarding contractual clauses by following the listed questions for the agent based model. The collected data from this sheet is stored in another Excel sheet where calculated estimates (min, max and most likely) about the cost drivers is also collated. All this information feeds into a software package called AnyLogic for the Agent Based Model to operate.

**Input to AnyLogic-Agent Based Model**

a) Most likely cost estimate	1000	Move the arrow (left to right)			
b) pain/gain share fraction		0	1	1	0.1
c) Spares form what percentage of the Total cost (support cost)	0	0	1	4	0.2
d) Resource form what percentage of the Total cost (support cost)	0	0	1	0	0
e) GFX Labour Rate		0	1	7	0.7
f) Rate of obsolescence (support)	0	0	1	8	0.8
g) Rate of cannibalisation		0	1	7	0.7
h) Rate of training (support cost)	0	0	1	4	0.4

Figure 3 Input: Gathering requirements for the Agent Based Model

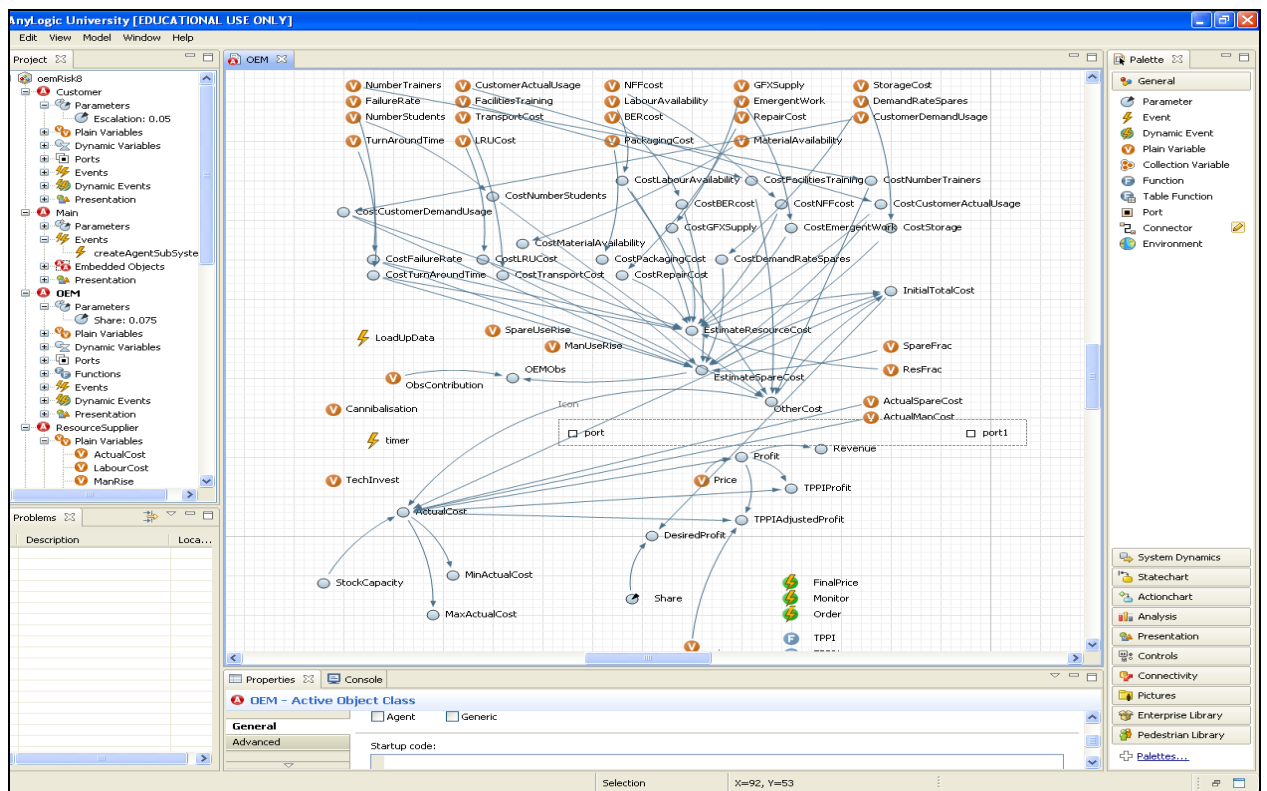


Figure 4 Snapshot of the solution provider agent from AnyLogic

## G.1.2 Applied codes

### Customer agent

The code presented below demonstrates how calculations for the key variables including “savings” and “value” within the customer agent are conducted.

Import

```
import com.xj.*;
```

Implements interfaces

Startup code

```
String s = ExcelFile.getValue( "SELECT PainGainShare FROM [Sheet1$A1:as25];" );
```

```
PainGainShare=Double.valueOf( s ).doubleValue();
```

```
String s1 = ExcelFile.getValue( "SELECT GFXLabor FROM [Sheet1$A1:as25];" );
```

```
GFXLabor=Double.valueOf( s1 ).doubleValue();
```

```
ordering newTimer = new ordering(0.01);
```

Equations

```
Savings = PainGainShare*main.oEM.TPPIProfit
```

```
Value = Escalation*Price+Savings
```

Additional class code

### Original Equipment Manufacturer agent

Import

```
import com.xj.*;
```

Implements interfaces

Startup code

```
String s = ExcelFile.getValue( "SELECT SpareCost FROM [Sheet1$A1:as25];" );
```

```
SpareFrac=Double.valueOf( s ).doubleValue();
```

```
String s1 = ExcelFile.getValue( "SELECT ResCost FROM [Sheet1$A1:as25];" );
```

```
ResFrac=Double.valueOf( s1 ).doubleValue();
```

```
//Monitor newTimer = new Monitor(0.02);
```

```
FinalPrice newTimer2 = new FinalPrice(0.5);
```

```
Order newTimer1 = new Order(0.02);
```

Equations

```
TPPIAdjustedProfit = TPPI1(Profit,ActualCost,1-main.customer.PainGainShare)
```

```
TPPIProfit = TPPI(Profit,ActualCost)
```

$OtherCost = InitialTotalCost * (1 - SpareFrac - ResFrac)$   
 $EstimateResourceCost = InitialTotalCost * ResFrac$   
 $EstimateSpareCost = InitialTotalCost * SpareFrac$   
 $DesiredProfit = InitialTotalCost * Share$   
 $Revenue = Profit * 0.5$   
 $Profit = Price - ActualCost$   
 $ActualCost = OtherCost + ActualSpareCost + ActualManCost + CapacityCost$   
 $InitialTotalCost = Price * 100 / 107.5$   
 Additional class code

### Spares supplier

Import

Implements interfaces

Startup code

//UpdateRate newTimer = new UpdateRate(0.15);

//TechInvest=1;

String s = ExcelFile.getValue( "SELECT OEMShare FROM [Sheet1\$A1:as25];" );

OEMShare=Double.valueOf( s ).doubleValue();

SparesSupply newTimer = new SparesSupply(0.025);

Equations

$ActualProfit = ActualPrice - ActualCost$

$ActualPrice = (1 + Profit) * ActualCost$

$Invest = 0.1 * ActualCost$

$ObsMiti = 0.25 * ActualCost$

$ContractPrice = main.oEM.EstimateSpareCost$

$Cost = ContractPrice / (1 + Profit)$

Additional class code

### Resource supplier

Import

Implements interfaces

Startup code

//UpdateRate newTimer = new UpdateRate(0.1);

SubConHeadSupply newTimer = new SubConHeadSupply(0.03);

Equations



ActualProfit = ActualPrice-ActualCost  
 Cost = ContractPrice/(1+Profit)  
 ContractPrice = main.oEM.EstimateResourceCost  
 ActualPrice = (1+Profit)\*ActualCost  
 Additional class code

### Customer – Original Equipment Manufacturer interaction

```

Contract t = new Contract();
TotalFlyingHoursReqd=29200;
Price=30;
if((int)(getTime())>3 && (int)(getTime())<=6)TotalFlyingHoursReqd=32850;
if((int)(getTime())>6 && (int)(getTime())<=9)TotalFlyingHoursReqd=25550;
if((int)(getTime())>3 && (int)(getTime())<=6)Price=45;
if((int)(getTime())>6 && (int)(getTime())<=9)Price=20;

t.Qty=TotalFlyingHoursReqd;
t.Rate=Price;

port.send(t);
ordering newTimer = new ordering(1);
  
```

### OEM –Supplier interaction

```

ActualSpareCost=main.sparesSupplier.ActualPrice;
ActualManCost=main.resourceSupplier.ActualPrice;
FinalPrice newTimer = new FinalPrice(1);

TechInvest=1;
OtherCost=(1-SpareFrac-ResFrac)*InitialTotalCost;
ActualSpareCost=main.sparesSupplier.ActualPrice;
ActualManCost=main.resourceSupplier.ActualPrice;
if (Cannibalisation>=(SpareUseRise-1))
{Negotiation nT = new Negotiation();
nT.Rate = 1;
port1.send(nT);
Negotiation1 mn = new Negotiation1();
mn.Rate = 1;
port1.send(mn);}
  
```

```

else {
TechInvest=SpareUseRise-Cannibalisation;
TechInvest*=1-main.customer.PainGainShare;
SpareUseRise-=TechInvest;
OtherCost=(1-SpareFrac-ResFrac)*InitialTotalCost*TechInvest;
if (OtherCost==0 && TechInvest>0) OtherCost=SpareFrac*InitialTotalCost*TechInvest;
Negotiation nT = new Negotiation();
nT.Rate = SpareUseRise;
port1.send(nT);
Negotiation1 nn = new Negotiation1();
nn.Rate = SpareUseRise;
port1.send(nn);}
Monitor newTimer = new Monitor(1);
SubContract t = new SubContract();
t.QtySpare=SpareUseRise;
t.QtyResource=SpareUseRise;

port1.send(t);
Order newTimer1 = new Order(1);

```

### Resource supplier

```

ActualCost=Cost;
ActualCost*=ManRise;
if (ManRise>1 && ManRise<2) ActualCost=1.5*Cost;
if (ManRise>=2) ActualCost=2*Cost;
if (ManRise<1) ActualCost=ManRise*Cost;
SubConHeadSupply newTimer = new SubConHeadSupply(1);

```

### Spares supplier

```

ActualCost=Cost;
ActualCost*=SpareRise;
if (SpareRise>1 && SpareRise<2) ActualCost=1.5*Cost;
if (SpareRise>=2) ActualCost=2*Cost;
if (SpareRise<1) ActualCost=SpareRise*Cost;
SparesSupply newTimer = new SparesSupply(1);

```