CRANFIELD UNIVERSITY

DUARTE POLÓNIA RODRIGUES

OPTIMISING COST AND AVAILABILITY ESTIMATES AT THE BIDDING STAGE OF PERFORMANCE-BASED CONTRACTING

SCHOOL OF AEROSPACE, TRANSPORT SYSTEMS AND MANUFACTURING

PhD
Academic Year: 2016 – 2017

Supervisor: Dr. John Erkoyuncu & Prof. Andrew Starr
June 2017

CRANFIELD UNIVERSITY

SCHOOL OF AEROSPACE, TRANSPORT SYSTEMS AND MANUFACTURING

PhD

Academic Year 2016 - 2017

DUARTE POLÓNIA RODRIGUES

OPTIMISING COST AND AVAILABILITY ESTIMATES AT THE BIDDING STAGE OF PERFORMANCE-BASED CONTRACTING

Supervisor: Dr. John Erkoyuncu & Prof. Andrew Starr
June 2017

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

© Cranfield University 2017. All rights reserved. No part of this publication may be reproduced without the written permission of the copyright owner.

ABSTRACT

Performance-Based Contracting (PBC), e.g. Contracting for Availability (CfA), has been extensively applied in many industry sectors such as defence, aerospace and railway. Under PBC, complex support activities (e.g. maintenance, training, etc.) are outsourced, under mid to long term contracting arrangements, to maintain certain level of systems' performance (e.g. availability). However, building robust cost and availability estimates is particularly challenging at the bidding stage because therei is lack of methods and limited availability of data for analysis.

Driven by this contextual challenge this PhD aims to develop a process to simulate and optimise cost and availability estimates at the bidding stage of CfA. The research methodology follows a human-centred design approach, focusing on the end-user stakeholders. An interaction with seven manufacturing organisations involved in the bidding process of CfA enabled to identify the state-of-practice and the industry needs, and a review of literature in PBC and cost estimation enabled to identify the research gaps.

A simulation model for cost and availability trade-off and estimation (CATECAB) has been developed, to support cost engineers during the bidding preparation. Also, a multi-objective genetic algorithm (EMOGA) has been developed to combine with the CATECAB and build a cost and availability estimation and optimisation model (CAEOCAB). Techniques such as Monte-Carlo simulation, bootstrapping resampling, multi-regression analysis and genetic algorithms have been applied. This model is able to estimate the optimal investment in the attributes that impact the availability of the systems, according to total contract cost, availability and duration targets.

The validation of the models is performed by means of four case studies with twenty-one CfA scenarios, in the maritime and air domains. The outcomes indicate a representable accuracy for the estimates produced by the models, which has been considered suitable for the early stages of the bidding process.

ACKNOWLEDGEMENTS

This research could not have been completed without the great support that I received from many people over the three years of this PhD. I would like to offer my heartfelt thanks to those people, which include:

Dr. John Erkoyuncu, my first academic supervisor, for all continuous guidance and support that gave me from the first day, which has been crucial to overcome the many challenges that I faced during my research, and to point me out in the right direction. Prof. Andrew Starr, my second academic supervisor, for all the valuable advices and feedback that he provided me in crucial phases of the PhD. Dr. Patrick McLaughlin as independent chairman, and Dr. Konstantinos Salonitis as subject adviser, for their constructive feedback.

Steve Wilding, Alan Dibble and Martin Laity, my industrial supervisors, for showing passion and dedication to my research, and continuously contributing for defining research directions and gathering information for developing new findings and validation. Tony Horner, from Babcock International, for his important contribution in the validation phase of the research and in the review of this thesis. Richard Parker from BAE Systems, also for his important contribution during the validation of the results. Richard Owen, from BAE Systems, and Neil Priestley from Finmeccanica, for their significant contribution at understanding the industry current practices. And all the other industrial and academic experts that provided important information during the course of this study such as Christopher Lambert, Ian Cowper, Chris Saxby, Gary Simpsons, Ambrose McDonough, Mark Harvey, Matt Morbey, Laura Lacey, Professor Rajkumar Roy, Nikolaos Tapoglou and Shane Targett.

Maria, my wife, for the continuous support and dedication devoted during the course of my research. My parents, grandmother, and other family and friends that provided enthusiasm and support.

LIST OF PUBLICATIONS

Journal Papers

Rodrigues D., Erkoyuncu J., Starr A., Wilding S., Dibble A., Laity M. (2017) "Simulation Model for Cost and Availability Estimation", Submitted to Journal of Production Planning & Control, in 6th September 2017.

Rodrigues D., Erkoyuncu J., Starr A., Wilding S., Dibble A., Laity M. (2017) "A multi-objective optimisation approach for cost and availability to design performance-based contracts" (Journal paper - to be submitted in October 2017).

Conference Papers

Rodrigues D., Erkoyuncu J., Starr A., Wilding S., Dibble A., Laity M. (2015) "Review of the Modelling Approaches for Availability Contracts in the Military Context'', in Proceedings of the CIRP Industrial Product Service System conference, St. Etienne, France, 20-23 May 2015, pp. 451-456.

Rodrigues D., Erkoyuncu J., Starr A., Wilding S., Dibble A., Laity M. (2015) "A Conceptual Framework to Assess the Impact of Training on Equipment Cost and Availability in the Military Context", in Proceedings of the Through-Life Engineering Services Conference, Cranfield, UK, 03-04 Nov 2015, pp. 112-117.

Book Chapter

Rodrigues D., Erkoyuncu J., Starr A. (2017) The Design of Cost and Availability in Complex Engineering Systems. In: Redding L., Roy R., Shaw A. (eds) Advances in Through-life Engineering Services. Decision Engineering. Springer.

Non-Refereed Paper

Rodrigues, D.., Erkoyuncu, J., Starr, A., Wilding, S., Dibble, A., Laity, M. (2016). "An innovative framework to optimise cost and availability estimates for support contracts bids", Society for Cost Analysis and Forecasting (SCAF) workshop, Filton, Bristol, 15th November 2016.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CADMID	Concept, Assessment, Demonstration, Manufacture, In-Service, Disposal
CAEOCAB	Cost and Availability Estimation and Optimisation for CfA Bibs
CATECAB	Cost and Availability Trade-Off and Estimation for CfA Bids
CfA	Contracting for Availability
CfC	Contracting for Capability
EMOGA	Enhanced Multi-Objective Genetic Algorithm
GA	Genetic Algorithm
GT	Grounded Theory
HCD	Human-Centred Design
HF	Human Factors
ILS	Integrated Logistic Support
IM	Inventory Management
PSS	Product-Service System
IPSS	Integrated Product-Service System
IT	Information and Technology
KPI	Key Performance Indicator
MoD	Ministry of Defence
MS	Microsoft
OEM	Original Equipment Manufacturer
PBC	Performance-Based Contracting
PRISMA	Preferred Reporting Items of Systematic Review and Meta-Analysis
RN	Royal Navy
SE	Systems Engineering
SEM	Systems Engineering Management
SOM	Support Options Matrix
SOW	Statement of Work
TES	Through-Life Engineering Services
TLC	Through-Life Cost
V&V	Verification and Validation
VB	Visual Basic
VS	Visual Studio

SPECIALIST TERMS

Term	Definition
System	Is a composed of engineering elements such as subsystems, assemblies, components and parts, of complex nature. Complex systems/components are those composed of hardware, software, and/or humans, which are recognizable in terms of life cycle process (how to develop, manufacture, test, distribute, operate, support, train and dispose) (IEEE Standard, 2005). Examples of complex systems are: sensors and motion controls, altimeters and encoders, thermal control systems, antennas, brake control systems, cameras, radios, magnetometers, engines, computer systems and accessories, robots, satellites, autonomous vehicles, aircrafts, airships, submarines (Polishuk and Yin, 2013).
Cost	The cost of a system is the value of the resources needed to design, build, operate, and dispose that system. Because resources come in many forms - people, materials, energy, wind tunnels, factories, offices, and computers, etc. - it is convenient to express these values in common terms by using monetary units (such as dollars of a specified year) (National Aeronautics and Space Administration, 2008). In this thesis cost will be expressed in pounds.
Effectiveness	The effectiveness of a system is a quantitative measure of the degree to which the system’s purpose is achieved. Effectiveness measures are usually very dependent upon system performance. For example, launch vehicle effectiveness depends on the probability of successfully injecting a payload onto a usable trajectory. The associated system performance attributes include the mass that can be put into a specified nominal orbit, the trade between injected mass and launch velocity, and launch availability (National Aeronautics and Space Administration, 2008).
Cost-Effectiveness	The cost-effectiveness of a system combines both the cost and the effectiveness of the system in the context of its objectives. While it may be necessary to measure either or both of those in terms of several numbers, it is sometimes possible to combine the components into a meaningful, single-valued objective function for use in design optimisation. Even without knowing how to trade effectiveness for cost, designs that have lower cost and higher effectiveness are always preferred (National Aeronautics and Space

	Administration, 2008).
Support Services	Are those tasks, actions or activities required to provide supply, maintenance, overhaul planning and execution, support material, transportation, shipping, storage, disposal and facility management for sustaining operations. This includes the people (manpower) necessary to accomplish the support activities (IEEE Standard, 2005).
Product	A composed of system(s) and support services.
Availability	Refers to the operational availability of the system that is defined (in general terms) by the equation: $\frac{Uptime}{Uptime + Downtime}$ where *Uptime* is defined as the time that the system is capable of performing its primary function if called upon to do so, and *Downtime* is defined as the time during which the system is incapable of performing its primary functions (Pryor, 2008).
Attributes	A set of elements that have an impact on the availability targets in Contracting for Availability (e.g. Defence Lines of Development, Integrated Logistic Support Elements, Human Factors, etc. (Ministry of Defence, 2015; Morrow, 2008; Rodrigues, 2015)).
Investment	Refers to committed money or capital.
Optimisation	Process of searching for the best possible solution to achieve pre-defined targets.

1 INTRODUCTION

This study combines theoretical and practical knowledge in order to develop two simulation models to support strategic decision-making processes at the competitive bidding stage of CfA. An assessment of the specifications and requirements of the bidding process and a review of the industry current practices in bids preparation and cost and availability estimation was first performed. This enabled to collect the necessary and appropriate information to develop the models and ensure that they would be aligned with the needs and requirements of their end-users.

1.1 Research Background

Competitiveness in the manufacturing industry and an increased demand for improved through-life performance of the systems (e.g. availability), fostered the development of new strategies for doing business. In this context, services gained more relevance as they are the enablers to achieve and maintain a level of systems performance throughout the life cycle. Suppliers started to add more services to their products in order to offer complete and integrated solutions that guarantee the support and sustainability of the physical systems during the entire life-cycle. The addition of a service to a product offering is called servitization (Baines *et al*., 2007). This can be applied to the small business, by the concept of Product Service System (PSS), or to the big industrial markets as the Defence and Aerospace, by the concept of Industrial Product Service Systems (IPSS).

This PhD project is focused on IPSS applications for Defence. IPSS is the integrated and mutually determined planning, development, provision and use of product and service shares (Meier *et al*., 2005). A typical example of IPSS solution is Performance-Based Contracting (PBC). Depending on the type of performance required, different types of PBC can be defined. A typical example is availability performance, under the scope of Contracting for Availability (CfA). CfA is an IPSS application defined in the Defence sector as *“a commercial process which seeks to sustain a system or capability at an agreed level of* *readiness, over a period of time, by industry”* (Ministry of Defence, 2007). These are normally fixed price contracts celebrated between customer and supplier(s) for the provision of different types of support services (e.g. maintenance, training, etc.), for a certain period of time (e.g. 10/20 years).

These contracting practices are increasingly dominating the relationship between customer and suppliers, improving business but also raising new challenges. These challenges offer multiples opportunities for research and made the foundation for this PhD project, as described in the next subsection.

1.2 Research Motivation and Challenges

One of the most critical stages of PBC is the bidding. This is a complex process where cost engineers and project managers are challenged to submit competitive bid prices to win the contracts. However, this process requires building robust cost and availability estimates which is particularly challenging because of the uncertainty over the in-service requirements, the complexity of the systems and services required, the duration of the contracts, the lack of methods for cost and availability estimation, and the scarcity of data for analysis.

The presented research involved collaboration between Cranfield University and a multinational organisation from the defence industry. The motivation for research arose from challenges faced by the industry partner in building cost and system performance (e.g. availability) estimates at the bidding stage of mid/long-term PBC, and in particular CfA.

The industry motivation focused on the improvement of the current methods to build the estimates at the bidding stage, in order to establish a competitive position in the bids. Also, CfA has a mechanism of financial incentives that are based on performance targets. Thus, industry was motivated to make an effort to improve the reliability of their solutions in order to maximise profit and ensure the customer satisfaction.

On the other hand, this was a unique opportunity to fill a gap in literature regarding the problem of cost and availability estimation during bidding. No literature has been found presenting comprehensive processes or models for cost and availability estimation at the bidding stage, and in particular under limited data scenarios. This motivated the researcher to develop and apply scientific results to solve the practical challenge. In addition, this work represented a unique and exciting opportunity for the intellectual development of the researcher, and to give an important contribute for the research field and for a better operation of the support delivery in the manufacturing industry.

1.3 Industry and Academic Collaborators

This section provides information about the organisations that were involved in the development of this research. The researcher interacted with different people from these organisations at the different phases of the research, as described in Section 2. The name of each industry organisation is non-specific, in order to safeguard their confidentiality.

University A: Cranfield University (Bedford)

Cranfield University at Bedford is a British postgraduate and research-based public university specialised in science, engineering, technology and management. The university works close with many industrial organisations such as Boing, Rolls-Royce, Nissan and BAE Systems towards producing applied research of high impact across sectors such as defence, aerospace and railway. The university also prepares specialist expertise in diverse areas such as: advanced casting science and technologies; aeronautical systems; aerospace manufacturing; computing, simulation and modelling; defence manufacturing and system engineering. The position of the university in the world university ranking has risen over the last years in the field of engineering and technology, being within the top fifteen.

University B: Cranfield University (Shrivenham)

Cranfield University at Shrivenham is a public British university specialised in defence and security education, and develops research applied to governments, armed forces, industry and security services. The university also provides consultancy services across defence and security science, engineering and technology, in themes such as: cyber security, digital warfare, robotics, forensic sciences and simulation and analytics.

University C: Coventry University

Coventry university is a British public university, with history from the beginning of the 19th centrury. The university focuses on impactful research regionally, nationally and across the world, in the fields of: agroecology, water and resilience; applied biological and exercise sciences; business in society; flow measurement and fluid mechanics; low impact buildings; manufacturing and materials engineering; mobility and transport; and technology. The university is also well known for its Institute for Advanced Manufacturing and Engineering, which plays a key role in the research to enhance the UK manufacturing business and processes.

Organisation 1: Project Sponsor

Is a multinational organisation headquartered in London, UK, which specialises in support services for complex engineering systems and infrastructures, operating in critical and safety environments around the world. The company has more than 35000 employees and operates in: Middle East (Saudi Arabia, United Arab Emirates, Oman and Kuwait), Europe (several bases from Scandinavia to Southern Spain), Canada, Brazil, Africa, and Australasia (Australia and New Zealand). The company is in clear expansion and its annual revenue increased more than 300% since 2010 (£4.8 billion in 2016).

The business strategy of the company is focused on long-term contracts with public and private sectors in the defence, oil and gas, civil nuclear, energy, emergency services, automotive, media and communications, education, rail and mining and construction sectors.

The core capabilities of the company are delivered through four divisions: marine and technology, defence and security, support services, and international.

They provide a broad portfolio of products and services that include:

- Submarine through-life support, refit and refuelling;
- Warships maintenance and refit;
- Surface ships maintenance, repair and overhaul;
- Etc.

The company runs different types of support service contracts, being CfA one of the preferable approaches in the business strategy. The company has awarded a number of major CfA projects over the last decade that include:

- Nine years contract worth £88 million to provide in-service support – managing and executing all upkeep support activities as well as providing logistics support for spares and repairable units - for Phalanx systems (started in 2006);
- Ten years contract worth £270 million to improve fleet availability of the metropolitan police service, by managing and overseeing the repair and maintenance of the vehicles and specialist equipment (started in 2006);
- Five years contract to support the weapon handling and launch system and submerged signal ejector equipment used on all classes of UK in-service submarines, and their associated training rings (started in 2014).

The researcher interacted with different project managers, cost analysts, cost engineers, modelling experts, and risk/uncertainty analysts from this organisation, who provided important information about the current practices and recognised opportunities for improvement, and gave an important contribution in the validation of all the results.

Organisation 2

Is a multinational organisation headquartered in London, UK, and it has operations worldwide. The company presented the third biggest revenue in 2016 among the most important global defence, aerospace and security services providers, and operates seven full-service shipyards around the world.

The portfolio of products and services provided include:

- Development of unmanned and future air system capabilities;
- Air support and training;
- Design and manufacture of defence avionics equipment;
- Etc.

Examples of important CfA projects awarded by this organisation are:

- Five years contract worth £2.5 billion to support Royal Air Force Operations of the Typhoon fleet (started in 2009);
- Five years contract worth £22 million for the support and maintenance of the Royal Navy's River Class Offshore Patrol Vessels (started in 2013).

The author interacted with the engineering department and with the applied intelligence laboratories. The engineering department is responsible for the design, development, test, maintenance and support of the engineering systems such as electronics. The applied intelligence laboratories is an international business and technology consulting firm owned by Organisation 2, specialised in security and intelligence and data modelling. The experience of the specialists from this department had an important impact in the quantitative validation of the outputs of this research.

Organisation 3

Is a multinational organisation created in the 20th century that provides cost analytic solutions and consultancy services to the industry. The company is headquartered in Philadelphia US, and employs about 200 people including cost estimators, cost analysts, model builders, project leaders, mathematicians, logisticians, hardware and software engineers, computer scientists, and consulting professionals

The company focuses on improving cost management processes, cost schedules, risk estimates and business cases across different sectors such as aeronautic, aerospace, defence and security and automotive.

The portfolio of services that the company provides includes:

- Parametric estimating;
- Closed loop estimating;
- Data driven estimating;
- Mentoring cost estimating;
- Etc.

Organisation 3 provides other organisations with the capability to take informed project investment decisions and facilitates the communications between the customer and the suppliers, in PBC projects.

The author interacted with a business development specialist of the company, which is responsible for the cost and schedule generation/purchase and project estimation and monitoring. He provided important insights and advises that enabled to confirm the innovation and valuable application of the results of this research to industry and academia, as well as to define future work directions.

Organisation 4

Is a multinational aerospace, defence and security company headquartered in Rome, Italy, and with operations worldwide. In 75 years the company became the ninth-largest defence contractor in the world. The company employs about 47,600 people and had an overall revenue of € 12 billion in 2016 out of which €507 million was profit.

The company is organised into seven divisions: Helicopters, Aircraft, Aerostructures, Airborne & Space Systems, Land & Naval Defence Electronics, Defence Systems, Security & Information Systems.

The wide range of support services provided by Organisation 4 include: spares & repairs; maintenance; health usage monitoring systems; integrated support solutions (e.g. CfA); training and simulation; provision of naval weapon systems, and develops and implements advanced technologies in the area of: software, materials, electronics, optronics, mechanics, modelling & simulation, system design, autonomous systems, and cyber security.

Some of the major performance-based contracts awarded by this organisation over the last decade include:

- Ten years contract worth £5 million to deliver logistic support and maintenance for air traffic control radars in Portuguese airports (started in 2014);
- Five years contract worth £580 million to deliver support for air vehicle avionics for the UK MoD (started in 2015);
- Ten years contract worth £2.1 billion to support Royal Air Force Typhoon fleet (started in 2016).

Organisation 5: UK Ministry of Defence

Is the UK ministerial department responsible to protect the security, independence and interests of the UK people at home and abroad. The organisation is an active customer, spending about £19 billion per annum in performance-based contracts with the UK industry, expecting to acquire the most cost effective solutions to support the armed forces with the training, equipment and other support necessary for their work. The UK regular military forces comprise the navy, army and air domains.

As a customer, MoD always demands for the maximum competence, effectiveness and trustiness from its suppliers, to ensure that the necessary resources are available when needed.

The MoD typical performance-based contracts cover the following areas of support:

- Technology: cloud and digital, network services, software and technology products and services;
- Vehicle platforms: the procurement and support of ships, submarines, aircraft, vehicles;
- Supporting services: weapons and general requirements including food, clothing, medical supplies and temporary accommodation;
- Buildings: facilities management, maintenance and repair, utilities and fuel;
- People: permanent and temporary staff (including clinical staff), outsourced services (such as language and employee services) and advisory services.

Organisation 6

Is a Technical Consulting and Information Technology company, dedicated to the delivery of effective services to meet the business transformation challenges within the Defence and Energy markets. The company is headquartered in UK.

The company supports other organisations with the good practices and consultancy services for the implementation of long-term contracting solutions (e.g. CfA). The main areas of expertise of this organisation are: supportability engineering and information and knowledge management

The company has a dedicated team of developed by engineers and technology specialists that deliver solutions and services based on best practice processes and proven technologies.

Organisation 7

Is a consultancy organisation, headquartered in UK. The company has extensive experience in the defence sector by providing support to military and offshore platform procurement decisions. It focuses on all the stages of the projects lifecycle – from early research, through life concept studies, development and manufacture, and in service life to end of life disposal.

Nonetheless, the assessment phase is a key competence of the company. The planning, estimating and communicating of costs across a diverse and complex project structure can include:

- Cost and schedule risk analysis;
- Investment appraisal;
- Affordability analysis;
- Industry bid support;
- Etc.

The company has contributed to the planning and implementation of a number of recent large-scale UK defence projects, such as the Type 26 Global Combat Ship. The services provided have the contribution of a wide range of specialists from different areas of expertise such as Naval Architecture, Manufacture, Support, Systems and Software Engineering, Financial Mathematics and Business Analysis.

1.4 Research Scope, Aim and Objectives

This section starts by presenting what was the question that defined the challenge for this PhD, and then presents the research scope, aim and objectives.

1.4.1 Research Question and Scope

The question that defined the challenge for this PhD is described as such:

> What is a suitable process to build cost and availability estimates at the early stages of the bidding process in Contracting for Availability?

As a result, the following topics were agreed to make the scope for this research:

- Industrial Product-Service Systems (IPSS)
- Performance-Based Contracts (PBC);
- Contracting for Availability (CfA);

- Bidding Stage;
- Through-life Engineering Services (TES);
- Complex Engineering Systems;
- Cost Estimation;
- Availability Estimation;
- Cost and Availability Trade-off Analysis;
- Modelling and Optimisation.

Considering these themes, the research focused on exploring the link between IPSS, PBC and CfA, and identifying the particularities of the bidding stage as an important life-cycle stage of the contracts. Also, the scope of the research covered TES, as these type of services were recognised as the support required in the contracts and in particular to maintain the availability of complex engineering systems. In addition, and aligned with the research question, cost and availability estimation and trade-off was investigated as a challenge experienced during the bidding stage, and modelling and optimisation were seen as possible solutions.

1.4.2 Research Aim and Objectives

The aim of this research is to develop a process to simulate and optimise cost and availability estimates at the bidding stage of Contracting for Availability.

The research objectives are to:

1. Identify the attributes that impact the cost and availability targets in Contracting for Availability;
2. Develop a process for identifying and assessing the interrelationships between the attributes;
3. Build a process to measure the impact of each attribute in the availability of the systems;
4. Design and develop a simulation model to trade-off and estimate cost and availability at the bidding stage of CfA;

5. Design and develop a simulation model to calculate the optimal financial investment in each attribute to achieve a total contract cost and system availability targets;
6. Verify and validate the models with "real-life" case studies.

The link between the research objectives and the contents of the chapters of this thesis is described in Figure 1-1. Chapters 1, 2 and 9 are excluded from this connection as they are not directly related to the research objectives.

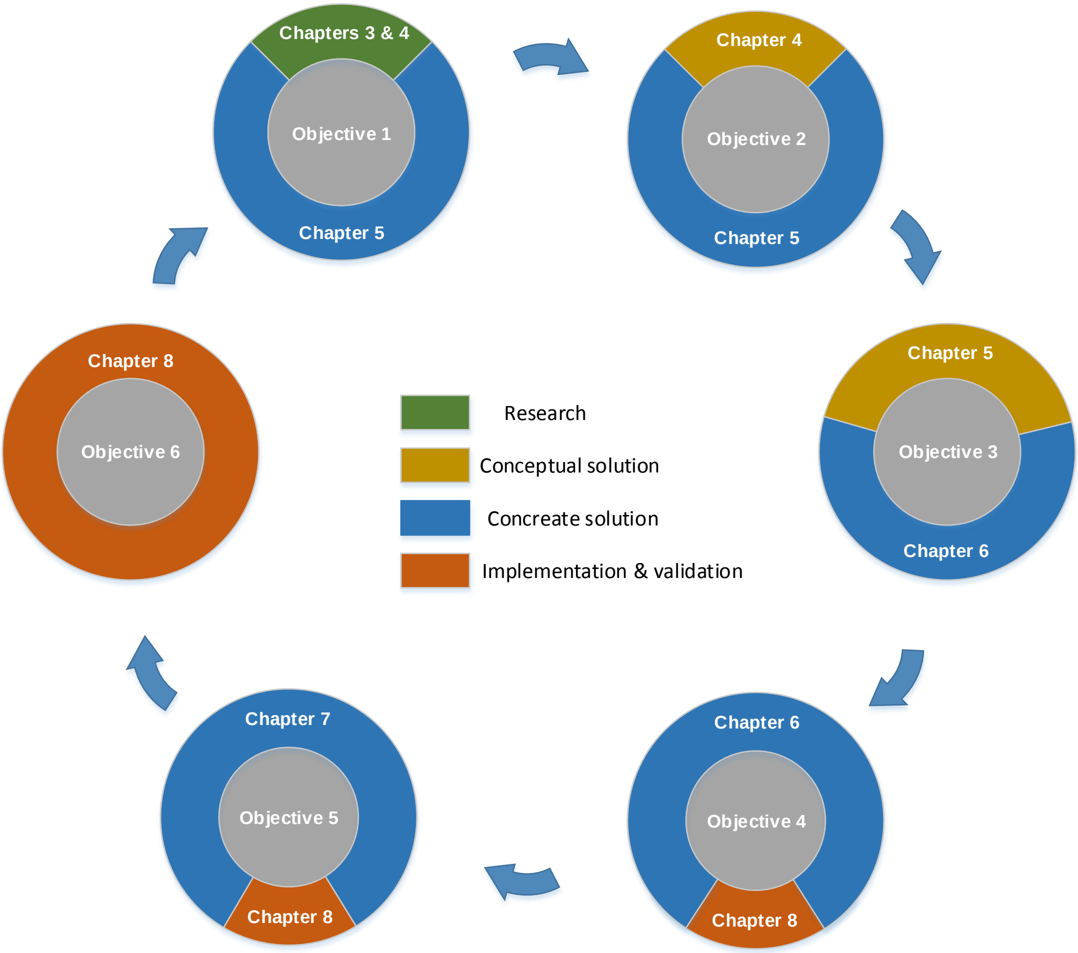


Figure 1-1 Link between Research Objectives and Thesis Chapters

1.5 Research Phases

This research was divided in six main phases consisting of:

Phase 1: Defining the Focus of the Research

The definition of the research focus followed the process illustrated in Figure 1-2, in the sequential order presented.

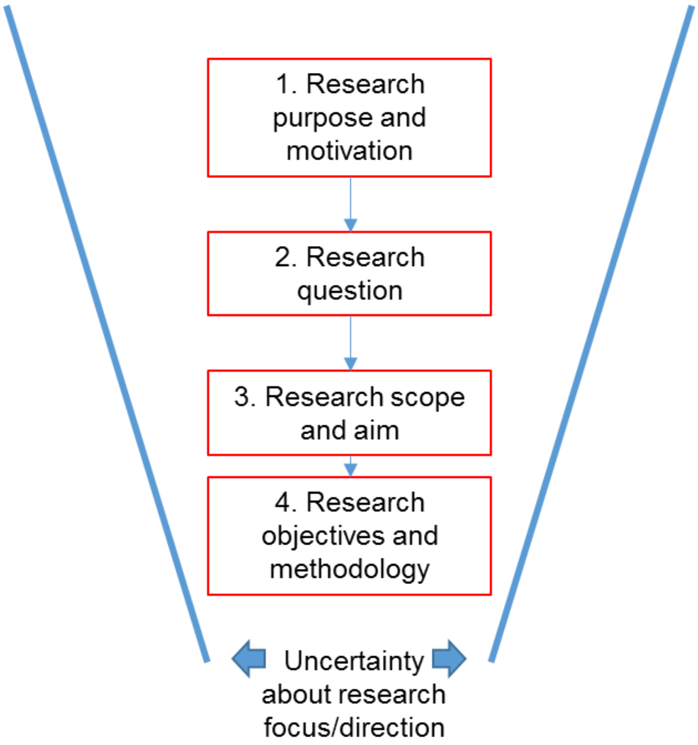


Figure 1-2 Adopted Steps to Define the Research Focus

Firstly, the research purpose was defined in collaboration between Cranfield University and Organisation 1, which co-sponsored this project. This process involved a number of interviews between the researcher, the academic supervisors, and senior managers from the organisation. The motivation for starting this project raised from the current challenges experienced by project managers from Organisation 1 during the bidding stage of CfA, and in particular at building the cost and availability estimates and trade-off analysis for the contracts. They recognised that higher availability could be achieved for lower cost, if they could optimise the investment across key attributes that drive the performance of the systems (e.g. availability). However, this requires an analysis of the interrelationships between the attributes and an assessment of the impact of each attribute in the other attributes and on availability. Hence, they recognised not having the tools and knowledge to make this type of analysis and therefore they could not explore new opportunities to optimise their investment across the attributes, at the bidding stage.

Moreover, CfA is a contracting approach with increased preference in the manufacturing industry, as it seeks to reduce the through-life cost and improve performance of complex engineering systems. A collaboration between academia and industry can enhance the design (e.g. bidding process) and delivery of CfA, in order to achieve the best through-life performance of the systems for the lowest cost. This collaboration brings benefits for both parties in the following perspectives: for the industry point of view, the academic contribution can provide best-practices, methods and tools that will help the industrial practitioners to understand what are the attributes that have higher impact on cost and availability in PBC (e.g. CfA), and to perform an analysis across those attributes to trade-off between cost and availability in order to design optimised solutions at the bidding stage, fostering competitiveness and innovation. On the other hand, this is an opportunity for academia to have an impact on improving major business processes (e.g. contracts worth £5+ millions) in the manufacturing industry, and to develop innovative applied research to enrich/expand the scientific knowledge. For Cranfield University, and in particular for the Through-life Engineering Services (TES) centre that cooperated in this project, this is an opportunity for developing new knowledge, technology demonstrators, and novel methodologies and techniques to provide the manufacturing industry with the capability of planning and delivering high value contracting solutions, through optimisation of TES design.

Along these lines, these partnerships have aimed at producing the best quality outputs, bringing together the most advanced scientific knowledge in TES and practitioners from the manufacturing industry with extensive experience in PBC. For the researcher, this was a unique opportunity to apply the knowledge acquired during his academic path in the development of high impact applied research, and expand the boundaries of theory to practice giving a valuable contribution to science and industry.

With all these conditions met, the research started with three initial interviews with four project managers and through-life support engineers with more than 20 years of experience, of two hours duration each, to define the research question, as presented in Section 1.4.1. Two more interviews were then conducted with the same participants to define the scope of the research, as presented in Section 1.4.1, and agree the objectives for the study as presented in Section 1.4.2.

The selection for the appropriate research methodology was then performed by the researcher and supervisors, after a review and comparison between different research methodologies presented in literature, as described in Chapter 2.

Defining the research scope, aim, objectives, and methodology, allowed to narrow down the uncertainty about the research direction, and establish the focus for research. This consisted of achieving each research objective, in the sequential order and following the guidelines of the methodology selected, and validating all the findings with the stakeholders to assure alignment with the research scope and aim.

Phase 2: Performing As-Is Analysis: Literature and Industry Current Practices

This phase covered a dedicated review of the literature to explore the relevant topics and identify research gaps, as presented in Chapter 3, and an interaction with industry stakeholders to identify their current processes of designing and delivering PBC solutions, and in particular to identify how they build the cost and availability estimates at the bidding stage, as presented in Chapter 4.

Phase 3: Building Conceptual Solution

During this phase, all the information collected in the literature review (based on a defined methodology as described in Section 3.2) and industrial interaction (covering eleven interviews and three case-studies and using the appropriate methods as presented in Section 2.6) was “digested” and used to build a conceptual solution to the research question, aligned with the research aim and objectives, as presented in Chapter 5. This phase covered an extensive desk-based work and interaction with the stakeholders to ensure that the solution was being developed according to the scope, aim and objectives established for the research.

Phase 4: Building a Simulation Model

This phase covered the most extensive desk-based work, where the researcher applied all of his knowledge and experience to develop the conceptual solution developed in Chapter 5, and implement as concrete modelling applications. This process covered the development of two mathematical models to support management level decision-making at the bidding stage, as presented in Chapters 6 and 7 respectively. The modelling techniques used to develop the models were selected based on an assessment of the literature review results, as presented in Chapter 3, and considering the context of application (e.g. amount of data available, level of complexity accepted, and type of analysis required) identified during the industrial interaction, as presented in Chapter 4. Also, adequate software platforms were selected based on the literature review results and an interaction with other researchers, to develop the simulation environment for the models.

Phase 5: Verifying and Validating

This phase covered the verification and validation of the models developed in Chapters 6 and 7.

The verification process covered an exhaustive search for any errors in the models and in their software implementation (e.g. equations, software code, etc.). It also covered a verification that the models where aligned with the research objectives and with the stakeholders expectations.

The validation process covered the application of twenty-one case studies, corresponding to past and comparable CfA projects, to run the models and assess the innovation, usefulness, and accuracy of the estimates. This assessment was based on the feedback of different subject matter experts with extensive experience in CfA bids planning, as presented in Chapter 8.

Phase 6: Discussion and Conclusions

The last phase of the research consisted of a discussion about the research process and results, covering a critical analysis of the outputs of each chapter of this thesis. The quality of the results produced is also discussed, as well as the applicability and generalisability of the research findings. The author concludes with outlining the main conclusions of the study, and giving suggestions for future work.

1.6 Thesis Layout

The remaining of this thesis is organised in eight.

> Chapter 2 starts with a review of different research types, methodologies and techniques based on literature. It then feeds into the selection of the appropriate methodology and techniques for this research according to the research type.
>
> Chapter 3 presents a broad review of the literature about the topics defined in the research scope, exploring the definition of each topic, identifying related topics, and establishing the linkage between concepts. Different modelling techniques are also identified and assessed, and guidance is provided to the selection of the appropriate technique(s) to develop the

models. The literature gaps within the context of CfA planning and delivery are also presented.

Chapter 4 covers an interaction with different subject matter experts from industry (from the list presented in Section 2.7) towards identifying the industry current practices and confirming/exploring the challenges that motivated this research. The opportunities for improvement are also identified, from the point of view of the practitioners.

In chapter 5 the key attributes that impact the cost and availability targets in CfA are identified and assessed, and a conceptual framework is presented to assess the interrelationships between attributes and their impact on cost and availability.

Chapter 6 presents a simulation model which is a development/implementation of the conceptual idea proposed in Chapter 5, following guidance of the results from the literature review chapter to the selection of the appropriate techniques to develop the model, and the suitable software platforms for implementation.

Chapter 7 presents a simulation model which is an upgrade of the model presented in Chapter 6, through development and implementation of an enhanced genetic algorithm for optimisation.

Chapter 8 comprises all the process of verification and validation of the models presented in Chapters 6 and 7.

Chapter 9 is the last chapter of the thesis and comprises a comprehensive discussion over each theme covered in this study and the research findings, the conclusions, and suggestions for future work.

Figure 1-3 presents an overall picture of the thesis layout and flow, showing the linkage between the different research phases and chapters (e.g. updating loops and information interchange).

The next chapter presents the methodology and methods applied in this research.

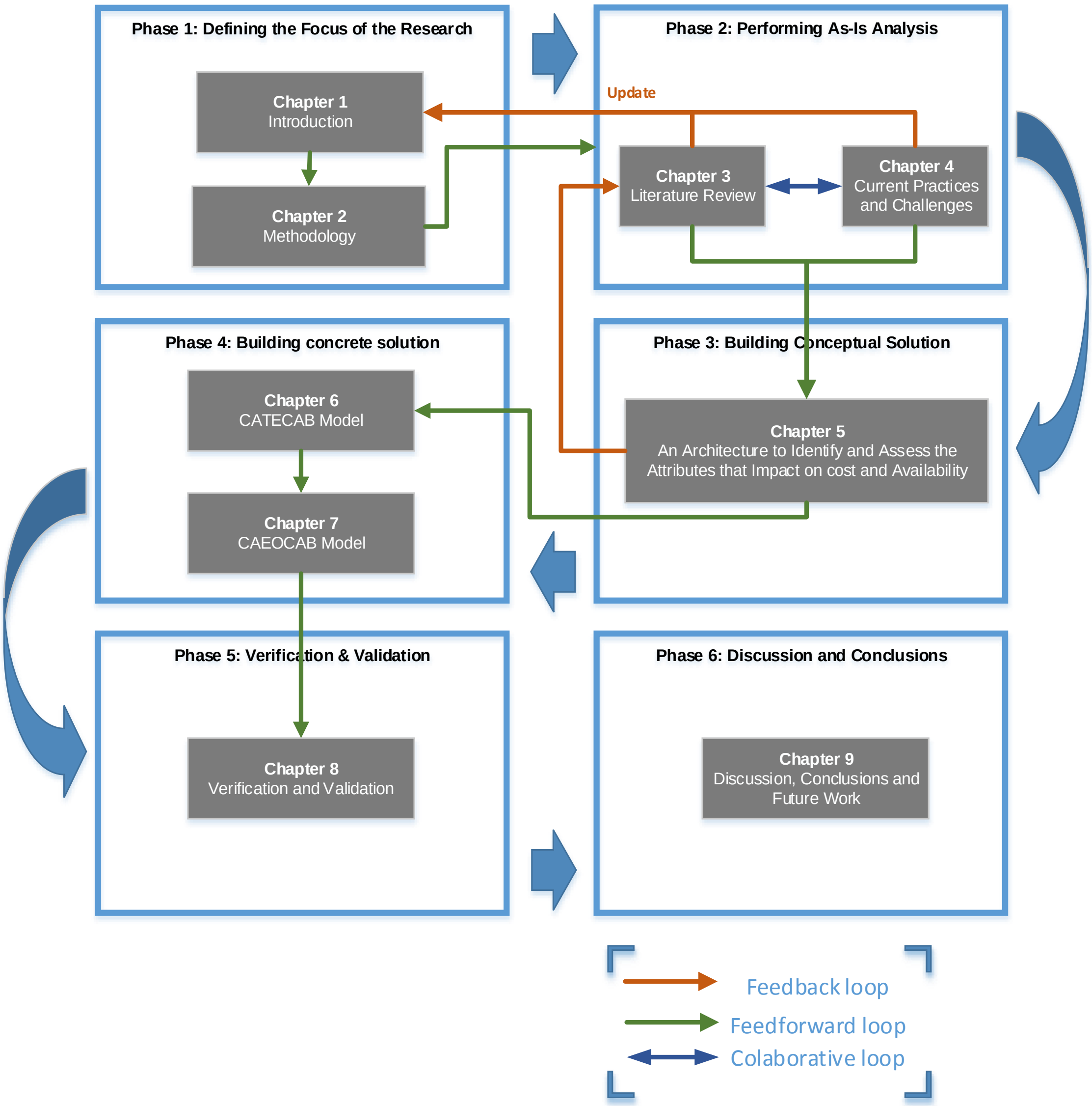


Figure 1-3 Research Flow

2 METHODOLOGY

2.1 Introduction

This chapter describes the methodology adopted to carry out the research process, and is divided in three main parts consisting of:

1. Review of Research Methodologies and Techniques: Essential definitions that grounded the search for the appropriate methodology and techniques are provided in Section 2.2. Then, a review of different types of research is performed in order to define the nature of this study, as presented in Section 2.3. It is followed by a review of different research techniques and methodologies, as presented in Sections 2.4 and 2.5 respectively.
2. Selection of the Appropriate Methodology and Techniques for this Research: The most appropriate methodology for this research and the appropriate research techniques to be applied are presented in Section 2.6, and were selected considering the nature of this research.
3. Research Methodology Implementation: Finally, details about the implementation of the selected methodology and techniques are presented in Section 2.6.1.

The chapter ends with the risks and mitigations plan adopted throughout the research.

2.2 Definitions Underpinning the Selection of the Research Methodology

What is research?

Research is a logical and systematic search for new and useful information on a particular topic (Rajasekar *et al.*, 2006). The main characteristics of a research are (Blessing and Chakrabarti, 2009; Bricki and Green, 2009):

- It demands a clear research question and definition of research scope, aim and objectives;
- It requires a research methodology;
- It builds on existing data, using both positive and negative findings, by applying research techniques for data acquisition and analysis;
- New findings should be aligned to the research methodology and answer to the research question.

In the context of this study, research was all the investigation processes needed to build the solution that answers to the research question.

What is a research methodology?

Research methodology is a systematic way to solve a problem. It is a science of studying how research is to be carried out. Essentially, research methodology identifies the procedures by which researchers go about their work of describing, explaining and predicting phenomena. It is also defined as the study of methods by which knowledge is gained and its aim is to give a work plan of research (Babariya and Rajguru, 2017). The methodology guides the researcher in the selection and application of the right methods for research (Khusainova, 2015).

In the context of this study, the research methodology presented the guidelines to the researcher to systematically build the different research phases, and to appropriately select the methods and approaches to achieve the research objectives.

What is a research method/technique?

Research methods or techniques are the various procedures, schemes and algorithms used in research. They are essentially planned, scientific and value-neutral, and they include theoretical and experimental techniques, numerical schemes, statistical approaches, etc. Research methods help at collecting samples, data, and find solutions to a research problem. In particular, scientific research methods call for explanations based on collected facts, measurements and observations and not on reasoning alone (Hooley *et al.*, 2012).

In this research the selection of the methods to do the research was according to the methodology adopted, and different techniques were applied in order to deal with the different challenges and needs of each research phase.

2.3 Types of Research

There are many types of research recognised in literature. Most of the authors describe the different types as a complementary pair. This section presents a description of the most popular pairs of research types suggested in literature (Khanka, 2002).

2.3.1 Applied vs. Fundamental

Applied research is designed to solve practical problems rather than to acquire knowledge for knowledge’s sake. The goal is to improve the human condition (Akpan, 2017). The findings of an applied research project can be very helpful in theory development to be used in business, medicine and education in order to find solutions that may cure diseases, solve scientific problems or develop technology (Mcauley, 1987).

Fundamental research is an investigation for occurrence of a particular event or process or phenomenon, and is driven by a scientist's curiosity or interest in a scientific question. It does not generate findings that have immediate applications in a practical level, and the main motivation is to expand man's knowledge for knowledge’s sake (Garofalo and Parello, 2007). Fundamental research is driven by curiosity and the desire to expand knowledge in specific research area. This type of research makes a specific contribution to the academic body of knowledge in the research area. The main differences between applied and fundamental research are summarised in Table 2-1.

Table 2-1 Fundamental Research vs. Applied Research (Saunders *et al.*, 2012)**.**

Fundamental Research	Applied Research
Expand researchers’ knowledge	Improve understanding of particular business or management problem
Results in universal principles relating to the process and its relationship to outcomes	Results in solution to problem, and new knowledge limited to problem
Findings of significance and value to research community in general	Findings of practical relevance and value to industry organisations
Undertaken by university researchers typically	Undertaken by people based in a variety of settings including organisations and universities
Choice of topic and objectives determined by the researcher	Objectives negotiated/agreed with an organisation that will benefit from the results
Flexible time scales	Tight/limited time scales

2.3.2 Descriptive vs. Analytical

Descriptive research includes surveys and fact-findings enquires of different kinds. The major purpose of descriptive research is description of this type of research is that the researcher has no control over the variables of study as he can only report what has happened or what is happening (Kothari and Garg, 2014).

Analytical research involves critical thinking skills and the evaluation of facts and information relative to the research being conducted. A variety of people including students, doctors and psychologists use analytical research during studies to find facts or information already available, and analyse it to make a critical evaluation. It aims to explore each topic in-depth, often beginning with a question that asks why or how. Unlike descriptive research, which aims to determine what something is, analytical research is an attempt to establish why something is a certain way or how it came to be that way. It starts by setting out primitive assumptions that reflect generally accepted ways to representing the structure of the problem, and then proceeds to derive the results using formal logic or some results from mathematics or economics (Christensen, 2011). A summary of the differences between descriptive and analytical research are presented in Table 2-2.

Table 2-2 Descriptive Research vs. Analytical Research

Descriptive Research	Analytical Research
Describes what happened	Critics and analyses what happened
States what something is like	Evaluates strengths and weakness
Tells the story exactly how it is	Critics, analyses and concludes based on different information
Says how to do something	Argues a case according to evidence
Explains how something works	Shows how something is relevant or suitable
States the order in which something happened	Makes reasoned judgements of that order

2.3.3 Qualitative vs. Quantitative

Qualitative research is characterised by its aims, which relates to understanding some aspect of social life, and its methods which (in general) generate words, rather than numbers, as data for analysis (Bricki and Green, 2009). This data relates to the social world and the concepts and behaviours of people within it. Qualitative research can be found in all social sciences and in the applied fields that derive from them, for example, research in health services, nursing, and pharmacy (Anderson, 2010).

Quantitative Research is used to quantify the problem by way of generating numerical data or data that can be transformed into useable statistics. It is used to quantify attitudes, opinions, behaviours, and other defined variables – and generalise results from a larger sample population. Quantitative Research uses measurable data to formulate facts and uncover patterns in research. Quantitative data collection methods are much more structured than Qualitative data collection methods (Monfared and Derakhshan, 2015). A summary of the comparison between qualitative and quantitative research is presented in Table 2-3 (Hoepfl, 1997; Reddy and Acharyulu, 2008; Knapp, 2016).

Table 2-3 Qualitative Research vs. Quantitative Research.

Qualitative Research	Quantitative Research
Uses the natural setting as the source of data. The researcher attempts to observe, describe and interpret settings as they are, in a qualitative manner	The data is usually gathered using structured research instruments
The researcher acts as the "human instrument" of data collection	Researcher uses tools, such as questionnaires or computer software, to collect numerical data
Predominantly uses inductive data analysis	Data is analysed using measurement instruments, mathematical equations, statistical processes, etc.
Reports are typically descriptive and in a text form	Results are in the form of numbers and statistics, often arranged in tables, charts, figures, or other non-textual forms
Has an interpretive character, aimed at discovering the meaning that events have for the individuals who experience them, and the interpretations of those meanings by the researcher	Research outputs can be used to generalise concepts more widely, predict future results, or investigate causal relationships
Pays attention to the idiosyncratic as well as the pervasive, seeking the uniqueness of each case	The results are based on larger sample sizes that are representative of the population
Is judged using special criteria for trustworthiness	It is validated in a quantitative manner, comparing numerical results with acceptable figures

Many researchers actually indicate that qualitative and quantitative methods should not necessarily be seen as opposed approaches to research. On a practical level, they suggest that both qualitative and quantitative should be combined in a mixed-method (Ritchie *et al.*, 2013). Mixed methods research is formally defined as the class of research where the researcher mixes or combines quantitative and qualitative research techniques, methods, approaches, concepts or languages into a single study (Johnson and Onwuegbuzie, 2004).

2.3.4 Conceptual vs. Empirical

Conceptual research is that related to some abstract idea(s) or theory, typically reported in a conceptual framework (Jabareen, 2009).

The conceptual framework contributes to the research by identifying the research variables and clarifying the relationships between them in order to guide the research process towards producing concreate solutions. It basically presents a conceptual solution to the research question, and drives the investigation being reported (McGaghie *et al.*, 2001). A conceptual framework is often represented by diagrams (Paradies and Stevens, 2005).

The conceptual framework lies within a much broader framework called empirical framework, built from the experience of the researcher and that normally presents a concrete solution to the research problem, translating the conceptual idea. Empirical research is data-driven, coming up with solutions and conclusions which are capable of being verified and validated by observation or experiment (Kothari and Garg, 2014). It means that research is conducted through investigation and the conclusions are drawn on the basis of collected evidences. It is a practical and experimental approach of research. A summary of the differences between conceptual and empirical research are presented in Table 2-4.

Table 2-4 Conceptual Research vs. Empirical Research

Conceptual Research	Empirical Research
Related to some abstract idea(s) or theory	Related to some concreate and objective solution
Product of philosophic thinking	Product of experience and/or observation
Verification and validation based on qualitative judgement	Verification and validation based on observation or experiment

Creates conceptual solutions to drive research	Translate concepts into facts

2.3.5 Other Types of Research

All other types of research are variations of one or more of the above stated, based on factors such as research purpose, time required to accomplish research, the environment in which research is done, or on the basis of some similar factors (Kothari and Garg, 2014). Thus, other types of research include:

Action research: detail findings to improve the quality of action in the social world, and has been developed differently for different applications. It is seen as a general term for diagnostic, participant, empirical and experimental (Tripp, 2005).

Explanatory research: search explanations for events and phenomena, for example, finding answer to the question “why are the things like what they are?” (Rajasekar, Philominathan and Chinnathambi, 2006).

Exploratory research: emphasis the accurate description of some aspect of society. It is conducted to clarify ambiguous situations or discover potential business opportunities. It is not intended to provide conclusive evidence from which to determine a particular course of action. In this sense, exploratory research is not an end unto itself (Zikmund, 2010).

Comparative research: focus on obtaining similarities and differences between events, methods, techniques, etc, by comparing data from more than one time period in more than one data source (Schutt, 2012).

Causal research: seeks to identify cause and-effect relationships. When something causes an effect, it means it brings it about or makes it happen. The effect is the outcome. Outcomes from causal research aim at impacting in decision making in a positive way (Zikmund, 2010).

Predictive research: aims to forecast the likelihood that particular phenomena will occur in given circumstances. It also seeks for the explanation of relationships between dimensions or characteristics of a phenomenon or differences between groups, trying to answer questions such as “what is the effect of *a* in *b”*? Predictive research relies heavily upon the use of data to build the predictions, and it is inherently susceptible to changes in environment, consumers, or the market in general (Andrew *et al.*, 2011).

2.4 Research Techniques

This section presents the most important techniques suggested in literature to carry out research. Other techniques may be available that are derivative from the ones presented or that are not appropriate to the context of this research.

Surveys and questionnaires

Survey research refers to the selection of a relatively large sample of people from a pre-determined population of interest, followed by the collection of a relatively small amount of data from those individuals. The researcher therefore uses information from a sample of individuals to make some inference about the wider population (Kelley *et al.*, 2003). Different types of surveys include: on-line surveys, paper surveys, mobile surveys, kiosk survey, mail survey, and structured questionnaires (Szolnoki and Hoffmann, 2013).

Questionnaires are a sequence of questions that constitute the basis for every structured interview or every survey-based statistical measurement (Lima and Paulino, 2006). A basic process of applying a survey research can be defined as: (1) defining research aim; (2) identifying population sample; (3) deciding the type of survey; (4) designing the questionnaire; (5) launching the survey; (6) collecting and analysis the responses (Burgess, 2001).

Discourse analysis

Discourse analytic studies encompass a broad range of theories, topics and analytic approaches for explaining language in use (Shaw and Bailey, 2009). The analysis may be based on a variety of different sources containing discourse including written documents, speeches, media reports, interviews and conversation (Ritchie *et al.*, 2013), and should be critical. Quotation, like summarising, is not discourse analysis in itself (Shaw and Bailey, 2009).

Secondary data analysis

Secondary analysis involves the use of existing data, collected for the purposes of a prior study, in order to pursue a research interest which is distinct from that of the original work; this may be a new research question or an alternative perspective on the original question (Heaton, 1998).

Systematic observation

Consists of viewing a fact or occurrence, following a systematic plan, for collecting data. The scientist needs to select a way of performing the data gathering from the observations without questioning or communicating with the people involved. The systematic process must be followed strictly without any bias (Pieth and Thelesklaf, 2009).

Focus groups

Also known as brainstorming sessions or workshops (Maiden *et al.*, 2004), focus groups involve several people brought together to discuss a research topic as a group, and aims at gathering data from that discussion by exploring how people think and talk about a topic, how their ideas are shaped, generated or moderated through conversation with others. Because group discussions allow participants to hear from others, they provide an opportunity for reflection and refinement which can deepen respondents' insights into their own circumstances, attitudes or behaviour, and it enables creative thinking (Ritchie *et al.*, 2013).

Interviews

The interviews are guided with a range of topics or themes that can be adjusted during the study, and aim at: understanding the personal context, exploring in depth and detail, understanding complex processes and issues (e.g. motivations, decisions, impacts and outcomes), and exploring private subjects or those involving social norms. The interviews can be face-to-face, by telephone, or by computer assisted, and they can be structured and unstructured (Edwards and Holland, 2013).

A structured interview follows a specific questionnaire and this research instrument is usually used as the basis for most quantitative surveys. A standardised structured questionnaire is administered where specific questions are asked in a set order and in a set manner to ensure no variation between interviews. In unstructured interviews the questions are made according to the flow of an informal conversation, guided by a pre-defined list of issues. Informal interview is normally conducted as a preliminary step in the research process to generate ideas/hypotheses about the subject being investigated so that these might be tested and explored in more depth in structured interviews (Crawford, 1997).

The identification of research problems about particular topics can arise from structured or unstructured interviews with practitioners who provide insight into new directions for future research and how to make research findings more relevant to practice. Discussions with experts in the field, such as, teachers, social workers, health care providers, lawyers, business leaders, etc., offers the chance to identify practical, “real world” problems that may be understudied or ignored within academic circles. This approach also provides some practical knowledge which may help in the process of designing and conducting the research study (Chirban, 1996).

Documents review and analysis

Involves the study of existing documents, either to understand their substantive content or to illuminate deeper meanings which may be revealed by their style and coverage (Ritchie *et al.*, 2013). The documents may be internal to a program or organisation or may be external. Documents may include administrative records such as images, sounds and news archives, or documents from library repositories or internet databases (Bowen, 2009).

Experiments

Is one major primary data collection strategy that consists of manipulating one variable, in a controlled environment, while holding all the other variables constant in order to establish a causal relationship. Experiments must create artificial situations so that they can obtain the particular data needed and can measure the data accurately (Reddy and Acharyulu, 2008).

Case Studies

A case-study is an empirical inquiry that investigates a process or a complex real-life activity in great-depth and within its real-life context, especially when the boundaries between the activity/process and its context are not clearly evident (Baharein and Noor, 2008; Yin, 2009). Scores obtained from cases-studies assessment can be analysed in a qualitative and quantitative manner (Dul and Hak, 2008). This method is particularly well suited to new research areas or research areas for which existing theory seems inadequate. This type of work is highly complementary to incremental theory building from normal science research. The former is useful in early stages of research on a topic or when a fresh perspective is needed, whilst the latter is useful in later stages of knowledge (Eisenhardt, 1989).

2.5 Research Methodologies

A research methodology focuses on defining the general approach to carry out the research and to select the kind of tools and techniques to be used. This section describes four important research methodologies identified in literature.

2.5.1 Narrative Review

Narrative review is a research methodology adequate to perform literature reviews. This approach is also called non-systematic review methodology. An expert in a particular field will review studies, decided on the relevance, and highlight the findings, both in terms of results and, to a lesser degree the methodology. Such narrative reviews tend to be unsystematic and susceptible to many biases. Firstly, no systematic approach is prescribed to obtain the primary data and to integrate the data. Often, subjective judgment of the reviewer was used. There were often no explicit standards exist to assess the quality of review. Moreover, narrative reviewer also does not synthesize data quantitatively (Wong, 2007).

2.5.2 Systematic Review

A systematic review is a review of a clearly formulated question that uses systematic and explicit methods to identify, select, and critically appraise relevant research, and to collect and analyse data from the studies that are included in the review. Statistical methods (meta-analysis) may or may not be used to analyse and summarise the results of the included studies (Higgins and Green, 2011).

Reviewing research systematically involves three key activities: identifying and describing previously published relevant research; critically appraising the research methods, and bringing together the aggregated findings into a synthesis of research findings. Systematic reviews are more rigorous than a traditional literature review because they use a systematic approach to search, select, and appraise the produced evidence (Ham-Baloyi and Jordan, 2016). Strengths and limitations of the systematic review methodology are presented in Table 2-5.

Table 2-5 Advantages and Disadvantages of Systematic Review Methodology (Ham-Baloyi and Jordan, 2016)**.**

Advantages	Disadvantages
Use clear and thorough methods to identify and critically appraise relevant studies in order to answer a well-defined research/review question	Can be time consuming depending on the amount of relevant literature available and the search requirements
Student learns both systematic evidence-based review processes, as well as learning to use primary research methods	Difficult to implement effective systematic review methods

Critical analysis skills are encouraged and can be mastered	Infrastructural constraints if students do not have adequate access to electronic databases
Students learn new methods to do independent research	Depending on the research question, a large or little amount of literature can constrict the literature review process
Systematic reviews provide an opportunity for students to engage in a broader range of research methodologies	Assessment tools and tested algorithms may not be available for certain qualitative research methods
For Ph.D. students a more rigorous research foundation for their dissertation topic is established	Systematic reviews are often difficult to publish in peer-reviewed journals
No ethical approval is necessary due to its exclusive use of secondary data	

2.5.3 Human-Centred Design

The human centred design (HCD) methodology is tailored for problem solving, incorporating the wants and needs of people that will benefit from the research output. It is all about a deep empathy with the people that the research is designing a product/solution for, and it ends with new solutions that are tailored to suit their needs (Rouse, 2001; ISO 9241-2010, 2010).

The term user-centred is related to stakeholders. The latter indicates a recognition that requirements originate from a wide group of people beyond the immediate users. Users such as secondary and indirect users (for example managers who read reports the research but do not use directly the research outcomes, e.g. simulation model), people involved in writing technical documentation (for example on-line help, manuals tutorials), in training, in support (help desk staff), and other researchers (International Standards Organisation, 1999).

HCD can be employed across products, services, and technologies (Johnson and Onwuegbuzie, 2004), following an interactive process that answers to a set of questions as presented in Figure 2-1. These questions are considered key to the social acceptance, commercial success, brand identity and business strategy, of the research outputs (Giacomin, 2014).

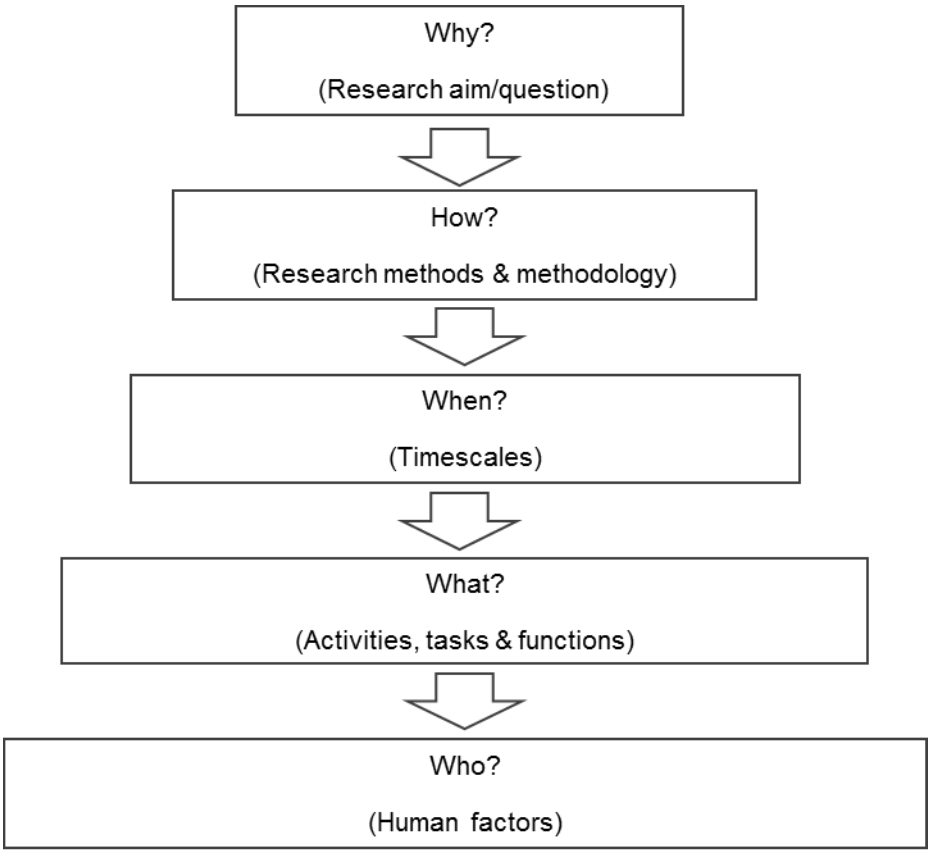


Figure 2-1 The Questions that Drive the Iterative HCD Methodology (Giacomin, 2014)**.**

The HCD methodology is underpinned by four main principles which consist of (Maguire, 2001):

- Establishing a systematic and active involvement with the project stakeholders:

One of the key strengths of human-centred design is the active involvement of the project stakeholders who have knowledge of the context in which the research will be performed.

Involving stakeholders can also enhance their acceptance of the final results of the research and their commitment during the research process, as they come to feel that the research outcomes are being designed in consultation with them rather than being imposed on them.

- Finding the appropriate allocation of function between user and model:

Regarding to the outputs of the research, e.g. model producing, it is important to determine which aspects of a job or task should be handled by people and which can be handled by software and hardware. This division of labour should be based on an appreciation of human capabilities, their limitations and a thorough grasp of the particular demands of the task.

- Planning iterative stages for the research development:

Iterative research design entails receiving feedback from the stakeholders following their use of early design solutions. These may range from simple presentations with graphs and diagrams with conceptual solutions to software prototypes with greater fidelity. The stakeholders attempt to accomplish “real world'' tasks using the prototype. The feedback from this exercise is used to develop the design further.

- Using a multi-disciplinary approach for the development and validation of the research and results.

HCD development is a collaborative process which benefits from the active and effective involvement of various parties, each of whom have insights and expertise to share. It is therefore important that the development team be made up of experts with technical skills and those with practical experience. The team might thus include managers, usability specialists, end-users of the research outputs, software engineers, graphic designers, interaction designers, training and support specialists and task experts.

In addition, a review of pertinent literature should include examining research from related disciplines that can reveal new avenues of exploration and analysis, in order to construct a more comprehensive understanding of the complexity of the research issue.

Any research following a HCD methodology must include the following objectives/actions (International Standards Organisation, 1999):

- Understanding and specifying the context of use of the research outputs;
- Specifying project stakeholders requirements;
- Producing more than one candidate design solution;
- Evaluating designs against requirements.

Some advantages and disadvantages of the HCD methodology pointed out by different authors are summarised in Table 2-6 (Rouse, 2001).

Table 2-6 Advantages and Disadvantages of HCD methodology

Advantages	Disadvantages
Begins from a deep understanding of the needs and motivations of people	It may be time consuming
It is collaborative	Requires considerable effort in identifying relevant stakeholders
It is optimistic	It may be too specific to a set of stakeholders
Focuses on experimenting and learning by doing	Difficult to formulate the right research problem
Stakeholders feel sense of responsibility and impact over the research outputs	Difficult to plan the iterative research phases
Enhance human abilities	Difficult to integrate solutions within the real-world context
Aims at overcoming human limitations	Difficult to obtain general consensus among the stakeholders about the appropriateness of solutions

2.5.4 Grounded Theory

Grounded Theory (GT) is an inductive research methodology which focuses on the identification and integration of concepts/categories of meaning from data, through a systematic research. These concepts/categories are related to each other as a theoretical explanation of the action(s) that continually resolves the main concern of the participants in a substantive area. Grounded Theory can be used with either qualitative or quantitative data (Glaser, 1978).

GT methodological emphasis is on the actors' own ('emic') interpretations and meanings to emerge with minimal researcher intervention ('etic'). Through constant comparison, coding and analysis of interview and observational data, theory that is grounded in these data emerges. GT seeks to approximate to the context of that being studied, that is, for example: a business, its actors, their interactions and interrelationships; thus conveying a conceptual understanding of issues that make up their naturalistic world (Maanen, 1979).

Fundamental characteristics of grounded theory are described as (Hallberg, 2006):

- Collection and analysis of data are made in simultaneous;
- Includes intensive interviewing towards an in-depth exploration of the topics;
- Categories/concepts and their qualities/properties are generated from the data rather than being directed by the researcher's hypotheses and preconceptions.
- Aims at identifying and assessing relations between emerging and existent concepts;
- Focuses on identifying a central concept for research and then all the findings are integration into a conceptual framework or theory grounded in the central concept. This central concept determines and delimits the theoretical framework.

- There is a detailed memo-writing during the entire research study which requires writing down ideas, assumed associations, and theoretical reflections related to each of the emerging concepts.

Some advantages and disadvantages of the GT methodology pointed out by different authors are summarised in Table 2-7 (Douglas, 2003; Walsh *et al.*, 2015).

Table 2-7 Advantages and Disadvantages of the GT Methodology

Advantages	Disadvantages
Strong interaction with stakeholders	Does not include predetermined research problem
Considers both qualitative and quantitative type researches	Risk of data misuse
Considers theoretical sampling (e.g. the process selecting the sample, e.g. stakeholders, dynamically according to the research interests and directions)	Requires a strong understanding of its epistemology, under penalty of deficient research design
Data are continuously compared with previously collected and analysed data to identify similarities and differences	Complex and not widely applied
Collects knowledge from empirical research	Requires good description, conceptualisation and integration, under penalty of deficient research design if one of these phases are not considered

2.6 Methodology and Techniques Selected for this Research

For the selection of the appropriate research methodology for this study, an assessment was previously made about the research type, by reviewing the different types of research described in Section 2.3, and comparing with the specifications of this study. As follows, this study was primarily considered as an applied research because it started from the motivation of developing outputs that will be applied to mitigate challenges experienced in industry. However, the objectives agreed for this research required a descriptive and analytical investigation of both qualitative and quantitative nature, to produce conceptual and empirical results such as: exploring concepts and interrelationships between concepts, predicting performance metrics (e.g. availability) and cost, and validating results in “real-world” scenarios. Therefore, this study was considered a multi-type research that required a continuous and effective engagement with the industry partners towards establishing a solid collaboration to the development and implementation of solutions.

Thus, a Human Centred Design (HCD) methodology was preferred to conduct the overall study. From a comparison between the different researches methodologies presented in Section 2.5, this was believed to be the most appropriate approach as it explicit focuses on the targeted audience that will benefit from the results, in the level of analysis required, and in the use context. Due to the strong industry-focused nature of this research, these aspects were fundamental to develop the most adequate output that would serve the industry needs and fill the literature gaps. Moreover, the HCD methodology seeks for increased research productivity, acceptance and reduced errors, and is widely accepted in the research community (Maguire, 2001).

Although there is the GT methodology that also seeks for a strong interaction with the people that would benefit from the research results, it was excluded because it is not underpinned by a predetermined research question and it is a less popular approach than HCD among the literature reviewed. The other two methodologies (narrative review and systematic review) were also not considered as they are not broad enough in terms of scope to guide a full PhD study, and are more appropriate for pure descriptive and qualitative type research.

Nonetheless, this PhD study is divided in six main phases, as presented in Section 1.5, and each phase has its own nature and specifications, which required explicit methodologies to be applied accordingly. Thus, although the HCD methodology guided the overall study, there were specific methodologies that guided the development of each research phase. These different methodologies are presented at the beginning of each chapter, as well as the methods applied to gather and analyse information.

The overall methods applied in this research were selected accordingly to the requirements of the HCD approach, by assessing the definitions of each method as presented in Section 2.6. As this research was recognised to have a multi-type nature, and because of the requirements of the HCD approach, almost all the methods recognised in Section 2.6 were applied throughout the study (only the *experiments* method was not applied). Figure 2-2 illustrates the different research methods and techniques applied in each research phase.

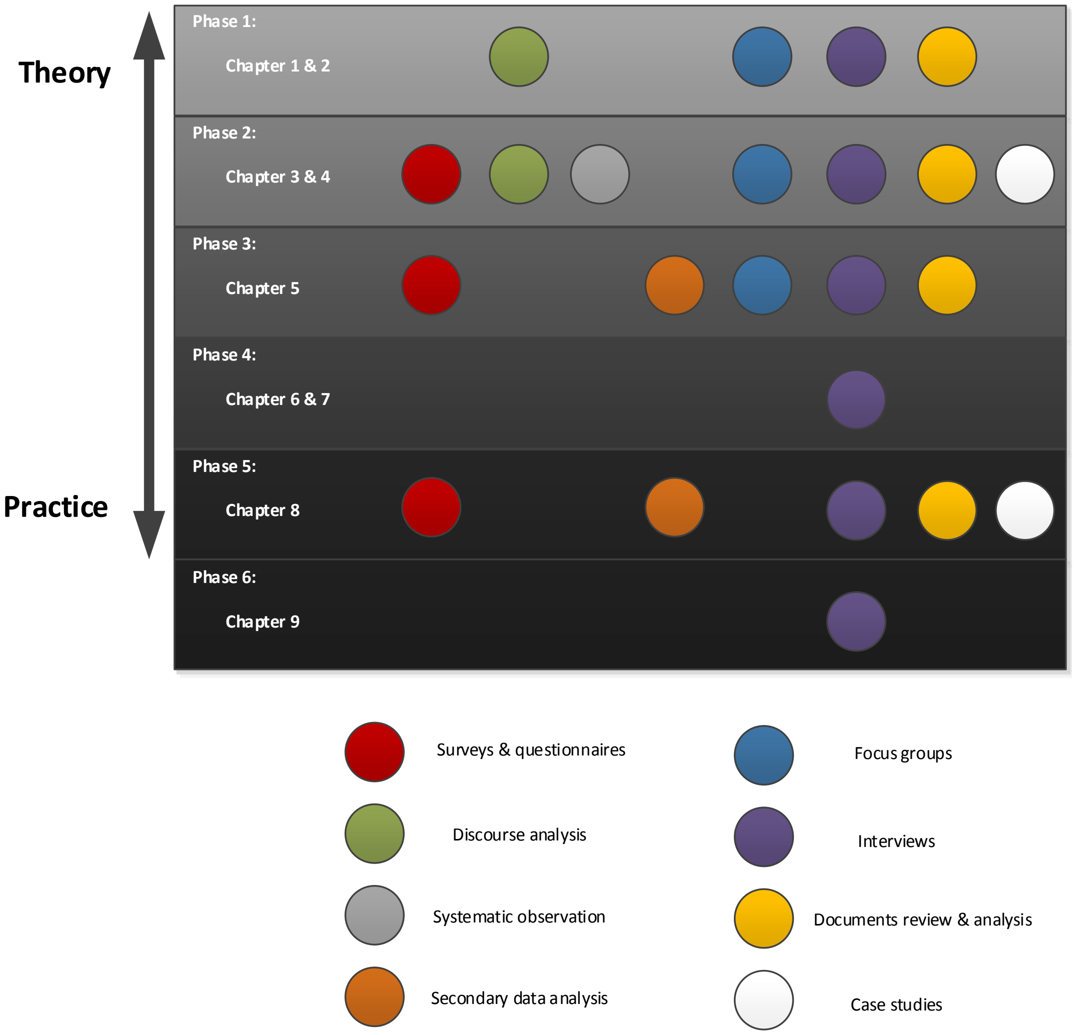


Figure 2-2 Research Methods Applied Across the Research Phases

2.6.1 Human-Centred Design Implementation

The HCD methodology aims at achieving usable and useful results throughout the research process, by focusing on the users, their needs and requirements, and by applying ergonomics and scientific knowledge and techniques. The implementation of this methodology aimed at guiding the researcher to achieve effective results**,** the stakeholders' satisfaction**,** and a sustainable research**.** The stakeholders of this project are all of those individuals who affected or were affected by the research findings, objectives and policies.

For the implementation of the HCD methodology, each of the HCD principles identified in Section 2.5.3 was interpreted and planned, and details of their practical implementation is presented in the next sub-sections.

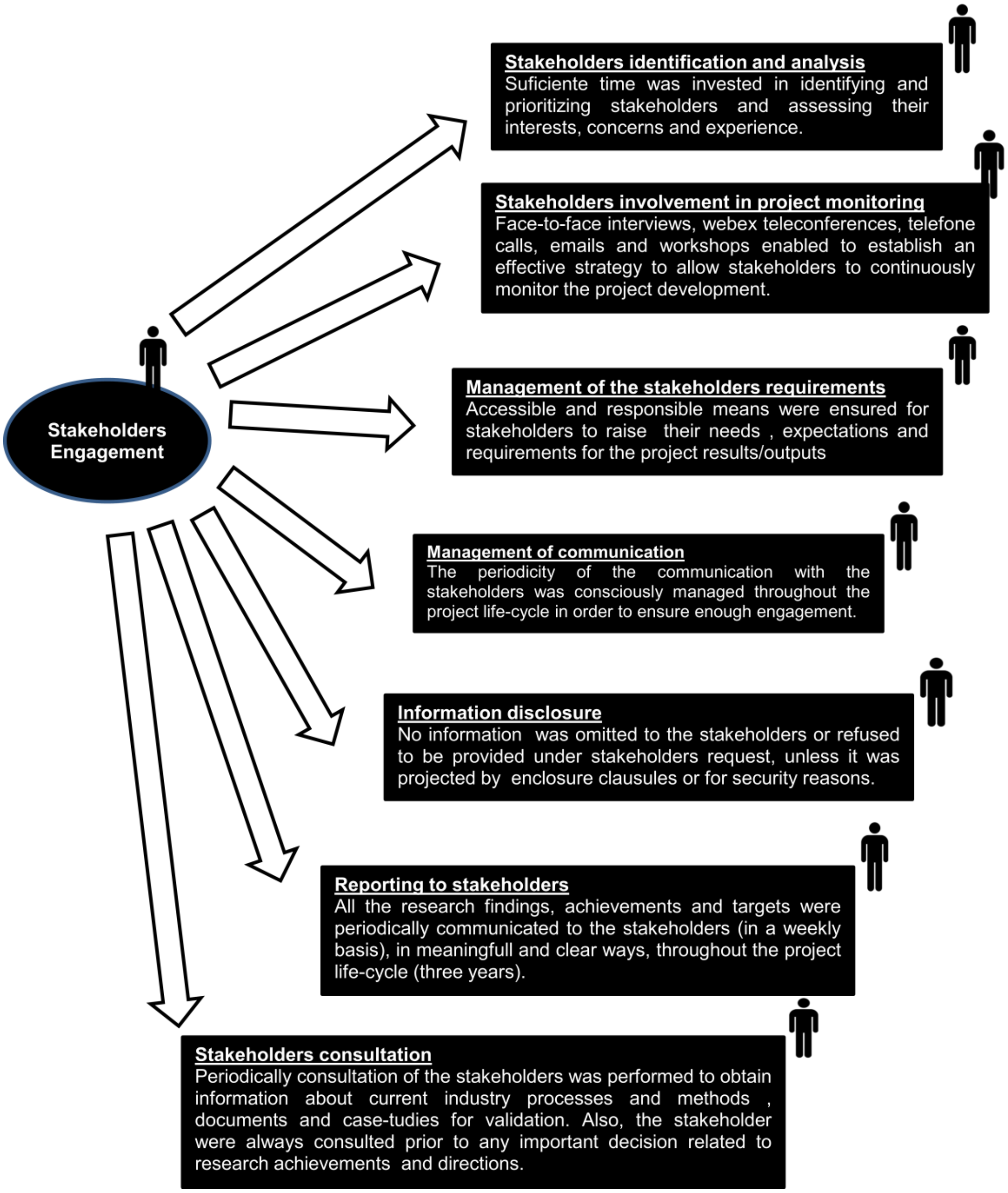
2.6.1.1 Systematic and Active Interaction with the Project Stakeholders

To achieve an active and effective engagement with these stakeholders, the following techniques were adopted: semi-structured face-to-face, teleconferences (e.g. WebEx), telephone calls, emails, workshops and participation in events of interest such as seminars and conferences for presenting the research results and networking. The effectiveness of these techniques in engaging with the project stakeholders was recognised based on the definitions provided in Section 2.4.

The application of these techniques towards achieving an effective engagement with the stakeholders was planned in the following way:

- Setting up regular interviews;
- Building structured questionnaires to support each interview with relevant questions reflecting the aim and objectives of the interview;
- Reporting and validating the summary of each interview;
- Highlighting the importance of an active cooperation of the stakeholders towards achieving valuable and useful results;
- Including the stakeholders in all the important stages of the project, and address their comments and suggestions throughout the research process.

Moreover, seven aspects have also been considered to ensure a quality engagement with the stakeholders, as proposed in literature (Damodaran, 1996), and are illustrated and described in Figure 2-3.



Stakeholders identification and analysis
Suficiente time was invested in identifying and prioritizing stakeholders and assessing their interests, concerns and experience.

Stakeholders involvement in project monitoring
Face-to-face interviews, webex teleconferences, telefone calls, emails and workshops enabled to establish an effective strategy to allow stakeholders to continuously monitor the project development.

Management of the stakeholders requirements
Accessible and responsible means were ensured for stakeholders to raise their needs , expectations and requirements for the project results/outputs

Management of communication
The periodicity of the communication with the stakeholders was consciously managed throughout the project life-cycle in order to ensure enough engagement.

Information disclosure
No information was omitted to the stakeholders or refused to be provided under stakeholders request, unless it was projected by enclosure clausules or for security reasons.

Reporting to stakeholders
All the research findings, achievements and targets were periodically communicated to the stakeholders (in a weekly basis), in meaningfull and clear ways, throughout the project life-cycle (three years).

Stakeholders consultation
Periodically consultation of the stakeholders was performed to obtain information about current industry processes and methods , documents and case-tudies for validation. Also, the stakeholder were always consulted prior to any important decision related to research achievements and directions.

Figure 2-3 Stakeholders' Engagement

2.6.1.2 Allocation of Function between User and Model

This research is aimed at delivering a model to be used by project managers at the bidding stage of CfA projects, to build cost and availability estimates. Before designing such model, it was important to agree what is the right/ideal balance between what should be estimated by the model, and what should be estimated/delivered by the user. This includes establishing the amount and type of information that can be inputted to the model based on an appreciation of the human capabilities and level of access to data (e.g. historical data). Overall, the designing of the model tries to minimise the required human effort in terms of input data required to produce estimates, and maximise the automatic generation of estimates.

2.6.1.3 Iterative Process

The HCD approach was planned iteratively according to the process illustrated in Figure 2-4. A number of feedback loops were considered to enable comments and updates to the results at each stage of the project development. The description of each stage of the project is presented in the next paragraphs.

The focus in Stage 1 was, in a fist instance, on understanding the context of the research. To achieve this target, an initial discussion with participants SH1 and SH2, succeeding three more interviews with participants SH1, SH2, SH3 and SH4 served to identify relevant scientific terms and concepts, to be further explored in detail in a systematic review of the literature, at Stage 2. These interviews also served to clarify the project scope, aim and objectives. Collaboration with researcher SH10 from University B and researcher SH11 from University C also enabled to analyse other projects and models that have been developed or were under development related to the context of this research.

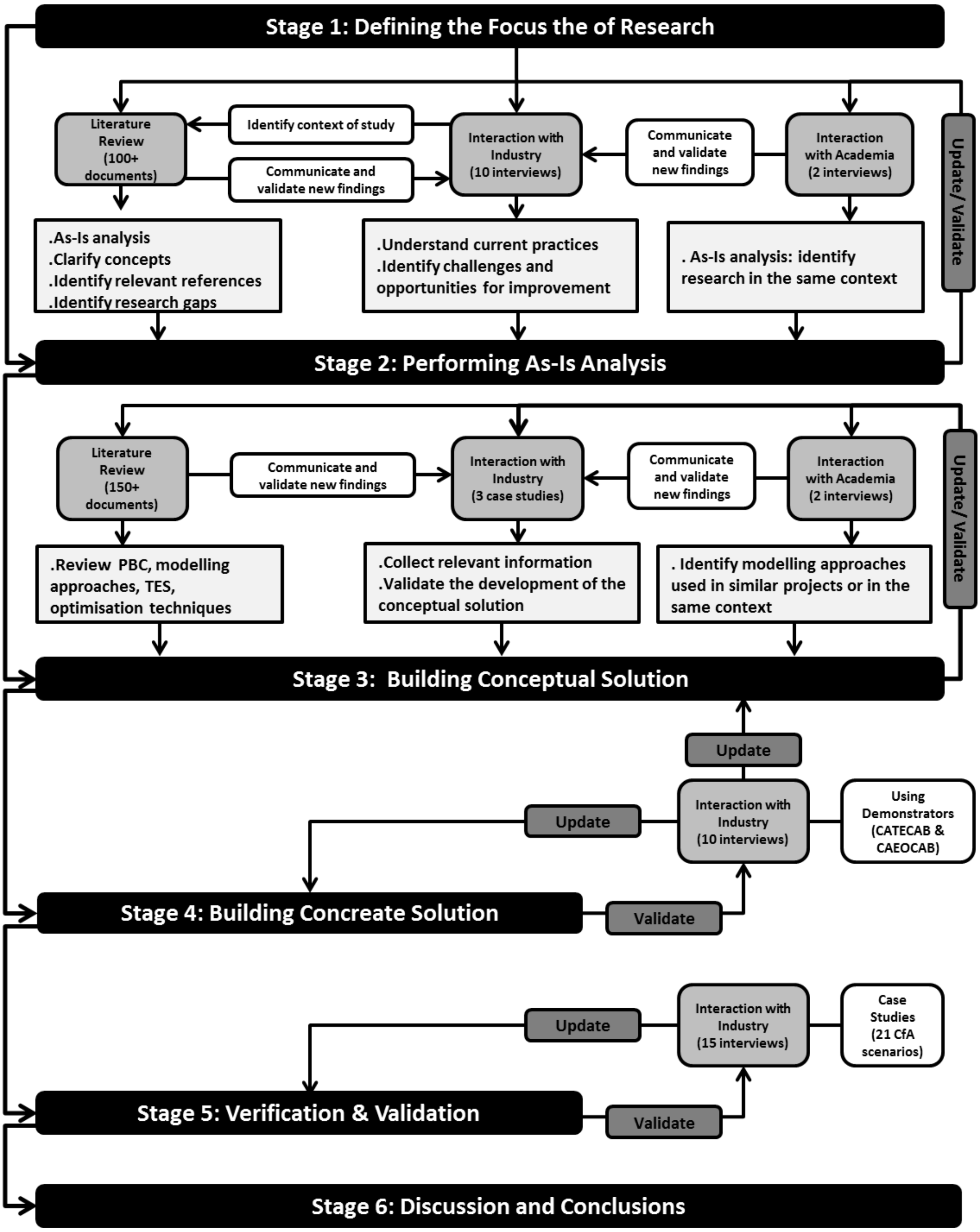


Figure 2-4 Iterative Research Methodology

Stage 2 covered an extensive review of the literature towards building a comprehensive mind map of the concepts that underpinned this research, as well as presenting a clear definition for each of those concepts. The results from the literature review are presented in Chapter 3. In parallel, a wide interaction with industry stakeholders enabled to identifying the current practices in estimating cost and availability at the bidding stage of CfA, and their recognised challenges and opportunities for improvement. More than fifteen practitioners from four different organisations (three of those typically providing support and the other typically contracting support under the umbrella of CfA) participated in this process that covered: semi-structured interviews, informal conversation in events of interest, sharing and analysis of un-published documents, and three case studies. All the results of this interaction were recorded and validated will all the participants, and are reported in Chapter 4. These findings served to align the research objectives towards providing a useful output that could assist on improving the industry current practices and mitigating their challenges.

In Stage 3, the main goal centred on developing a conceptual solution based on the challenges identified through the interaction with industry and the research gaps spotted through the review of the literature. First, a list of attributes recognised at impacting the performance of the systems in CfA was elaborated based on two interviews with participants SH1, SH2, SH3, SH4 and SH6 (two hours duration each), one workshop with participants SH1, SH2, SH3, SH4 and SH13 (three hours), literature review results, and one on-line survey. Then, based on this information and in the other results from the literature review and industry interaction a conceptual solution was built for: (1) assessing the interrelationships between the attributes, (2) assessing the impact of the attributes on availability, and (3) performing a trade-off analysis between cost and availability. At this stage, there was already a good understanding about: (a) project scope, aim and objectives; (b) industry current practices and challenges; (b) list of attributes that impact the performance of the system(s) in CfA; (c) conceptual solution to answer to the research question. The results from this stage are presented in Chapter 5.

In Stage 4, the models development took place. The first model called Cost and Availability Trade-Off and Estimation for CfA Bids (CATECAB) was aligned with the fourth objective of this research, and the second model called Cost and Availability Estimation and Optimisation for CfA Bids (CAEOCAB) was aligned with the fifth research objective.

The CATECAB consisted of a mathematical model which calculates cost and availability estimates and that allows a trade-off analysis between these two elements. The results from literature review about modelling where used to select the most appropriate technique to develop the model based on the conceptual solution presented in Chapter 5. After completing the development of the CATECAB, the CAEOCAB started to be designed and developed. This model consisted of an enhanced version of the CATECAB, able to perform optimisation analysis. This optimisation analysis covered an automatic estimate of the optimal investment in different attributes to achieve pre-defined targets of total contract cost and system availability, for a certain contract duration. The results from literature review where used to select the most appropriate optimisation technique to apply. The CATECAB model is presented in Chapter 6 and the CAEOCAB is presented in Chapter 7. The development of both models had a continuous monitoring of the academic and industry supervisors.

Stage 5 focused at verifying and validating the models developed at Stage 4. The verification consisted of making sure that all the methods and formulas were applied correctly, and the models were producing outputs aligned with the objectives of the research and expectation/needs of the end-users. The validation covered a continuous validation throughout the models development, and a final validation through the application of twenty-one case studies to assess about the innovation, usefulness and accuracy of the models. For the CATECAB model, the validation throughout the development covered fourteen semi-structured interviews involving participants SH1, SH2, SH3, SH5, SH10, SH14, SH15, SH16, SH18 and SH24, one conference presentation, and one presentation to an academic audience of fifteen researchers from system engineering, and the final validation covered the application of the model in nine case studies. For the CAEOCAB model, the validation throughout the development covered seven semi-structured interviews involving participants SH1, SH2, SH3, SH5, SH17, SH18, SH20, SH21, SH22, SH23, SH27, SH28 and SH29, and the final validation included twelve case studies. The validation of the models throughout the development is included in Chapters 6 and 7, and the final validation is presented at Chapter 8.

Stage 6 consisted of a discussion of the research results by the researcher. This included the results from the literature review and industrial interaction, the quality of the research methodology applied, and the results from the model validation. This section also includes the main conclusions of this research and suggestions for future work.

2.6.1.4 Multidisciplinary Approach

This research benefited from an active participation and contribution of professors, lecturers and researchers from different areas of expertise (e.g. mathematics, economics, etc.), and from professionals from industry with experience in different areas such as defence, aerospace and railway. Each individual provided important insights and shared experience that enabled to approach the problem outside the normal boundaries and reach solutions based on different understandings and opinions.

Moreover, the literature review covered different disciplines such as modelling, simulation, through-life engineering, and optimisation, which enabled to build a deep understanding of the research context and the techniques and methods available to build solutions for the research question.

Finally, the case studies used for validation covered different CfA scenarios in the maritime and aviation context, and were selected based on their degree of similarity and quality/type of data available for analysis. The validation through case studies gave confidence about the level of applicability and aptness of the models to “real-world” bids.

2.7 Project Stakeholders

The outputs of this research target project managers and cost analysts from large manufacturing organisations, responsible for decision-making at the early stages of PBC projects, and in particular at the bidding stage of CfA. Therefore, these project managers and cost analysts were the main stakeholders of the project. Other stakeholders included: industrial and academic supervisors, research partners and collaborators, and the UK Ministry of Defence (MoD).

The list of stakeholders is presented in Table 2-8. This list does not include the project supervisors, as their impact is naturally assumed. The list includes person name (represented in a symbolic form to ensure confidentiality), name of the organisation as described in Section 1.3, job role, main responsibilities in the organisation, and years of experience.

Table 2-8 Project Stakeholders

Name	Organisation	Job Role	Main responsibilities	Practice (years)
SH 1	Organisation 1	Operations manager	Design support solutions for military contracts	10
SH 2	Organisation 1	Bid technical manager	Design support solutions for military contracts	33
SH 3	Organisation 1	Through life support manager	Design support solutions for military contracts	5
SH 4	Organisation 1	Through life engineer	Design support solutions for military	13
SH 5	Organisation 1	Senior manager	Coordinates warships engineering activities	40
SH 6	Organisation 2	Engineering manager	Policy development and implementation, capability development and management, obsolescence management	25
SH 7	Organisation 5	Programme support manager	Project planning, engineering design	28
SH 8	Organisation 1	Modelling engineer	Create models to support data analysis	12
SH 9	Organisation 5 / University 2	Lecturer in systems engineering	Teaching defence related subjects such as: acquisition, availability definition and sustainability.	20
SH 10	University 3	Lecturer	Uncertainty modelling in industrial applications	20
SH 11	University 2	Investigator in design engineering	Design and testing technology for defence and security	30
SH 12	Organisation 5	Head of profession for cost forecasting within cost assurance and analysis services	Program management, operational planning, cost engineering	15

SH 13	University 1	Systems modeller	Design and develop modelling applications	15
SH 14	Organisation 4	Business development manager	Developing and managing business solutions	5
SH 15	Organisation 4	Project manager	Business development and contracts design	15
SH 16	Organisation 4	Project manager	Capability development and budget investment management	15
SH 17	Organisation 1	Head of the marine warships support programs	Responsible for the delivery of all warship support programmes for the Royal Navy	37
SH 18	University 2	Lecturer	Senior lecturer in optimisation	30
SH 19	Organisation 5	Project leader – land domain	Plan and coordinate support activities for complex engineering systems	27
SH 20	Organisation 1	Head of supply chain analytics	Integrated business planning and strategic activities	10
SH 21	University 1	Professor	Professor in manufacturing processes and through-life engineering	11
SH 22	Organisation 1	Team leader	Supervise naval maritime operations	15
SH 23	Organisation 1	Program manager	Provide support to marine businesses	21
SH 24	Cranfield	Researcher in manufacturing	Development of models to solve manufacturing issues	10
SH 25	Organisation 7	Project manager	Whole life cost estimator, investment appraisal, business case support, cost model development	10
SH 26	Organisation 3	Business development specialist	Cost modelling, parametric forecasting, cost estimation, risk and uncertainty management	20
SH 27	Organisation 2	Principal reliability/ modelling specialist	Systems engineering, maintenance planning, reliability engineering	35
SH 28	Organisation 6	Principal consultant in information management	Business process mapping, project planning, systems thinking, change management, benefits realisation	32
SH 29	Organisation 1	Project leader – capability manager	Project management and engineering management	11
SH 30	Organisation 1	Principal consultant in risk and assurance	Capability planning, cost estimation, project planning, contract negotiation	15

2.8 Summary

This chapter introduces the definitions that guided the author in the selection of the appropriate methodology and techniques for the research. It presents the results from a literature review of different types of research, research methods and techniques, and research methodologies, to define the ground for selecting the most appropriate methodology and techniques for this research.

HCD is then discussed as the most appropriate methodology for this research, from a comparison between the different options reviewed. The main reason for selecting this methodology is its focus on the involvement of the project stakeholders (e.g. end-users of the models) in all the stages of the research development, and reflect their needs and requirements in the research outputs. The information from the participants was captured through the application of a wide range of techniques such as interview, workshops, surveys, case studies, etc.

In summary, the HCD methodology guided this research at:

- Establishing a systematic and active involvement with the project stakeholders;
- Finding the appropriate allocation of function between user and model;
- Planning iterative stages for the research development;
- Applying a multi-disciplinary approach for the development and validation of the research and results.

A mitigation strategy was also considered from the beginning of the project to avoid any possible scenario that could harm the research results/outputs, as well as a Gantt chart for the project activities.

The following chapter presents the results of the literature review.

3 LITERATURE REVIEW

3.1 Introduction

This chapter presents the information collected from the literature review that was based on an exploration of the concepts defined for the research scope, as illustrated in Figure 3-1.

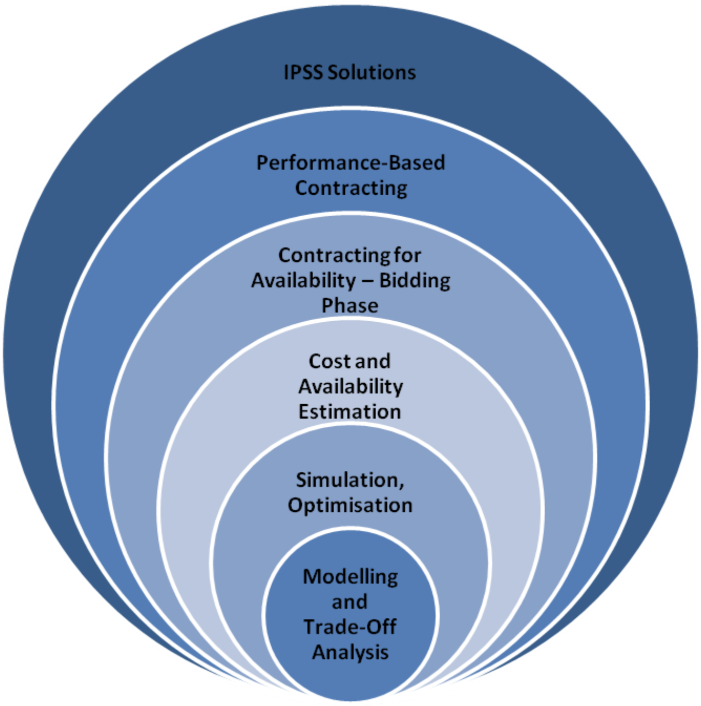


Figure 3-1 Research Topics that Guided the Literature Review

The initial section of this chapter is dedicated to the explanation of the methodology adopted to perform the literature review. Then Section 3.3 is dedicated to the concept of Integrated Product-Service Systems (IPSS), and includes a review of the different PBC approaches (e.g. CfA), and an identification of different TES. Section 3.4 explores the concept of System Engineering (SE), identifying it as a scientific discipline that supports the design and implementation of TES in PBC approaches, through the development and application of models and optimisation techniques. Different techniques for modelling and optimisation are also reviewed in this section.

The chapter ends with a summary of the concepts and interlinks between concepts that made the scope of this literature review and that underpinned the development of the research.

3.2 Methodology

The review of the literature followed a systematic review approach. A systematic review is a protocol driven comprehensive review and synthesis of data focusing on the topic of interest and related key questions. A protocol is a document that presents an explicit plan for a systematic review. The protocol details the rationale and *a priori* methodological and analytical approach of the review (Moher *et al.*, 2015). A systematic review provides a structured way of mapping published papers about the theme of study and assist in the preparation of summaries about existing knowledge (Russell, Chung and Balk, 2009). The aim of this approach includes “clear goals, reproducibility, a broad and inclusive search based on merit thereby reducing reviewer bias, and incorporating as synthesized approach to organise the literature” (Walker, 2010).

The protocol selected to conduct the systematic review process was the Preferred Reporting Items of Systematic Review and Meta-Analysis (PRISMA). This protocol was selected among others such as: Consolidated Standards of Reporting Trials (Moher *et al.*, 2010), Transparent Reporting of Evaluations with Nonrandomised Designs (Treasure, 2004), Meta-analysis Of Observational Studies in Epidemiology (Stroup *et al.*, 2000), and Strengthening the Reporting of Observational Studies in Epidemiology (Noah, 2008), because it is the most recommended approach for conducting systematic reviews and meta-analyses (Sambunjak and Franić, 2012). Meta-analysis is the use of statistical techniques to combine and summarise the results obtained in the systematic review process (Moher *et al.*, 2009).

The PRISMA protocol consists of a seventeen item checklist intended to facilitate the preparation and reporting of the review process (Moher *et al.*, 2015). Among those seventeen items, five were not included either because they were considered out of scope, not applicable, or repetitive. The twelve items considered consisted of:

- **Research Abstract**: This review covers advanced IPSS business models and in particular PBC. The objectives for this review were defined as: (1) Identify the position of PBC in the IPSS development hierarchy; (2) Identify the specifications, advantages and disadvantages of PBC; (3) Identify the different types of PBC that are established across different industry sectors between large organisations (e.g. CfA); (4) Identify the processes and methods that are applied to design (e.g. bidding stage) and implement CfA solutions, at the management level; (5) Identify the current challenges and research gaps at designing and implementation CfA;
- **Research Protocol**: This literature review followed the PRISMA protocol;
- **Eligibility Criteria (for documents to review)**: Were considered eligible for review all the documents resulting from the search process that appeared to fit within the scope of the research. The quality, validity and relevance of each document source was also included in the selection criteria.
- **Information Sources**: The information sources considered included: journal papers, conference papers, reports, books, and the input of academic experts and industry practitioners.
- **Search Process**: The search for documents was performed in physical and online libraries and included: google scholar, scopus, sciencedirect, and webpages of relevant journals. Direct search on google was also performed to identify specific documents and to make a wider search about specific topics.
- **Study Selection**: In the online search for relevant documentation, automatic filters were activated in the databases to select only peer reviewed documents such as books, conference papers and journal papers; other document types such as surveys, informal notes or

editorials were excluded to avoid material that has not passed for a strict review and validation processes. Moreover, preference was given to papers from journals of high impact factor, and high number of citations. More than 600 documents passed this first “filtering criteria”. Then, titles, abstracts and conclusions of those documents were carefully read and the most relevant were selected for a full review based on a critical assessment made by the researcher. Approximately 150 documents were considered for full review.

- **Data Collection Processes**: The data was collated using tables, summaries, flowcharts and graphs. MS Excel, MS PowerPoint and MS Visio were important software tools that supported at building tables, graphs and figures.
- **Risk of Bias**: To reduce the risk of bias, different references were reviewed for each topic considered, in order to make a triangulation between the perspectives from different authors. Moreover, an extensive and multidisciplinary group of people (e.g. academic and industry supervisors) was involved in the review of the literature review outputs.
- **Synthesis of Results**: Each identified source of information has been manually text-mined and the relevant ideas and mind-maps where explored in detail and recorded. Graphs, flowcharts and tables where used to summarise contents and to perform meta-analysis.
- **Additional Analysis**: A sensitivity analysis of the literature review results was performed by the researcher, by reviewing the report and confirming the results by reassessing the literature sources, and by the academic and industry supervisors in detailed reviews.
- **Limitations**: Time constraints may have limited a wider and deeper analysis of the concepts, although it was possible to achieve all the objectives of the study.
- **Conclusions**: Conclusions from the literature review are addressed in Section 3.6.

This check list aimed to ensure that all the material, criteria and processes were ready to conduct the research. Then, a four-phase flow diagram suggested in the PRISMA protocol was also implemented and adapted to the context of this research, as presented in Figure 3-2. The flow diagram describes the way in which research was conducted and covers the following phases (Kim *et al.*, 2015): identification, screening, eligibility, and included.

The *identification phase* encompassed the identification of the relevant topics for research such as: IPSS, CfA, Cost Estimation, TES and Optimisation.

The *screening phase* covered the selection of relevant literature for review through exclusion of those documents whose source or nature was not sufficiently robust, or whose title, abstract and conclusions did not link to the project scope, aim and objectives.

The *eligibility phase* covered the final selection of the relevant literature based on a stricter eligibility criteria.

Finally, the *included phase* covered the full review of the selected documents and the report of the findings. From the review of these documents new topics appeared that linked to the research scope such as: systems engineering, simulation and modelling. To explore these terms two processes where applied: (2) on-line search for documents linked to the topics; (1) review of references suggested in relevant documents reviewed.

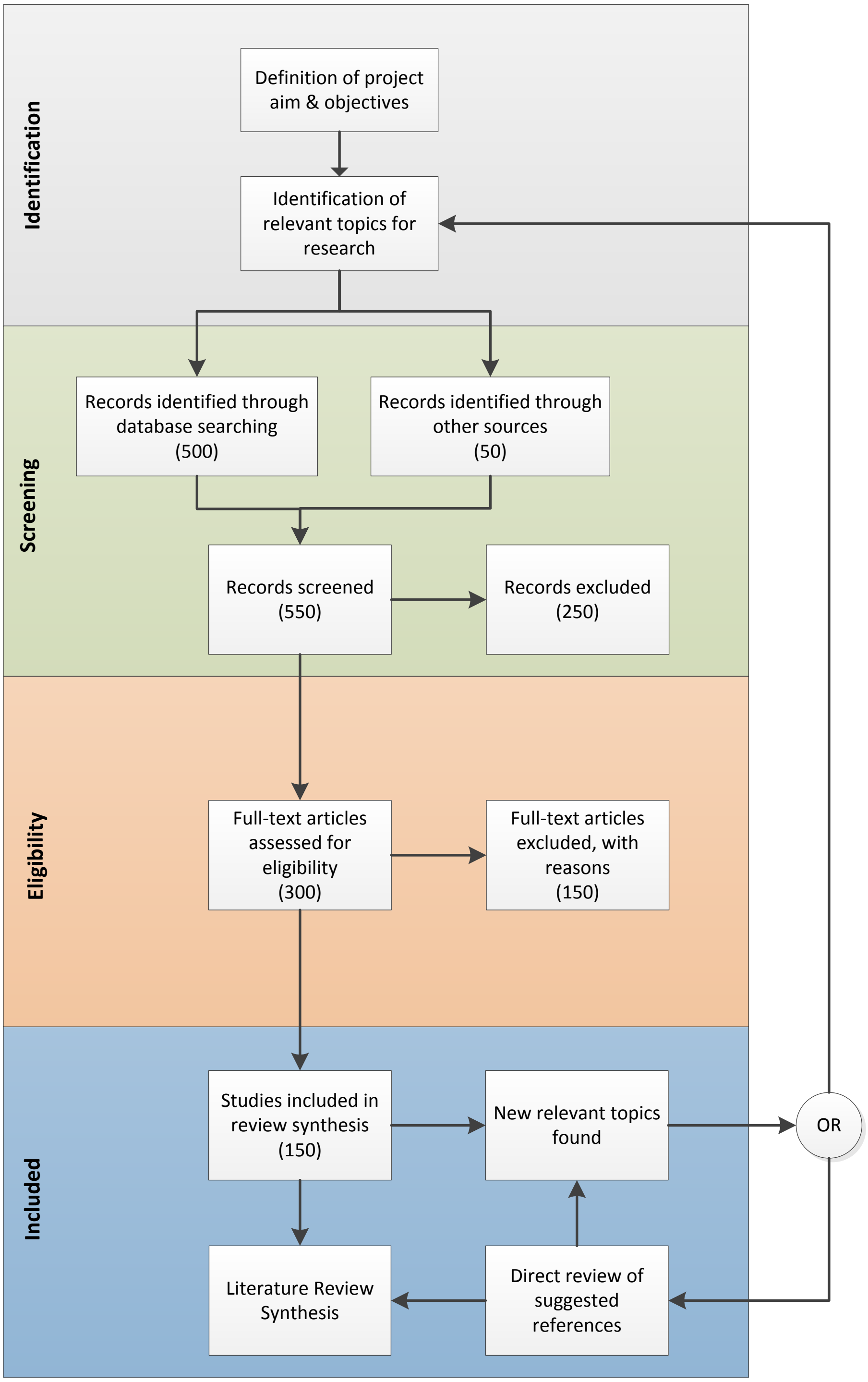


Figure 3-2 Literature Review Methodology

3.3 Integrated Product-Service System

Integrated product-service systems is an innovative strategy that is shifting the business focus from selling physical assets and support services separately, to the design and commercialisation of a product of systems and services together, which are jointly capable of fulfilling specific customer demands (Maxwell and D., 2003), as illustrated in Figure 3-3. This business model found numerous applications and in particular in the industrial context under the concept of industrial product-service system (IPSS).

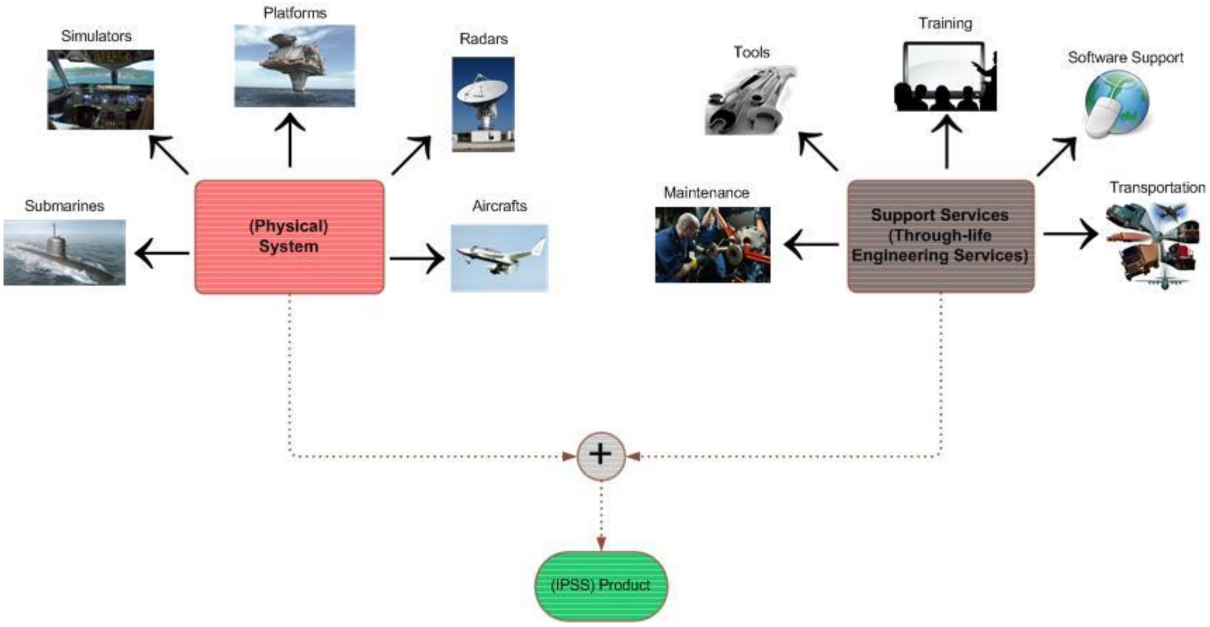


Figure 3-3 Integrated Product Service System: Physical System + Support Services

An IPSS is characterised by the integrated and mutually determined planning, development, provision and use of product and service shares including its inherent software components in business-to-business applications and represents a knowledge-intensive socio-technical system (Meier *et al.*, 2010). It covers an extended value creation network, comprising a manufacturer (main supplier), supply chain (other suppliers) and customer (Aurich *et al.*, 2006), as illustrated in Figure 3-4. The value of this network is customer-centred, as all the elements work cooperatively in order to deliver personalised solutions to the customer that are cost effective and foster innovation and better systems' performance (Medini and Boucher, 2016). There is also a mutual value recognised to this cooperative approach as it increases business sustainability (Thompson *et al.*, 2011).

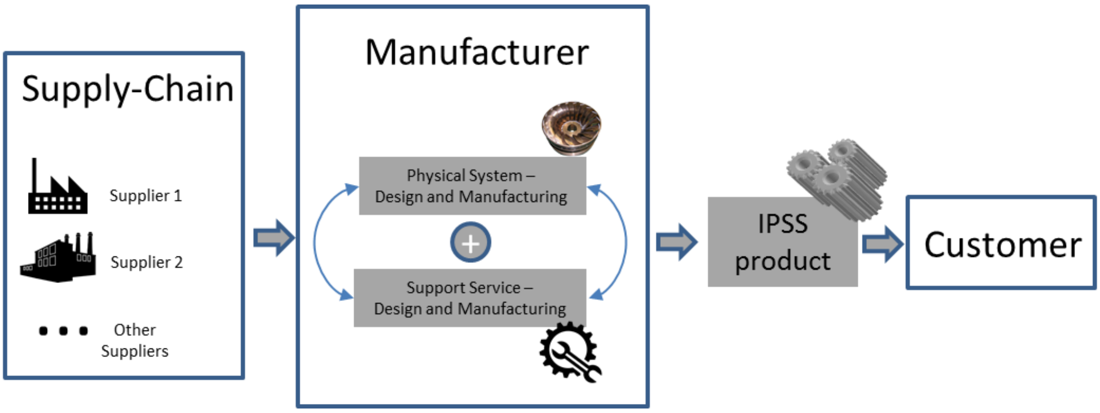


Figure 3-4 IPSS Customer-Centred Value Chain

IPSS represented a cultural change programme which forced manufacturers to change their working practices, processes, tools and techniques, in order to manufacture assets "designed for service", e.g. harmonise the product design and manufacture with a service strategy that constitute the full product package delivered to the customer (Harrison, 2006). When designed properly, IPSS can effectively contribute to achieving a business sustainability, being a competitive solution that satisfies the customer needs and that has lower environment impact than traditional business models (Kang and Wimmer, 2008).

There are three important dimensions in IPSS products (Schweitzer and Aurich, 2010):

1. The result dimension: physical (system) and non-physical (service) IPSS components together provide the customer with a certain set of expected functionalities;
2. The process dimension: IPSS realisation is based on different processes such as system maintenance and training that continuously change the

state of the product-user subsystem and the service subsystem along the life cycle;

3. The infrastructure dimension: the service network provides the resources needed for executing status changes as well as for providing the manufacturer with continuous product, customer and market feedback.

These three dimensions guide the creation of different types of IPSS. Currently, there are three main categories of IPSS which differ between each other in terms of level of service integration, customer/supplier responsibility over the product performance, and system ownership; they are (Baines *et al.*, 2007; Datta and Roy, 2009):

- Product-oriented: where the customer owns the product and relevant services are offered to ensure the product’s functionality and durability (e.g. after-sales services such as installation, maintenance, repair, upgrading and recycling, and helping customers optimise the application of a product through training and consulting);
- Use-oriented: comprising product rental, leasing, sharing and pooling, where the ownership of the product remains under the supplier responsibility and the consumer pays a fee only to use a specific product;
- Result oriented: selling a result or capacity instead of a product (e.g. availability or reliability of an asset instead of repair services (Kim, 2016), or the full availability of an aircraft instead of the aircraft itself (Holmbom *et al.*, 2014)). The ownership of the physical assets can be either with the customer or the supplier depending on the type of agreement, and customer pays to the provision of a result which is a function of asset(s) performance.

The result-oriented IPSS solutions are often referred as performance-based contracts (PBC). They emerged as a natural evolution of the IPSS concept and attempt to better align the interests of both customer and supplier (Kim, 2016). A more detailed analysis of PBC is performed in the next section.

3.3.1 Performance-Based Contracts

The main goal of any IPSS approach is to reduce systems' life-cycle costs while simultaneously improving systems' performance and support. However, in initial IPSS solutions the customer acquired services for parts supply, which was given the supplier an incentive to sell as many parts as possible to the customer in order to maximise its own profit. These approaches do not necessarily improve the system performance (Gardner, 2008).

PBC emerged has an advanced and "fair-trade" IPSS business model that has the potential of bringing monetary and non-monetary advantages to both customer and supplier whereas ensures a better system performances (Loevinsohn, 2008). These potential advantages derive from three main specifications of PBC that make them unique among other business models and that consist of:

- Under PBC, the supplier is responsible for delivering an entire and measurable performance metric of the system (e.g. availability, capability, etc.) (Jin *et al.*, 2013; Caldwell and Howard, 2014);
- The contracts can last for many years (e.g. 10, 20 or even 30 or more) (Gruneberg *et al.*, 2007; Erkoyuncu, 2011; Erkoyuncu *et al.*, 2014). Typically, the longer is the period of the contract, more complex it is. This complexity is mainly at the bidding stage of the contract, as it is harder to forecast the total contract cost and the system performance as longer the contract is (Schoenmaker and de Bruijn, 2015). In the construction sector for example, PBC last between 1-4 years if they include pure routine maintenance, 4-12 years if they include routine and periodic maintenance, and up to 30 years if they include routine and periodic maintenance and construction (Zietlow, 2015). For each of these contracting scenarios, the complexity is recognised to be different as illustrated in Figure 3-5. There is a direct relationship between contract duration and design complexity;

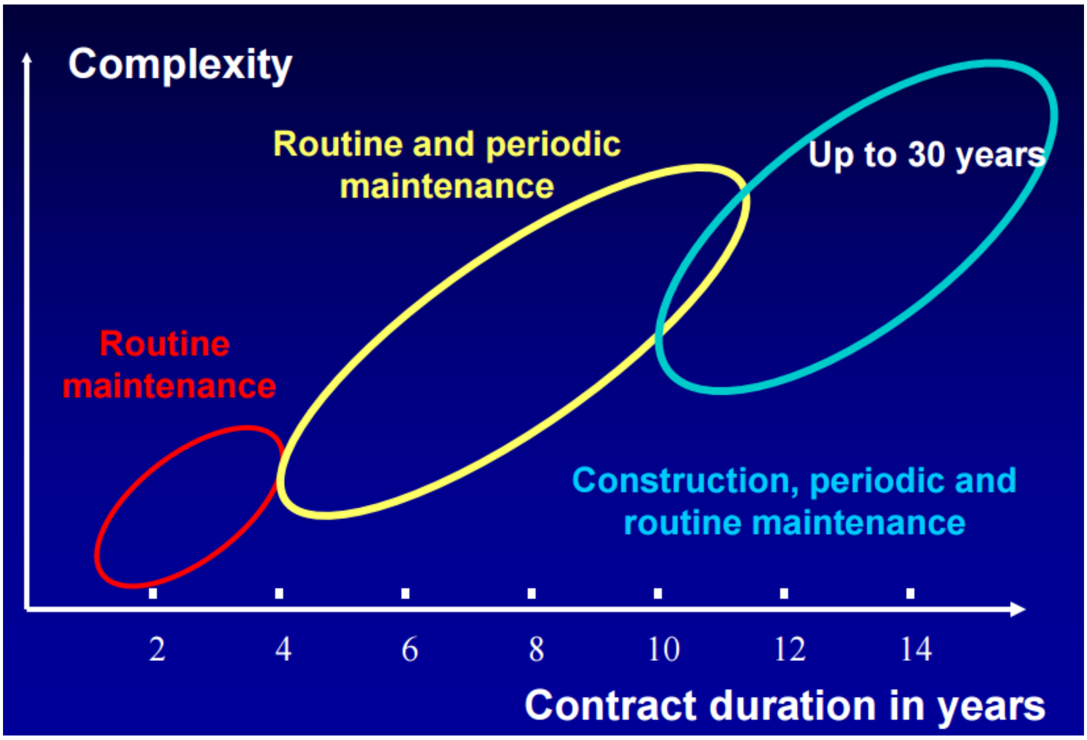


Figure 3-5 Relationship Between PBC Duration and Complexity in the Construction Sector (Zietlow, 2015)**.**

- The contracts have a (fixed)-based price, and they also include financial incentives for both parties that work on the basis of system usage for the customer, and system performance for the supplier (Jin and Wang, 2012). The value of this approach is to reduce uncertainty about the system through-life cost (through the fixed-base price nature), while ensuring better system performance through the supplier incentives mechanisms. This increase in the system performance can deal more effectively with the higher rates of system usage by the customer, as value-in-use increased (Cohen, 2012; Braamhaar, 2016).

The potential advantages of PBC can be summarised as follows (Berkowitz *et al.* 2005; Belz and Wuensche, 2007; Gardner, 2008; Toffel, 2008; Hypko *et al.*, 2010; Sultana *et al.*, 2013):

Advantages for the suppliers:

1. **Sustainable Competitive Advantage**: the supplier has the opportunity to analyse individual customers' needs in the long-term, and build/design personalised and cost-effective service-integrated offers that satisfy the customer needs and ensure the customer satisfaction, reinforcing their relationship and prevent out-suppliers from penetrating the customer-supplier relationship
2. **Lower Servicing Costs**: customer and supplier have a closer relationship which makes the suppliers more able to optimise and control outcome delivery. The increased control over the service delivery provides flexibility in reducing the cost of performance while achieving improved outputs.
3. **Opportunity for Innovation**: The close relationship between customer and supplier allows them to work alongside in order to boost innovation in the support solution while ensuring that customer needs and requirements are satisfied. Also, the supplier has easier access to the customer business and production processes, which facilitates not only the development of new products but also their continuous improvement. Moreover, the development of new products also promotes internal innovations in the supplier organisation.
4. **Improved Acquisition of Innovative Technologies**: In view of the cutting edge technologies, the customers not only lack the appropriate knowledge to maintain and operate but may also be uncertain about the actual benefits inherent in the offered innovations. The more uncertain the customers are about the actual benefits of highly innovative machinery or equipment, the more they will favour a performance based payment to the provider. Performance based contract constitutes a credible signal that the promised benefits will actually be realised and lessens the customer's uncertainty regarding potentially negative consequences.

5. **Improved Customer Loyalty**: the supplier is incentivised to maximise performance, effectiveness and efficiency of his service. This circumstance ensures an environment for continuous improvements, which may also benefit the customer. It forms the basis for satisfying the customer and enables the performance provider to profit from improved customer loyalty and long-term revenues.

Advantages for the customer:

1. **Increased Motivation to Provide High Quality Outcomes**: as the payment (and possible extra incentives) of the supplier is dependent on the achievement of pre-defined and measurable outcomes, it is of great interest for him to perform quality work. This includes the use of quality assets, knowledgeable operational personnel to perform the support tasks/activities, or even making enhancements on the system off the contract in order to improve performance, but that will increase the amount of return on its own investment.
2. **Cost Savings**: in traditional business models, the total cost of a system life-cycle was estimated as 30% for acquisition and 70% for the support services required, which gives a big margin for performing cost savings by optimising support delivery. Thus, by incentivising suppliers to optimise the support delivery, customers are more likely to profit from decreased through-life systems’ cost.
3. **Predictable Costs**: by paying a fixed price for a measurable specified outcome which is predictable, customers are able to make an accurate project of the total project cost.
4. **Reduced Investment Costs**: as the customer purchases a full performance of the system, he always try to make that price lower than if he had to buy multiple services and spares throughout the useful life of the system. Also, the costs incurred with machinery or equipment acquisition can be partially or totally transferred to the supplier.

In this context, the implicit assumption of PBC is that when the supplier is given the responsibility to deliver a certain performance level and freedom to design the product and production process accordingly, it will result in a high value solution with mutual advantages for both customer and supplier (Nowicki *et al.*, 2010; Holmbom *et al.*, 2014). Consequently, the utilisation of PBC became popular in industries where systems are expensive, complex, have long life-cycles and the consequences of system downtimes can be severe such as aerospace (e.g. aircrafts engines), defence (e.g. naval platforms, submarines) and healthcare (e.g. medical imaging devices) (Guajardo *et al.*, 2012).

PBC have developed over time in order to adjust to different industries' requirements, types of systems, and performance metrics. Thus, different PBC options are available such as:

- **Power-by-the-Hour**: applied typically in the aerospace domain; this concept has been introduced by Rolls-Royce where the supplier provides to the customer an integrated solution in the form of fixed price maintenance based on engine availability (Smith, 2013).
- **Contracting for Availability (CfA)**: widely applied across many industry sectors, CfA is a type of PBC where supplier is required to deliver outputs defined in terms of availability and reliability and is typically applied to systems such as ships, aircrafts and military vehicles (Hockley *et al.*, 2011). CfA is also known as performance-based logistics, and in particular in the US (Nowicki *et al.*, 2008);
- **Contracting for Capability (CfC)**: also applied across many industry sectors, CfC is an advanced type of PBC where the supplier is required to deliver a full capability of a system which includes operators, maintainers and all the support (Hockley *et al.*, 2011).

Different types of PBC can also be combined (perhaps with smaller scope and performance metrics) to establish a full support solution for a particular system. This approach gives more control to the customer over the support solutions. Figure 3-6 shows an example of four different types of PBC that are combined to ensure the full availability of a military aeroplane of the Australian Defence Force (Australian Department of Defence, 2009).

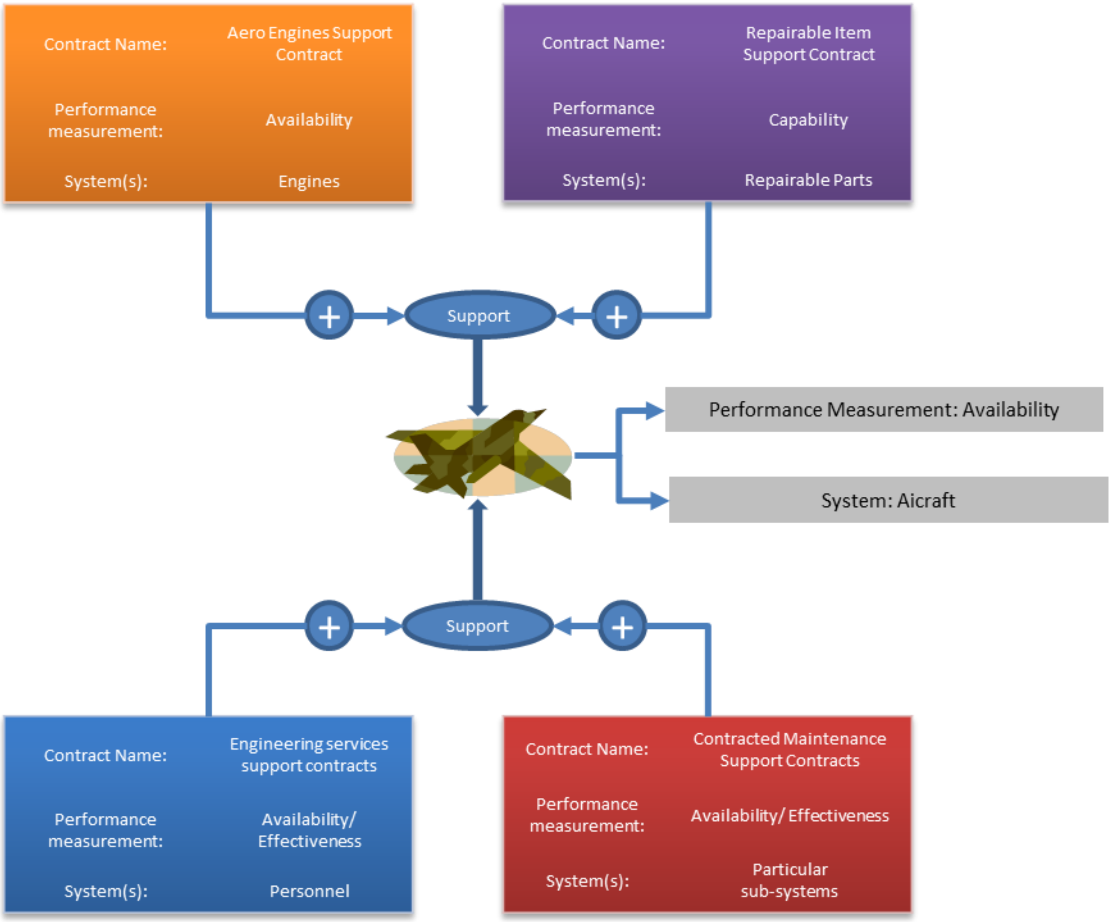


Figure 3-6 PBC to Support a Military Aircraft: A Case-Study from the Australian Military (Australian Department of Defence, 2009)**.**

These four contracts cover: contracted maintenance support contract (includes both scheduled and unscheduled maintenance as well as modification incorporation), repairable item support contract (for support of the avionics), aero engine support contract (to provide engineering support end engines), and engineering services support contract (which includes all types of engineering services required).

Up to this point, the evolution of the business models towards performance-based products has been discussed. Figure 3-7 summarises the topics discussed showing the business mechanism before the IPSS implementation, the business mechanism for the first IPSS approaches, and the business mechanisms for PBC. This business evolution represented not only a shift of responsibility from customer to supplier to achieve a certain level of system performance, but also an improvement of the support delivery strategies and processes. This improvement is mainly because the suppliers, which are often the manufacturers of the systems, are more skilled and knowledgeable to design and provide all the support activities that will maintain the system at the desired level of performance through each stage of its lifecycle from conception, through design, manufacture and operation life, to end of life disposal. These support activities are typically known as Through-life Engineering Services (TES) (Redding *et al.*, 2015).

Next section reviews TES in the context of PBC.

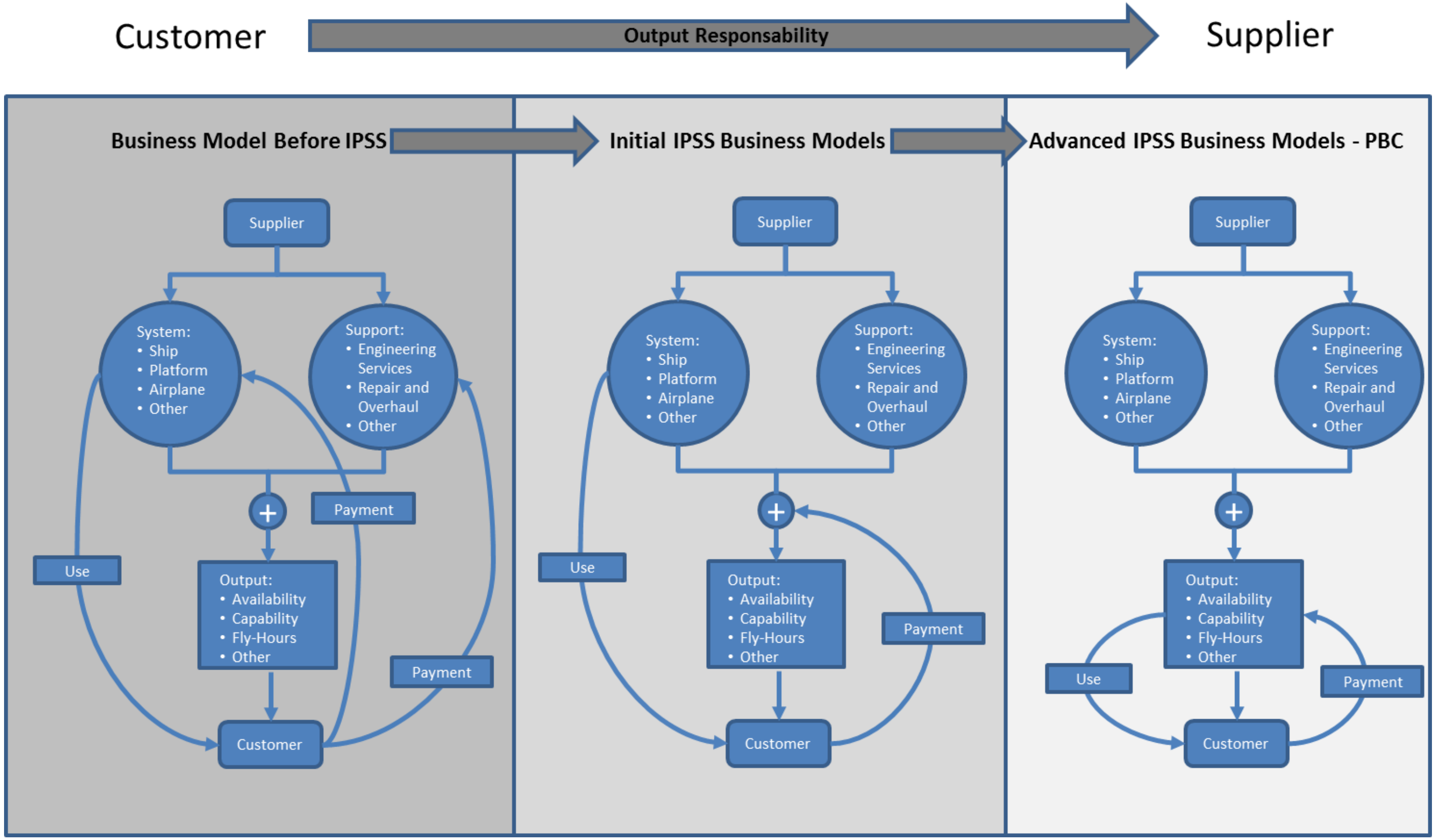


Figure 3-7 Evolution of Business Models in Large Industries Covering Complex Engineering Systems (Holmbom, Bergquist and Vanhatalo, 2014)**.**

3.3.2 Through-Life Engineering Services

Through-life engineering services (TES) are all the technical services that are necessary to guarantee the required and predictable performance of a complex engineering system through its expected operational life (Tasker *et al.*, 2014). They are the application of explicit and tacit “service knowledge” supported by monitoring, diagnostic, prognostic technologies and decision support systems whilst the product is in use (Redding *et al.*, 2015). TES focuses on those services that enable effective maintenance and feedback to products design in the context of IPSS, and they are the key elements to consider in the life-cycle management of the systems to reduce their overall cost (Redding, 2012; Tasker *et al.*, 2014).

Within the context of PBC, TES can be seen as the enablers to a collaborative provision of a holistic customer capability (the ways and means of capturing value which will vary over time) based on the assured performance metrics of the complex engineering systems (Tasker *et al.*, 2014).

The scope of TES is broad and therefore many types of TES are mentioned in literature such as:

- Routine maintenance, periodic maintenance, emergency services, improvements, and rehabilitation (American Association of State Highway and Transportation Officials, 2011);
- Maintenance activities, operational consultancy and overhaul data *(*Redding *et al.*, 2015);
- Software management (modifications, update, upgrade and downgrade) and data management (storage, acquisition, generation, transmission, distribution and presentation) (De Sordi *et al.*, 2016);
- Structural, mechanical, civil, instrumentation and electrical maintenance (Burdon and Bhalla, 2005).
- Spare parts provision, break-down response, insurance inspections, up-grades, scheduled and unscheduled maintenance activities, inspections based upon estimated wear and life interval (time based), reliability centred maintenance, diagnostics and emerging prognostics, condition based

maintenance, integrated vehicle health management, and real time data analysis and management (Redding *et al.*, 2015).

In the context of PBC, an interdisciplinary engineering approach has to be applied in order to design the TES integration throughout the contract lifetime, and estimate the associated costs and impact in the systems performance. Systems Engineering (SE) is the field of engineering that covers this purpose and it’s relation of PBC design and implementation is described in the next section.

3.4 Systems Engineering

Systems engineering (SE) is the branch of engineering concerned with the development, implementation, and use of large and complex systems (Badiru, 2005). It was first developed to manage the acquisition of complex systems such as those utilised in the defence, aerospace, and software development fields, during early development, and its scope was then extended (Tolk *et al.*, 2011) to enable enterprises to reinforce their competitiveness in global markets by delivering quality products on time and at an affordable cost (Chang *et al.*, 2008). The formal definition for SE varies between authors, but an embracing and consistent version defines SE as “a process that is comprised of a number of activities that will assist in the definition of the requirements for a system, transform these requirements into a system through design and development efforts, and provides for the operations and sustainment of the system in its operational environment” (Hall, 1962).

The scope of SE covers (Badiru, 2005):

- Designing integrated systems of people, technology, process, and methods;
- Developing performance modelling, measurement, and evaluation for systems;
- Developing and maintaining quality standards for industry and business;
- Applying production principles to pursue improvements in service organisations;
- Incorporating technology effectively into work processes;
- Developing cost mitigation, avoidance, or containment strategies;

- Improving overall productivity of integrated systems of people, materials, and processes;
- Recognizing and incorporate factors affecting performance of a composite system;
- Planning, organizing, scheduling, and controlling production and service projects;
- Organizing teams to improve efficiency and effectiveness of an organisation
- Installing technology to facilitate work flow;
- Enhancing information flow to facilitate smooth operations of systems;
- Coordinating materials and equipment for effective systems performance.

The objective of SE is to see that the system is designed, built, and operated so that it accomplishes its purpose safely in the most cost-effective way possible considering performance, cost, schedule, and risk (National Aeronautics and Space Administration, 2008), and it can be applied to any system regardless of the scope or scale of the project.

The application of SE covers three phases: development, function analysis & design, and integration (Defense Acquisition University, 2001; Dahmann and Kelley, 2009).

The development phase consists in the design/planning of a systematic and adaptive process for implementation (Sheard and Lake, 1998; Defense Acquisition University, 2001), tailored to the specific area in which it is expected to be applied, and create an engineer profile to define the purposes, qualities, and product/system development life-cycles (Saenz, 2005; Kopach-Konrad *et al.*, 2007). This profile must include (Tasker *et al.*, 2014; Boord and Hoffman, 2016):

- Framing the system, subsystems and components under study and well-define goals and expectations;
- Define system and sub-systems boundary;
- Performance objectives or measures of effectiveness;
- A concept of operations including the way the system is intended to operate, and the way the design, test, manufacturing, and deployment process is intended to operate;

- Requirements definitions that include functional, performance, and interface requirements;
- Defined constraints that include itemized cost, schedule, policy, logistics, human factors, and technology;
- Risk assessments that are itemized and time dependent with evolving mitigation plan;
- The program's milestone objectives and lifecycle reviews.

The functional analysis & design phase has the primary objective of defining and measuring the interrelationships between the different elements within the system, in order to generate information for decision-making. This process typically encompasses the design and development of engineering test models (e.g. computer-aided models (Kossiakoff *et al.*, 2011; Briscoe *et al.*, 2012)) to build a function of the systems and its elements in order to design and evaluate solutions (Eriksson *et al.*, 2006).

The integration phase covers the actual deployment of a designed solution, covering the support through engineering activities over the product life-cycle (Defense Acquisition University, 2001).

A summary of the SE application process is presented in Figure 3-8, and was built based on the literature reviewed.

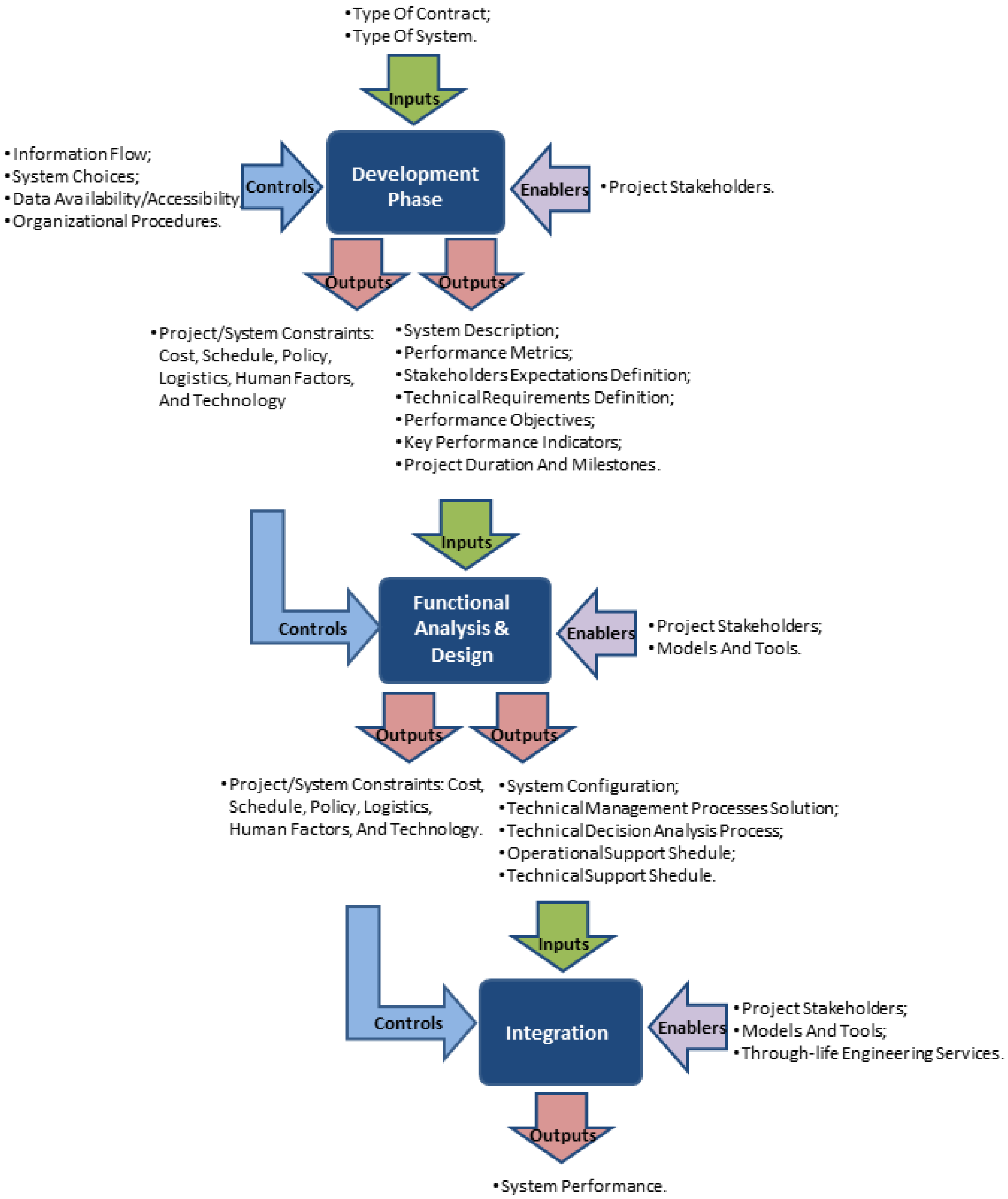


Figure 3-8 Systems Engineering Application Process (Defense Acquisition University, 2001)**.**

SE is commonly associated to project management activities. While systems engineers integrate and balance the work of numerous engineering and technical disciplines from the initial system design to the production and fielding of the final product, the project managers plan, organise, direct, coordinate, control and approve the activities of all aspects of programs as it proceeds through the life-cycle phases (USA Department of Defence, 2013).

Therefore, in the context of PBC, project managers apply SE to manage project costs and timescales, and to design and implement a through-life strategy of TES integration to satisfy the customer needs (Frezzini *et al*., 2010). The application of SE to assist in project management decision-making is generally referred as systems engineering management (SEM) (Defense Acquisition University, 2001). Figure 3-9 shows the activities that support SEM in the context of PBC highlighting the underpinning concepts: modelling, data assessment, trade-off analysis and optimisation.

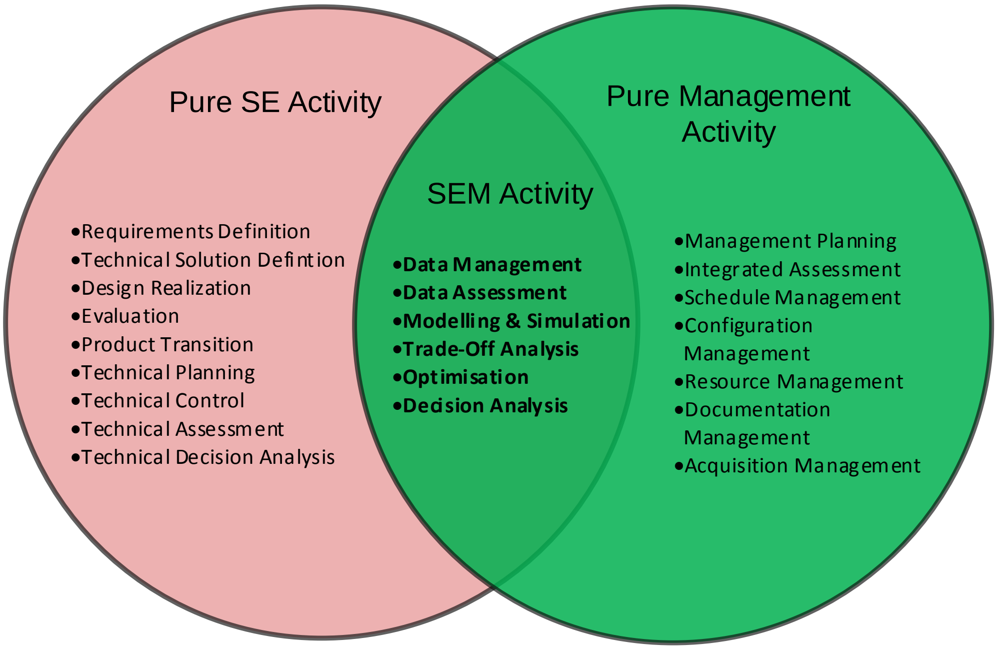


Figure 3-9 SEM in the Context of PBC (National Aeronautics and Space Administration, 2008)**.**

The concepts that make the SEM activities are explored in the next sub-sections.

3.4.1 Trade-Off Analysis

The art of SE takes the form of developing the right set of design alternatives and options and then developing the necessary trade-off studies that will help to identify the combinations/alternatives from which an investment decision(s) can be made, to achieve an optimised or balanced design while accounting for life-cycle considerations (Boord and Hoffman, 2016). Trade-off studies are a formal decision making methodology used to make choices and resolve conflicts during the systems engineering process and they can be used in all the life cycle phases (Wasson, 2005). It defines a structured evaluation and comparison of a range of potential solutions against defined objectives and constraints in order to deliver a cost effective solution according to the characteristics of the project (The National Archives, 2008). A general trade-off analysis process is illustrated in Figure 3-10.

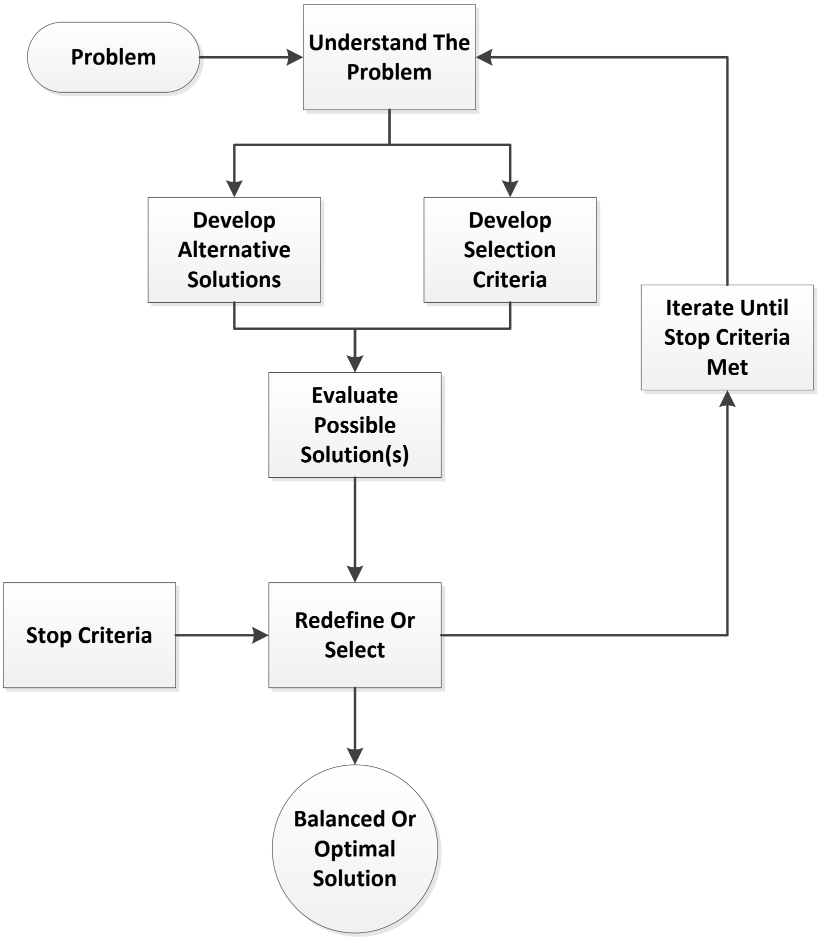


Figure 3-10 Trade-Off Analysis Process (Yoe, C., 2002)**.**

PBC design requires a great effort in trade-off analysis, considering system performance, contract cost and timescales (Defence Engineering Group, 2002).

3.4.2 Modelling and Simulation

An important concept underpinning SEM activities is modelling (Oke, 2005). A model is a simplified representation of an actual phenomenon, such as actual systems (e.g. real-world systems) or process. The phenomenon/system is represented by the model in order to explain, control and predict its response/behaviour under certain conditions (Heckman and Leamer, 2007). In SEM, the development of models is always associated to the need of performing quantitative measurements of the systems (e.g. cost, performance, etc.) to perform trade-off analysis and guide decision-making. The use of models to support SEM in trade-off analysis is called model-based SEM (Oliver, 1996; Nassar and Austin, 2013).

Figure 3-11 represents the basic structure of a model which consists of: inputs (e.g. assumptions, constraints, user requirements, historical data, setup parameters, etc.), mechanisms, which are attributes of the model such as equations and diagrams, and outputs, which is the predictable response of the system, through modelling analysis, to particular inputs (Lee *et al.*, 2014).

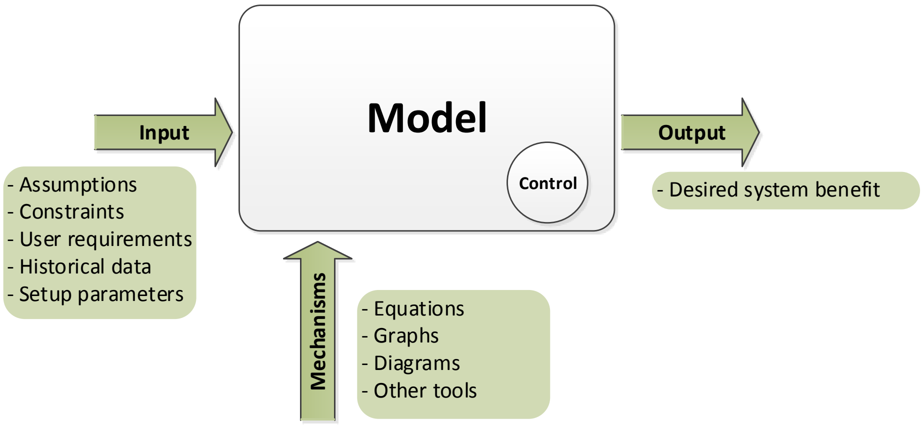


Figure 3-11 Model Structure

A model can be expressed in multiple forms as graphs, mathematical equations, maquettes, or verbal orientations. The most popular models applied in SEM are the mathematical models. With mathematical models the systems' elements are represented by mathematical symbols and equations. These equations will allow measuring the system performance through the articulation of the effort in the different variables. They articulate abstractions, thereby enabling us to distinguish between relevant and irrelevant features of the real system (Oke, 2005).

The development of a model for SEM can be summarised in six fundamental steps conducted iteratively in the following order (Barbour and Krahn, 2004; Kopach-Konrad *et al.*, 2007; Kim *et al.*, 2015):

1. Defining system purpose and scope, specifying required functions and resource types, defining system boundaries, and developing relevant performance measures along with desired performance thresholds.
2. Specifying, collecting, and developing required data through data collection methods.
3. Defining a theoretical model. This involves defining the purpose of the model and generate an abstractive solution to define the relationships inside the system that will be modelled;
4. Selecting the modelling technique(s) and developing the actual model;
5. Validating the model with a real-life case study;
6. Using the model to learn about system behaviour to find the best design alternative (e.g. trade-off analysis). The engineer often develops appropriate experiments for the studying the model and analysing the results.

The concept of modelling is typically associated to simulation. Simulation is a process that uses an existing model to predict the performance of a system under a specific set of inputs (Robinson, 2004). Generally, a model intended for a simulation study is a mathematical model developed with the help of simulation software, and called simulation model (Maria, 1997). Simulation modelling is typically applied in SEM to facilitate the evaluation and assessment of different solutions through the model implementation (Maria, 1997). Although original mathematical models are typically static (e.g. time invariant), they can be implemented as a simulation models to see their evolution over time (Biemer and Sage, 2009). Simulation models can be used to obtain, display and evaluate operationally relevant data in agile contexts by executing models and producing numerical insight into the behaviour of complex systems (Tolk, Adams and Keating, 2011). It is actually the preferred method of choice in SE to guide decision-making (Carley *et al.*, 1996).

Developing a simulation model requires a systematic process to be defined which involves, among other things, the selection of the appropriate software and programming language (Maria, 1997). A typical process for developing a simulation model is called “spiral model” (Boehm, 1988; Forsberg and Mooz, 1992) and consists in the sequence of steps presented in Figure 3-12.

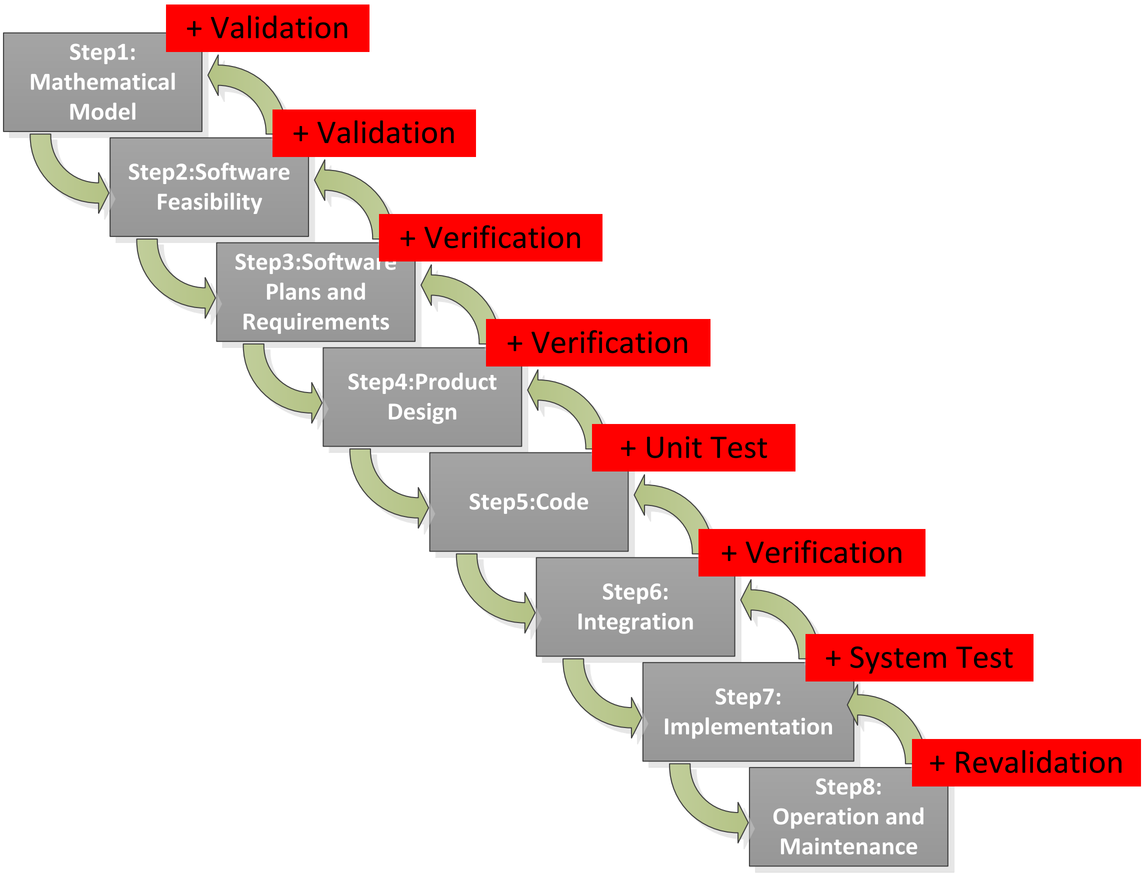


Figure 3-12 Spiral Model for Software Development (Boehm, 1988; Forsberg and Mooz, 1992)**.**

At each step of the spiral model presented in Figure 3-12, the following questions must be answered and verified (Royce, 1987):

- Step 1: Is the mathematical model fully developed and validated?
- Step 2: Is it feasible to implement the mathematical model in software?

- Step 3: Which is the software selected for implementation and code selected for programming and what are their requirements?
- Step 4: Is the strategy for implementing the mathematical model in the software established and validated?
- Step 5: Is the code developed by block and each block tested using unit tests?
- Step 6: Are all the code' blocks integrated/linked properly in order to represent the whole system?
- Step 7: Is the simulation software tested?
- Step 8: Have the enough number of tests been performed and all possible correction required been addressed?

Moreover, with respect to software tools/platforms that can be used to implement mathematical models as simulation models, different options can be found in literature such as: MS Excel, Matlab, Witness, AnyLogic, Visual Studio, Arena, Simio, Extend and Network (Cerqueira and Poppi, 1996; Casas, 2013). Among those, MS excel and Visual Studio are open source and are relatively easy to implement, and are the most used (Cogswell, 2003; Li and Wu, 2004).

3.4.3 Modelling Approaches for Systems Engineering Management

Many techniques were found in literature to develop models to support SEM in TES design and integration. The criteria to search for relevant literature was to find models or frameworks that aimed to support the design and integration of TES related issues such as logistics, maintenance, manpower, and to provide a short, medium or long term forecasting of performance metrics such as cost and availability of complex systems.

Six techniques distinguished from the others because of their increasingly preference in recent papers, and the relevance recognised by different authors, which are: (Multiple) Regression Analysis, Mathematical Programming, Bayesian Theory, Fuzzy Maps and Neural Networks, and Simulation Modelling. Table 3-1 summarises the assessment made to each of those techniques based on a detailed review of twenty-four references where those techniques were applied to develop forecasting models. The table includes the TES context covered in each reference, the performance metric(s) considered in the forecasting process, and the advantages and disadvantages recognised to each technique by each author(s).

Table 3-1 Literature Assessment for SEM: Modelling Techniques

	TES Context	Performance Metric(s)	Advantages	Disadvantages	Ref.
Regression and Multiple Regression	Logistics Manpower	Productivity	Able to handle big data sets Able to handle many variables Can produce better estimates than neural networks method	The quality of the estimates depend on the degree of linear relationship between the variables	(Al-Zwainy *et al.*, 2013)
	Electric Services Maintenance	Power Capacity	Able to handle linear and non-linear systems Highly accurate forecasts (can reach up to 90% in medium-term forecasting – 10+ years) Possible to produce generic models Simple input information required	Requires some complex mathematical analysis	(Abu-Shikhah *et al.*, 2011)
	Consultancy	Cost	Highly accurate forecasts Able to assess interrelationships between multiple variables Outperforms comparison-based methods	Depends on historical information	(Ismail *et al.*, 2009)
	Technical Services	Any Performance Metric	Simple and with good performance ratios Possible to estimate continuous levels of performance	Depends on historical information	(Gámiz and Miranda, 2010)
Neural Networks	General Application	General Application	Able to handle non-linear systems Able to assess relationships between multiple variables	Complex Requires good mathematical background Time consuming	(Errachdi *et al.*, 2011)
	Energy Services	Power Capacity	Applicable to short and long term forecasting (e.g. 20 years ahead) Able to assess relationships between multiple variables Flexible	Time consuming Complex Previous application to forecasting models produced results not very convincing or with no sufficient validation to demonstrate value	(Hippert *et al.*, 2001)
	Energy Services	Power Capacity	Suitable for mid-long term forecasting Produce results with little input data Produces results with level of accuracy comparable to other methods such as fuzzy-logic and regression models	Complexity on the development and interpretation of the results	(Nezzar *et al.*, 2016)
	Operation Maintenance Services	Power Capacity	Able to handle non-linear relationship between variables Able to handle many variables	Computationally intensive Results are based on statistical analysis	(Chang *et al.*, 2017)
Fuzzy Maps	Construction Services	Productivity	Determine relationships between quantitative and qualitative variables Able to assess relationships between multiple variables Low complexity for implementation and results interpretation	Hard the find/produce adequate data for analysis Depend on appropriate historical data to produce results Needs qualitative and quantitative input	(Elwakil *et al.*, 2015)
	Supply Chain Management	Cost	Mitigates uncertainty issues Able to assess relationships between multiple variables Models ambiguous and imprecise data	Needs qualitative and quantitative input	(Erginel and Gecer, 2016)
	Buildings Maintenance Actions	Durability Cost	Model multiple variables Applicable to problems where the relationships between variables is complex Capable to deal with uncertainty	Needs qualitative and quantitative input Requires large input data sets	(Vieira *et al.*, 2015)
	Power Plant Services	Cost	Simple implementation Deals with uncertainty issues	Needs qualitative and quantitative input Typically requires input from experts together with historical data	(Islam and Nepal, 2016)
Bayesian Theory	Maintenance Services	Multi Performance Parameters Cost Remaining Useful Life	Able to interpret and display data in various formats Produces highly accurate estimates	Some complexity in the implementation Requires statistical knowledge for implementation	(Zhao *et al.*, 2013)
	Power Plant Services	Cost	Able to address complex and uncertain dependencies/relationships between variables Can produce results even with	Is based on probabilistic approaches rather than exact functions Subjective results	(Islam and Nepal, 2016)

			inadequate and poor number of data sets Easier than neural networks method in terms of implementation		
	Inventory Management Maintenance	Availability Cost	Addresses uncertainty issues Can produce estimates based on judgmental input only	Outputs are based on statistical analysis and likelihood functions	(Bergman *et al.*, 2017)
	Maintenance	Availability	Able to assess relationships between multiple variables Deal with uncertainty issues Works in limited data scenarios Combines real data with expert judgement Possible to implement as a simulation model (e.g. using Monte-Carlo simulation) Relatively simple application Recommended for limited data scenarios Outputs are more accurate than expert-opinion based estimates or traditional statistical forecasting methods	Outputs are based in statistical analysis which gives some subjectivity to the results	(Wang *et al.*, 2017)
Mathematical Programming	Maintenance Services	Cost	Accurate Easy Implemented As A Simulation Model (E.G. Using Monte-Carlo Simulation) Suitable For Trade-Off Analysis	Complex Static Requires A Lot Of Information To Produce Estimates (E.G. Cost Of Each Activity)	(Chattopadhyay, 2004)
	General Support Services In Manufacturing	Multi Performance Parameters	Possible to apply to linear and non-linear systems Possible to predict multiple performance metrics Accurate predictions	Requires a lot of information to produce estimates	(Singh and Yadav, 2015)
	Supply Chain Management	Availability Cost	Capacity of handling complex problem Feasible computational times to calculate solutions Objective and exact solutions	Big amount of data required	(Pires and Frazzon, 2016)
	Maintenance	Production Availability Cost	Suitable for medium-term forecast models Suitable for complex problems Suitable to perform optimisation analysis	Requires specific data Requires big amount of information	(Amaran *et al.*, 2016)
Simulation	Maintenance	Availability	Able to reproduce and solve real-word problems Assesses and reproduces the dynamics of the real-world system Able to try alternatives	Requires advanced mathematical and computer skills	(Krishnan, 1992)
	Maintenance	Availability Cost Time	Enable to assess the current and future state of the system' components Suitable to be applied in the planning phase	Computer intensive – requires advanced software knowledge Events are often defined based on probability	(Denkena *et al.*, 2012)
	Job Shop Scheduling	Time Availability Capability	Able to run mathematical algorithms and assess different performance metrics Able to be implemented as an artificial knowledge base Able to try alternatives	Requires advanced level of knowledge of software, mathematics and practical processes, for implementation Requires high amount of data for analysis	(Abdallah, 1995)
	Operations Management	Speed Cost Quality Others	Suitable for supporting business analysis and re-engineering of processes Suitable for dynamic, iterative and complicated systems Able to communicate process	Requires strong software knowledge for implementation Difficult to implement when the method of carrying out tasks is evolving over time Is built upon a number of assumption and probability parameters	(Greasley and Barlow, 1998)

The literature definition of each technique was also reviewed and can be presented as such:

- **Regression analysis**: is a quantitative modelling approach which is used when the study involves the analysis of several variables. The method generates an equation to describe the statistical relationship between the variables (Alexopoulos, 2010).

- **Neural networks**: is normally applied as a computer-based system made of a number of simple and highly interconnected processing elements which assess information based on their dynamic state response to external inputs (Caudill, 1987). It is inspired by the way biological nervous systems such as the brain process information (Stergiou and Siganos, 1997), and is usually employed in statistics, cognitive psychology, and artificial intelligence models. It works very well in systems where the relationship between variables is vaguely understood or difficult to describe adequately.
- **Fuzzy maps**: Fuzzy cognitive maps are fuzzy-graph structures for representing causal relationships between the system' elements (Kosko, 1986). This technique applies expert judgement to define qualitative rules about the behaviour of the system, translating them in quantifiable values and applying a logical decision mechanism to produce quantitative outputs. It is commonly applied to model complex system elements such as: fault detection, decision-making, business, management, prediction, text categorisation, industrial analysis, and system control (Elomda *et al.*, 2015).
- **Bayesian theory**: is a mathematical technique for performing inference or reasoning, using probability (Olshausen, 2004). Its defining property is the interpretation of probabilities as degrees of belief in propositions about the state of the world relative to an inquiring subject (Ortega, no date).
- **Mathematical programming**: this technique aims to represent a system by means of mathematical equations. The different elements of the system are represented by the variables of the equations. Feasible solutions for these equations represent possible configurations to the system that satisfy the set of constraints that have been previously imposed (Bradley *et al.*, 1977).
- **Simulation**: simulation modelling is a combination of mathematical modelling and computer simulation. The models can be mathematical intensive (e.g. built with mathematical techniques such as fuzzy maps and Bayesian theory) and the simulation environment is implemented afterwards to evaluate different solutions (Parry, 1985), or they can be purely simulation focused and

the mathematical elements (e.g. equations, probability distributions) are included afterwards to define the behaviour of the system. Good examples of simulation focused techniques are agent based, discrete event, system dynamics and dynamic systems (Karnon *et al.*, 2012; Shafiei *et al.*, 2013).

Based on what was learnt from the literature review performed, a critical assessment of each modelling technique was elaborated and is presented in Table 3-2. This table aims to guide the selection of the appropriate technique to develop a forecasting model to support decision-making in SEM. Seven metrics were considered in this assessment, and were defined based on key issues for data models (West, 2011) and in key models' features (Tehrani *et al.*, 2010), and are described as such:

- **Flexibility (F)**: is the technique able to adapt to changes in the behaviour of the system or in the outputs required?
- **Execution time (ET)**: how long does it take to be implemented and to run and obtain solutions?
- **Implementation complexity (IC)**: does it require many/sophisticated resources to be implemented (e.g. Software, knowledge, etc.), or a strong mathematical background?
- **Accuracy (A)**: how accurate are the model' outputs likely to be?
- **Outputs comprehensively (OC)**: does the method produce comprehensive outputs?
- **Amount of input data required (ADR)**: does it need a lot of input information to produce results?
- **Complexity of input data required (CDR)**: is the input information required difficult to be obtained?

Each metric was evaluated based on a scale of low, medium and high.

Table 3-2 Strengths and Limitations of each Modelling Technique

	F	ET	A	IC	OC	ADR	CDR
Regression analysis	High	Low	High	Medium	High	Medium	Low
Neural networks	Medium	High	High	Medium	Medium	Medium	Medium
Fuzzy maps	Medium	Low	Medium	Medium	High	Medium	High
Bayesian theory	Medium	Medium	Medium	Medium	Medium	Low	Low
Mathematical programming	Low	Medium	High	High	High	High	High
Simulation	High	Low/ Medium	Medium	High	High	Medium/ High	High

One important aspect that impacts on the selection of the modelling technique is the type of decision required which in engineering management can be classified as strategic, tactical and operational (White, 2009). Strategic level decisions cover the design of the whole logistics network of the system, including prescribing facility locations, production technologies and plant capacities. Tactical decision cover shorter range planning for particular parts of the system and includes material flow management policies, including production levels at all plants, assembly policy, inventory levels, and lot sizes. Operational level decisions link strategic and tactical goals in the planning of decision-making to assure in-time delivery of final products to customers (Schmidt and Wilhelm, 2000). Therefore, from the strategic to the operational level, the complexity of the decisions may increase due to the increased level of technical detail, but also they become less abstract. Thus, the availability of historical information is more likely to be higher and more detailed in operational level scenarios. Thus, depending on the level of decision, the following requirements are normally expected from the models (Schmidt and Wilhelm, 2000):

- Any model applicable to strategic level must provide capacity to forecast the performance of the system based on observed precedence relationships among different attributes;

- Any model assisting both strategic and tactical decisions must be flexible in order to adapt to any design change of the product required;
- Any model assisting operational decision must be detailed and very accurate, as it has a direct impact on the execution of the operations.

Based on these results and conclusions, each technique was critically assessed in terms of its appropriateness according to each type of management decision required. The results of this assessment are presented in Figure 3-13. It has been recognised that regression analysis and simulation are appropriate to any level of decision whereas mathematical programming is more appropriate to operational decisions due to the high accuracy of the technique and level of detailed information required. Moreover, neural networks, fuzzy maps and Bayesian models are appropriate to assist tactical and strategic level decisions, where the historical information available is typically limited and the nature of the decisions is more abstract, thus requiring less accuracy.

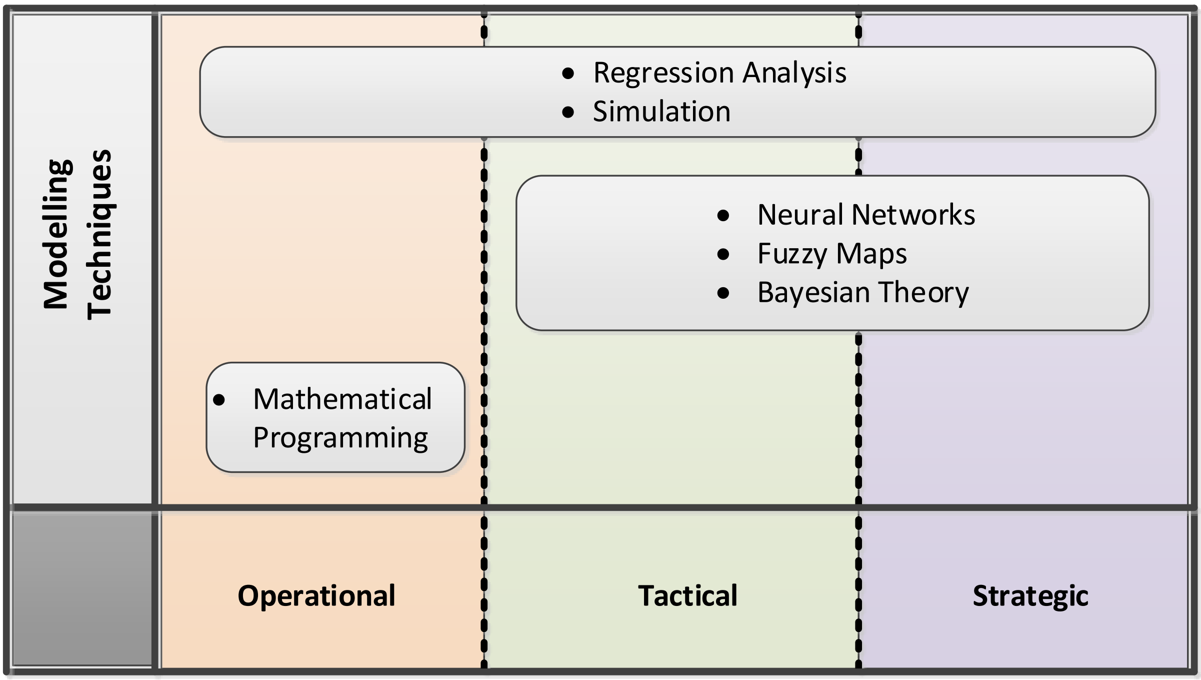


Figure 3-13 Guidance for the Selection of the Appropriate Modelling Technique According the Complexity of the Decision Required

It is important to refer that, despite the large number of alternatives found in literature, the most popular forecasting models use regression analysis techniques (Haida and Muto, 1994; Hippert *et al.*, 2001; Ramanathan *et al.*, 2001). In particular, this technique is normally combined with simulation to allow performing dynamic experiments of the system, through the model, and anchor the decisions at various levels of management within the organisations (Barjis, 2011).

3.4.4 Optimisation

Optimisation is the process of finding the best possible solution to a given problem, considering a set of objectives and a set of constraints (Zaknich, 2005). For example, a surgeon aiming at delivering the operation that solves the patient's problem at the best, with the smallest amount of collateral effects or, a professor trying the most effective way to explain concepts to the students (Zemella and Faraguna, 2014). Optimisation is normally performed upon a given model that implicitly translates the feasible and non-feasible solutions space of the problem as illustrated in Figure 3-14. The process consists in performing a trade-off analysis between the different independent variables of the model until achieving the output solution that is the closest to the objective solution.

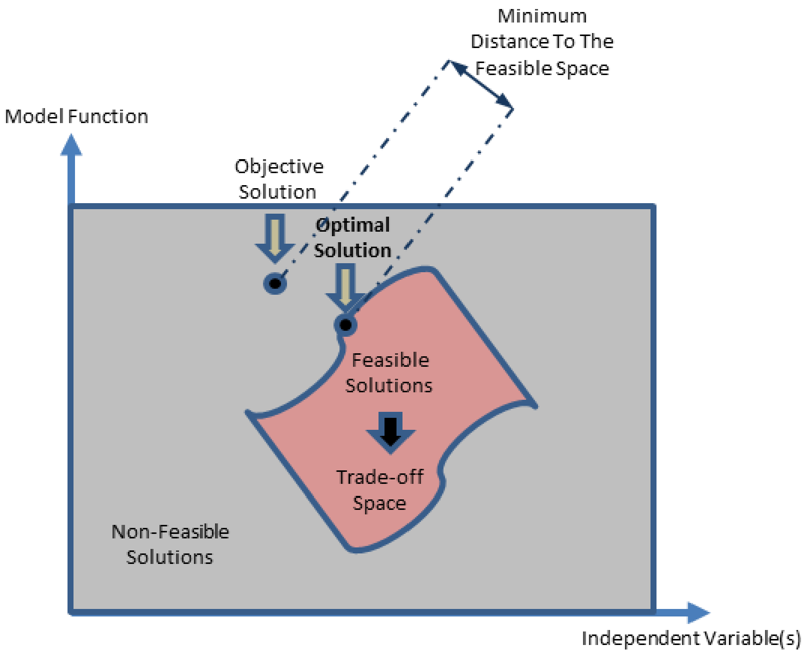


Figure 3-14 The Design of Optimal Solutions

Optimisation can be applied throughout the whole product life cycle from design, integration and disposal. When applied to the design of PBC, the process is called design optimisation (Martins and Lambe, 2013). Design optimisation is a powerful tool widely utilised by engineers to produce better performing, more reliable and cost-effective products (Kanarachos *et al.*, 2017).

The traditional optimisation problem aims to find the optimal value of a single variable (single-objective optimisation). However, in most real-world optimisation problems, there is a need to find the optimal balance between multiple variables, which are frequently in conflict with each other; this process is called multi-objective optimisation (Minku *et al.*, 2016; Punnathanam and Kotecha, 2017). There are multiple techniques to solve multi-objective optimisation problems, such as: (1) Genetic Algorithms (GA), (2) Multi-Objective Differential Evolution, (3) Multi-Objective Grey Wolf Optimiser (Mirjalili *et al.*, 2016), (4) Multi-Objective Particle Swarm Optimisation (Marini and Walczak, 2015) and (5) Multi-Objective Artificial Bee Colony (Xiang *et al.*, 2015).

Among those, GA seem to be the most powerful and they are widely applied as they present a better ratio between complexity of the algorithm and computational time required to find the optimal solution than the other approaches (Punnathanam and Kotecha, 2017). GA is an evolutionary optimisation approach which emerged as an alternative to traditional optimisation methods. GA are most appropriate for complex non-linear models where identifying the optimal solution is a difficult task. It may be possible to use GA techniques to consider problems which may not be modelled as accurately using other approaches. Therefore, GA appears to be a potentially useful and powerful approach to develop an optimisation model (Mardle and Pascoe, 1999).

3.5 Research Gaps in the Design and Implementation of Performance-Based Contracts

IPSS approach is seen as the key to the industrial success in the 21st century (Guidat *et al.*, 2014), and in particular through PBC. However, despite subjective evidences suggest that PBC (e.g. CfA) foster innovation in customer-supplier relationship (Sumo *et al.*, 2016), the understanding of the underlying mechanisms is limited to date (Sumo *et al.*, 2016). Although the number of studies in PBC is increasing, there are not many studies that examine and present solutions to the fundamental theoretical issues arising from the delivery of an outcome-based contract (Ng, Maull and Yip, 2009) such as: supplier selection and activity transfer (Lazzarotto *et al.*, 2014), improving bidding competitiveness through suppliers management mechanisms (Wacker *et al.*, 2016), alignment of customer and supplier(s) goals and incentives, risk and reward sharing (Selviaridis and Norrman, 2015), and understanding servitisation processes and the technologies and practices that underpin the implementation of servitised solutions (Baines and Lightfoot, 2013). In particular, research into the actual design of effective PBC solutions remains limited (Ng and Nudurupati, 2010; Hypko *et al.*, 2010), and no literature was identified that discusses the challenges related to cost and availability estimates during the bidding process of CfA, as identified in Section 4.5. The bidding phase is the last phase of the contracts design (Jackson, 2004), and it is where the competing suppliers communicate their service specifications and price of the bid to the customer who then evaluates the bids (Kreye *et al.*, 2013). In particular, there is no highlight about the challenges experienced by the suppliers in improving the competitiveness of their support solutions by optimising the investment in the different attributes that impact the through-life availability of the systems (e.g. through-life engineering services (Johnstone *et al.*, 2009)). Literature is rather more focused on developing mechanisms and good practices to identify and reduce uncertainty in the estimates (Erkoyuncu *et al.*, 2013; Parekh *et al.*, 2014).

The design and delivery of PBC links to the use of SE to manage (e.g. plan/forecast/predict) the effort in different TES that impact the system performance through the life cycle. Although SE is a discipline with many years of research, the concept of TES management knowledge has only started getting more attention quite recently (Masood *et al.*, 2014), and a lot of research gaps are recognised in particular at the bidding stage of PBC such as:

- The successful implementation of PBC requires robust estimation of costs at the early stage which is typically challenging as it is a very new concept and project managers lack tools and experience to do so (Sultana *et al.*, 2012);
- The models presented in literature do not present solutions for how to use/re-use service engineering knowledge in the design of new products. There is a lack of effective methodologies to capture service engineering knowledge gained from previous projects and then reuse by feedback to conceptual and

detailed product-design stages so that new/revised product design incorporates the new learning (Masood *et al.*, 2014);

- There is a lack of mechanisms for effective long-term planning of maintenance actions (Roy *et al.*, 2013);
- There is a lack of mechanisms and processes to build cost and availability estimates in limited data availability scenarios;
- There is poor control over uncertainties and project risks, lack of quality measurement techniques for services, and poor management of personnel training, qualification, and availability (Karsten, 2013; Lindstrom *et al.*, 2013);
- There is a lack of mechanisms to: reduce operation cost, manage operators' knowledge, effectively collect and analyse data, evaluate life time of assets, produce accurate preventions, and perform safe, consist and efficient maintenance (Shinjuku and Hino, 2013);
- Some key SE practices known to be effective are not consistently applied across all phases of the program life cycle (Wasson, 2012).
- Insufficient SE is applied early in the program life cycle, compromising the foundation for initial requirements and architecture development (Wasson, 2012);
- Requirements are not always well-managed, including the effective translation from capabilities statements into executable requirements to achieve successful acquisition programs (Wasson, 2012);
- The quantity and quality of systems engineering expertise is typically insufficient to meet the demands of PBC design and integration (Wasson, 2012);
- Collaborative environments, including SE tools, are inadequate to effectively execute SE at the joint capability of system levels (Wasson, 2012);
- Program success is often recognised as a function of how much of the program resources are invested in technical management activities. Typically, programs that spent little on technical management had a higher probability of cost overruns than those programs that spent more. However, due to lack of mechanisms and tools to assess the right investment in technical management activities, a lot of programs fail to adequately invest in technical

> management which result in failed, poorly-engineered, over-budget and inoperable systems (USA Department of Defense, 2013).

In addition, there are also research gaps across product life-cycle integration including the use of TES knowledge in reducing product life-cycle cost. The knowledge of previous service experience could help in identifying and reducing product life-cycle cost, for example, by prioritising risk mitigation imposed on those product commodities, which exhibit high costs. Currently, risks are identified based upon knowledge gathered from groups of experts. This means the decisions are dependent upon expert knowledge of the group rather than a valid tangible link to previous knowledge across the projects of similar nature. Establishing such a link to the knowledge of previous projects is challenging due to integration gaps (i.e. missing feedback loops). If the engineering risks are identified based upon previous TES knowledge, it could also lead to enhanced reliability (Masood *et al.*, 2014).

In summary, while firms engage in a complex and time-consuming process to bid and agree upon performance targets in PBC, they often fail in achieving excellence in all performance targets (Mouzas, 2016) due to difficulties in designing and implementing effective solutions. Also, current literature offers limited insights into strategic decision-making processes at the competitive bidding stage of the contracts (e.g. cost and availability estimation and trade-off) (Laryea and Hughes, 2011), and more effort has to be done to develop objective and effective solutions to support/improve industry in their current practices. Under these lines, some of the proposed research directions consist of: (1) development of a representation of the TES knowledge that can be used by design engineers (e.g. bid engineers) to improve product design; (2) identification of TES knowledge required by product-design engineers at conceptual and detailed design stages and (3) development of an effective methodology to reuse TES knowledge for product-design and service-engineering stages (Masood *et al.*, 2014). Achieving these targets would help mitigating the complexity of PBC in particular at the bidding stage, and achieving evidences that PBC can actually help improve performance (e.g. availability, capability) of the systems at reduced cost (Guajardo *et al.*, 2012).

3.6 Summary

This literature review presented the definitions and the linkage between the concepts that make the scope of this research.

It started by introducing the growth of the IPSS business approach, defining its main target as the development of products that include (physical) system(s) and TES. Different types of IPSS solutions were identified, emphasising PBC and in particular CfA. SE was then identified as the field of engineering that supports the design and development of PBC solutions, typically with the development of models to enable/facilitate the design and implementation of TES throughout the contracts' life-cycle. SE is also applied to support management level decisions, under the concept of SEM. Project Managers typically apply SEM at the design stage of the contracts (e.g. bidding phase) to enable/facilitate decision-making, using models to estimate the contracts cost and the systems performance (e.g. availability).

Figure 3-15 presents a summary of the scope of the literature review performed, highlighting the topics that underpinned the development of this research and their connections.

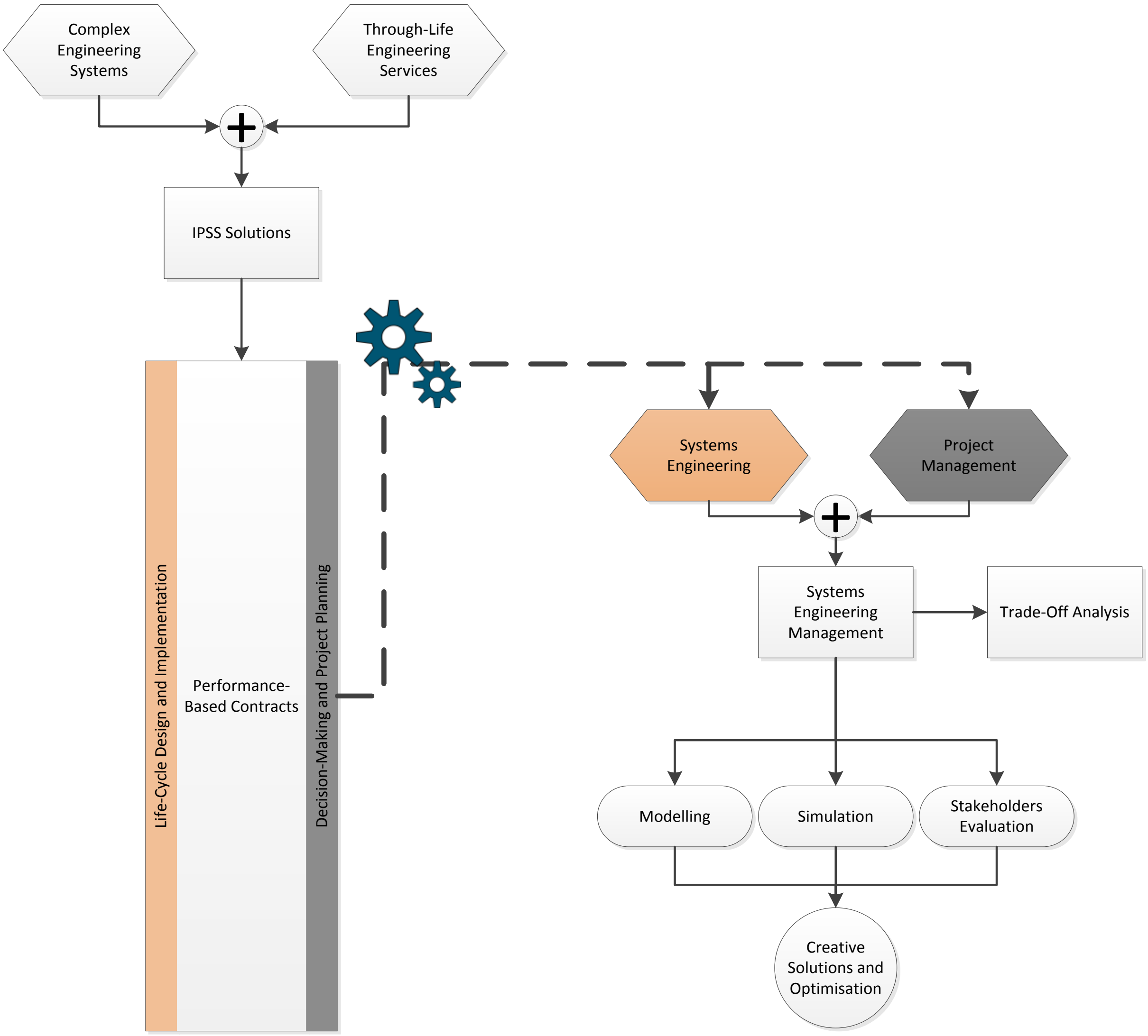


Figure 3-15 Literature Review Scope

The next chapter presents the results from the industry interaction, identifying the current process, challenges, and identified opportunities for improvement in the design of PBC (e.g. CfA) solutions, and in particular during the bidding stage.

4 CURRENT PRACTICES AND CHALLENGES IDENTIFICATION

4.1 Introduction

This chapter presents the current practices, challenges and opportunities for improvement during the design of PBC (e.g. CfA) solutions, highlighted across industrial interaction and review of relevant literature in the field. The focus was on the bidding stage, and in cost and availability estimation.

Section 4.2 starts with describing the methodology adopted to perform this part of the research. Section 4.3 presents a definition of CfA that reflects the view of practitioners with extensive experience in the field. The position of CfA in different PBC arrangements is also identified, as well as different types of CfA and the typical CfA life-cycle. Section 4.4 reviews the different phases of the bidding process in CfA, identifying key achievements/outputs at each phase and the stakeholders involved. In Section 4.5 the bidding process is highlighted within the scope of this PhD, and three case-studies are considered to describe the current practices and challenges of three large manufacturing organisations in the UK, covering the processes of CfA negotiation, and the cost and availability estimation at the bidding stage. Finally, Section 4.6 presents a summary of the challenges faced by the project managers and cost engineers during the preparing the CfA bids, related to cost and availability estimation.

4.2 Methodology

The identification of the industry current practices followed the structure of the HCD approach adopted to perform the full PhD research. First, the relevant stakeholders were identified and the engagement with them was performed by means of interviews, workshops, phone calls, emails, and networking in events of interest, to collect the relevant information.

Before each interview, workshop or phone call, clear objectives were defined and translated into a questionnaire that guided the conversations in order to achieve a quality and objective output. The notes taken in each session were articulated and written in a report, which was further validated with all the participants in the session. Results from phone calls conversations, summaries of non-published material provided by the stakeholders, and non-structured conversations in events of interest were also reported and validated using the same approach. Figure 4-1 describes the iterative sequence of steps that reflects the objectives outlined to the industry interaction and how the research process evolved towards gathering the information. The process consisted of:

(1) Defining CfA: this stage aimed at building a comprehensive definition of CfA from the perspective of professionals from industry with large experience in CfA; results from four semi-structured interviews, with an average duration of two hours, with participants SH1, SH2, SH3, SH4 and SH6 enabled to develop different views of the concept, which was also enhanced by a review of unpublished support documentation provided by the same participants.

(2) Positioning CfA: this stage aimed at identifying different types of CfA and other PBC, and the main distinguishes between them; an internal report was sent by SH2 with the different types of PBC ran by his company, which also identified different types of CfA and their specifications. The contents of the report were summarised and validated/updated in two semi-structured interviews with SH1, SH2 and SH3.

(3) Identifying CfA life cycle: this stage aimed at identifying the different stage of a CfA life cycle, and the specifications of each stage; one semi-structured interview with participant SH12, other with participant SH10 and other with participants SH2 and SH3 (with an average duration of two hours each) enabled to build an idea of the CfA life-cycle from two perspectives: customer and supplier, which was assessed and reflected in a general, after validation of all the participants.

(4) Capturing bidding process: this phase aimed at identifying the different phases of the bid and locating the bidding stage within the life cycle of the contract; relevant documents sent by SH3 and SH2 enabled to clearly identify the beginning and end of bidding phase within the contract life cycle, as well as identifying the iterative processes to prepare and submit the bid. In addition, the participation in two conferences and three industry-focused

seminars, enabled to confirm and add some more information to the research performed in Phases 1, 2, 3 and 4, which was updated in the reports and validated with the stakeholders that contributed with knowledge to perform that research.

(5) Identifying current practices and challenges in estimating cost and availability: this stage was considered the most important and aimed at reviewing the processes and methods applied by different industry contractors to prepare their bids, and in particular to build their estimates of cost and availability. To achieve this aim, three case studies were assessed, that consisted of assessing the outputs of three workshops organised with participants (bid managers) from three large manufactures with large experience in delivering support under CfA arrangements. Each workshop had an average duration of three hours, where the participants presented the current practices of their organisations.

The outputs of the three case-studies performed in Stage 5 allowed to identify the current challenges of the organisations in building their cost and availability estimates during the bidding stage. With these results, the objectives of the research were updated in order to be aligned with the industry needs, considering the initial scope defined to the research.

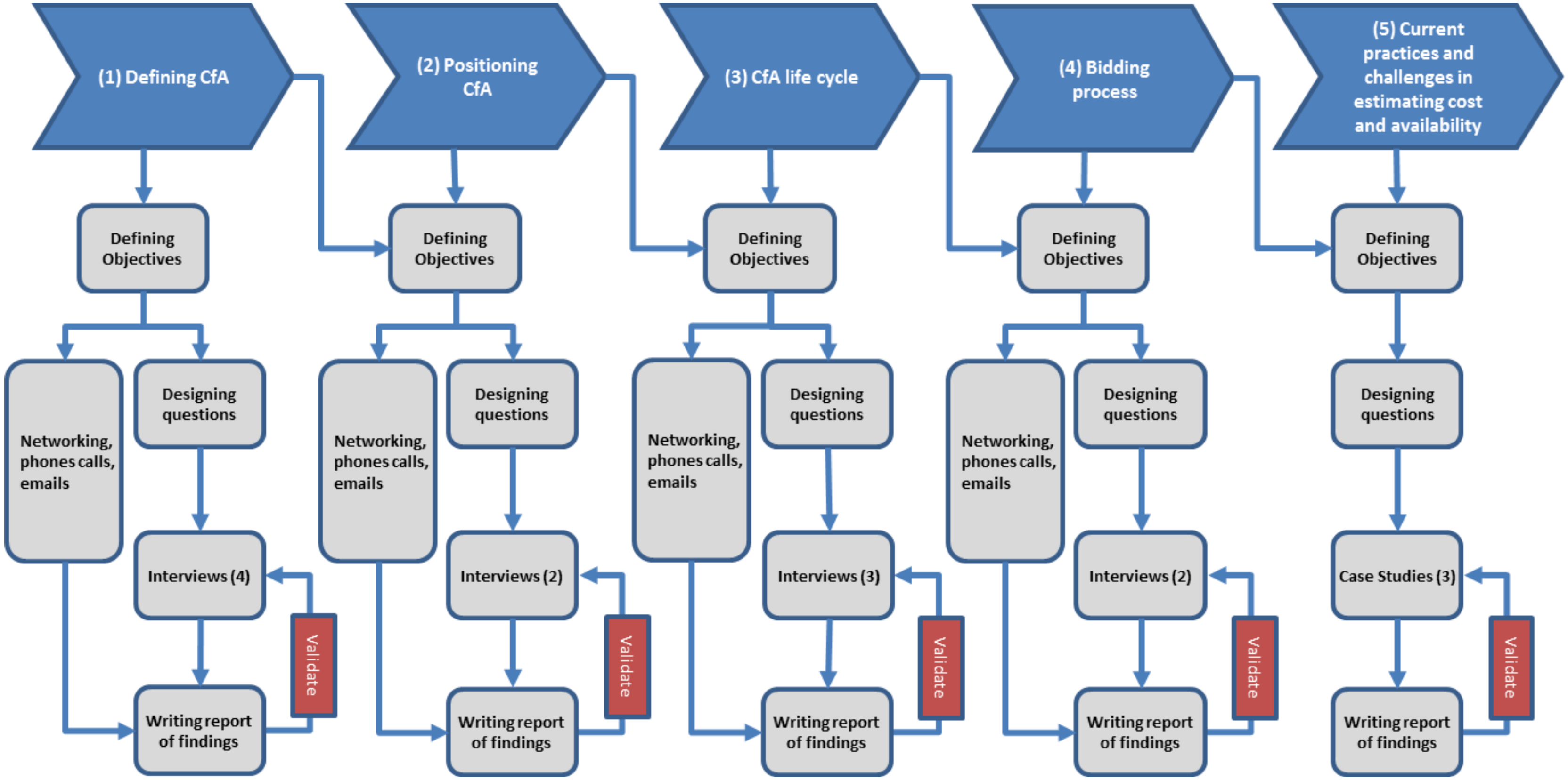
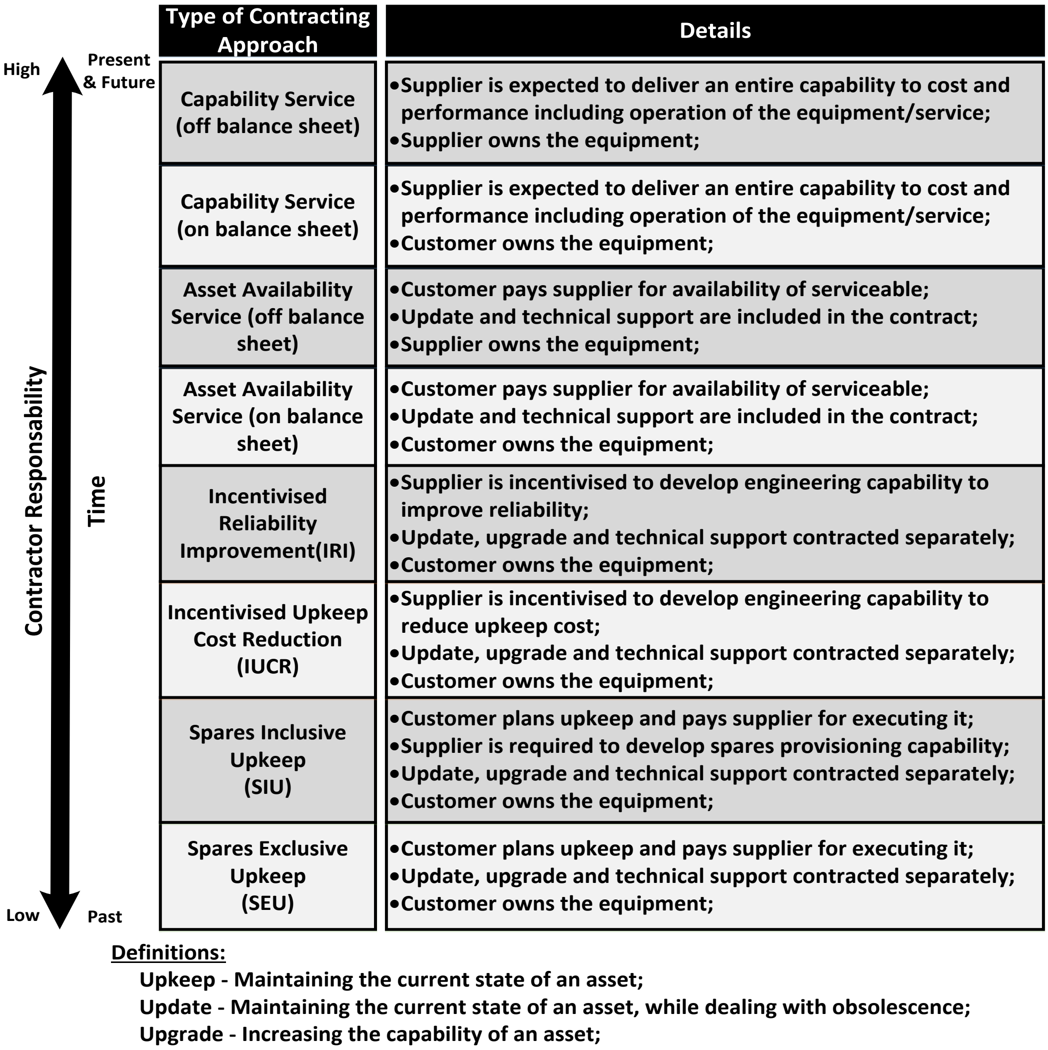


Figure 4-1 Methodology to Identify Industry Current Practices

4.3 Contracting for Availability

The general aim of CfA is: “making sure that specific system will be available to perform a task” [SH2]. This includes any type of system covered by the definition provided in the specialist terms section of this thesis. However, the definition of availability is not standardised because it depends on the context of application (e.g. deployment scenario - land, air or sea, complexity of the equipment/system, etc.). There are also other alternative terms that are closely related to availability and that are frequently used such as: “the supply of spares at the right time”, “the supply of specific equipment to be accountable to do a job”, “the management of equipment supplied that has to work when needed” or even “the management of spares on behalf of the customer”. These alternative terms were provided by participants SH2 and SH3. The existence of these variations can cause misunderstandings and drive to ambiguous requirements and specifications between different types of CfA (see, for instance, Figure 4-2). For example, in the defence context, these variations are typically limited to the boundaries defined in the support options matrix (SOM) model presented in the MoD acquisition operating framework (AOF) (The National Archives, 2008). SOM presents the different types of support service contracts in the UK defence and is granular in terms of rising of responsibility for industry (supplier) to deliver support. The SOM has 8 different contracting options as shown in Figure 4-2. The specifications of each contract type are described in the figure to better contextualise CfA among the other support service contracts approaches.



Type of Contracting Approach	Details
Capability Service (off balance sheet)	•Supplier is expected to deliver an entire capability to cost and performance including operation of the equipment/service; •Supplier owns the equipment;
Capability Service (on balance sheet)	•Supplier is expected to deliver an entire capability to cost and performance including operation of the equipment/service; •Customer owns the equipment;
Asset Availability Service (off balance sheet)	•Customer pays supplier for availability of serviceable; •Update and technical support are included in the contract; •Supplier owns the equipment;
Asset Availability Service (on balance sheet)	•Customer pays supplier for availability of serviceable; •Update and technical support are included in the contract; •Customer owns the equipment;
Incentivised Reliability Improvement(IRI)	•Supplier is incentivised to develop engineering capability to improve reliability; •Update, upgrade and technical support contracted separately; •Customer owns the equipment;
Incentivised Upkeep Cost Reduction (IUCR)	•Supplier is incentivised to develop engineering capability to reduce upkeep cost; •Update, upgrade and technical support contracted separately; •Customer owns the equipment;
Spares Inclusive Upkeep (SIU)	•Customer plans upkeep and pays supplier for executing it; •Supplier is required to develop spares provisioning capability; •Update, upgrade and technical support contracted separately; •Customer owns the equipment;
Spares Exclusive Upkeep (SEU)	•Customer plans upkeep and pays supplier for executing it; •Update, upgrade and technical support contracted separately; •Customer owns the equipment;

Definitions:

Upkeep - Maintaining the current state of an asset;
Update - Maintaining the current state of an asset, while dealing with obsolescence;
Upgrade - Increasing the capability of an asset;

Figure 4-2 Support Options Matrix (Ministry of Defence, 2013)

All the different contracting approaches presented in Figure 4-2 differ in terms of applicability, level of support involvement/responsibility, and equipment ownership. Actually, the main difference between “on” balance sheet contracts and “off” balance sheet contracts refers to the risk that each party retains the ownership of the facilities/assets necessary to deliver the service. In “on” balance sheet contracts, this risk is retained by the customer whereas in “off” balance sheet contracts the supplier owns that risk and the customer has the possibility of buying those assets at market value or walk away at the end of the contract. This research is focused on the asset availability service contracts, which is the similar term to CfA in the SOM, and covers both “on” and “off” balance sheet contracts.

4.3.1 Sole, Single and Multiple Source Contracts

There are different strategies of procurement within the context of CfA such as sole-source, single source or multiple source contracts.

Sole-source contract refers to the agreement of a contract with a single supplier because it is the only company in the market capable of producing a specific product or service. The main drawback of this contracting approach is the vulnerable position of the customer during contract negotiation due to nonexistence of competition, as the supplier can adopt an opportunistic position and inflate the cost of the product or service as much as he/she wants. However, not everything is bad in this contracting approach. It takes time and money to contract different suppliers or to select a single supplier from different suppliers, request quotes and negotiating the contracts. Having a sole supplier eliminates the time that is typically spent with bidding, and administrative costs are also often reduced because of less time haggling and acquiring the signed contract. Additionally, it may be the case that the supplier wants to make a fair trade in order to build a good image of the company in the market and create a great relationship with the customer to be preferred in future commercial deals.

When the customer identifies in the market different suppliers providing similar products or services to the ones he needs, he can decide from two types of acquisition: single source or multiple source contracts. A single source contract is when the company heads, managers or owners choose to sign the contract with a single supplier and pass up the opportunity to work with the other suppliers. On the other hand, a multiple source contract is when the customer decides to divide the product or service that he needs in parts and negotiate each part with different suppliers.

There are some clear benefits and drawbacks in these contracting approaches. For example, if the customer opts for a single source contract for example, he will benefit from higher discounts and preferential treatment. However, the customer faces the possibility that, once the contract is agreed with the supplier, this may demonstrate opportunistic behaviour and take advantage of the situation by raising prices. On the other hand, should the customer opt for multiple supplier, the overall price may be higher although it prevents opportunism of the suppliers, as it promotes competition among them and incentives for better services delivery at better value for money (Lee *et al.*, 1999).

Moreover, both single and multiple source approaches can be useful because they provide the customer with an alternative, which does not happen in sole source contracts.

4.3.2 The CfA Life-Cycle

A typical life-cycle of an availability contract, covering the support of complex equipment, includes the concept, assessment, demonstration, manufacture, in-service, and disposal (CADMID) as shown in Figure 4-3. It also covers two main gates – initial gate and main gate - that are important assessment point during the contract life cycle, where performance, cost and time boundaries are reviewed.

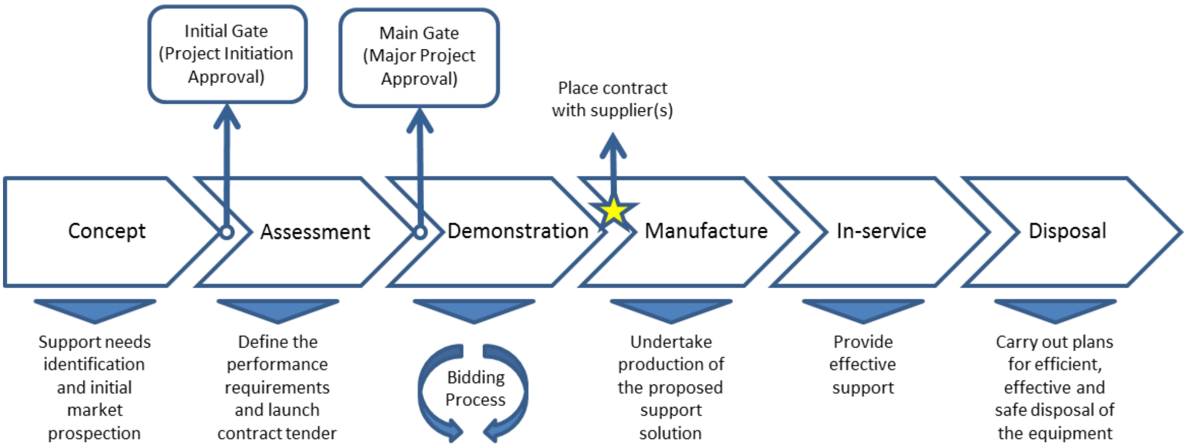


Figure 4-3 Contracting for Availability Life-Cycle (Rodrigues *et al.*, 2015)**.**

At the concept phase, the customer identifies the need(s) for support and produces and baselines a report of the outputs and/or results that he requires from the system, outlined as a user requirements document. At this phase, there is an initial involvement with the possible suppliers, by identifying technologies and procurement options for meeting the need that merit further investigation. The initial gate is passed in this phase once the initial performance, cost and time boundaries are validated for the project as a whole. An initial through-life management plan including cost of equipment/assets ownership statement must also be elaborated.

During assessment, the customer produces and baselines the system requirements document, defining what the system must do to meet the performance requirements as stated in the user requirements document. He also establishes and maintains the linkage between user and system requirements, and identifies the most cost-effective technology and procurement solution. Also, the through-life management plan for the project is updated and matured in order to pass the main gate. At this stage, the customer launches the contract tender.

At the demonstration phase, different competitors (if applicable) elaborate their projected solutions that will meet the customer support requirements for the system/equipment, and estimate the associated cost. The contract is then placed with the supplier(s) that demonstrate the ability/capability to deliver the most effective support at better value for money.

In the manufacture phase, the supplier(s) takes lead on the project and undertake production of the proposed support solution, is order to be ready for deployment at the start of the in-service phase. The through-life management plan is also updated to reflect latest assumptions made by the supplier.

The provision of effective support to the system is done during the in-service phase. There is a continuous monitoring during this phase to ensure that the levels of performance are within the agreed parameters and to carry out any upgrades or improvements, refits or acquisition increments needed.

Finally during disposal, plans are elaborated to carry out efficient, effective and safe disposal of the equipment, and a post project evaluation is made to register what could be learnt from experience for future contracts of similar nature.

The objective of the CADMID acquisition cycle is to assist the reduction of risk during the concept and assessment phases so that, at the main gate, there is a high level of confidence that project targets for time, whole-life cost and annual cost of ownership, and that the required system/equipment performance will be achieved. Moreover, the concept, assessment and demonstration phases are recognised as the period of the contract where the most cost commitments. It is also where the contract bids are planned, submitted and approved. A non-effective investment at this stage may incur in big cost slippage at later stages of the program life-cycle.

CfA can last from 5 years up to 10, 20 or more years. Thus, it is of interest for the contractor to optimise the through-life support performance by implementing best practices in order to increase profit. For example, repairing the parts instead of replacing the whole equipment is normally cheaper and increases the margin of profit of the supplier while still ensures that the required availability is achieved.

Other important aspect of CfA is its pricing mechanism. Although these are typically fixed price contracts, they can also include mutual benefits to be gained from incentives and gainsharing of any profit and efficiencies. Also, there are typically some milestones for renegotiation where the customer and supplier can review and update the contract terms and conditions. These renegotiation milestones typically occur in periods of 4/5 years from the date of agreement of the contract. This is an opportunity for the customer to assess the performance of its supplier(s), and put pressure on them to deliver better service against penalties and/or incentives, or even to decide for a different supplier(s) if necessary.

4.4 The Bidding Process for CfA

The information collected about the bidding process of CfA was provided by participant SH2, by email. The participant provided some unpublished material used by his organisation to guide across the different stages of the bidding process. This information was reviewed and summarised in a report that was then validated by participant SH30 in a three hours interview, where some more information was added.

The bidding process of an availability contract typically covers part of the assessment and demonstration phases of the CADMID cycle. This takes about 6-8 weeks in small/medium size projects, and can go up to 12 months in major projects. There are five decision gates that structure the whole bidding process from the exploration of the contract opportunity until the submission and acceptance of the final solution, as illustrated in Figure 4-4.

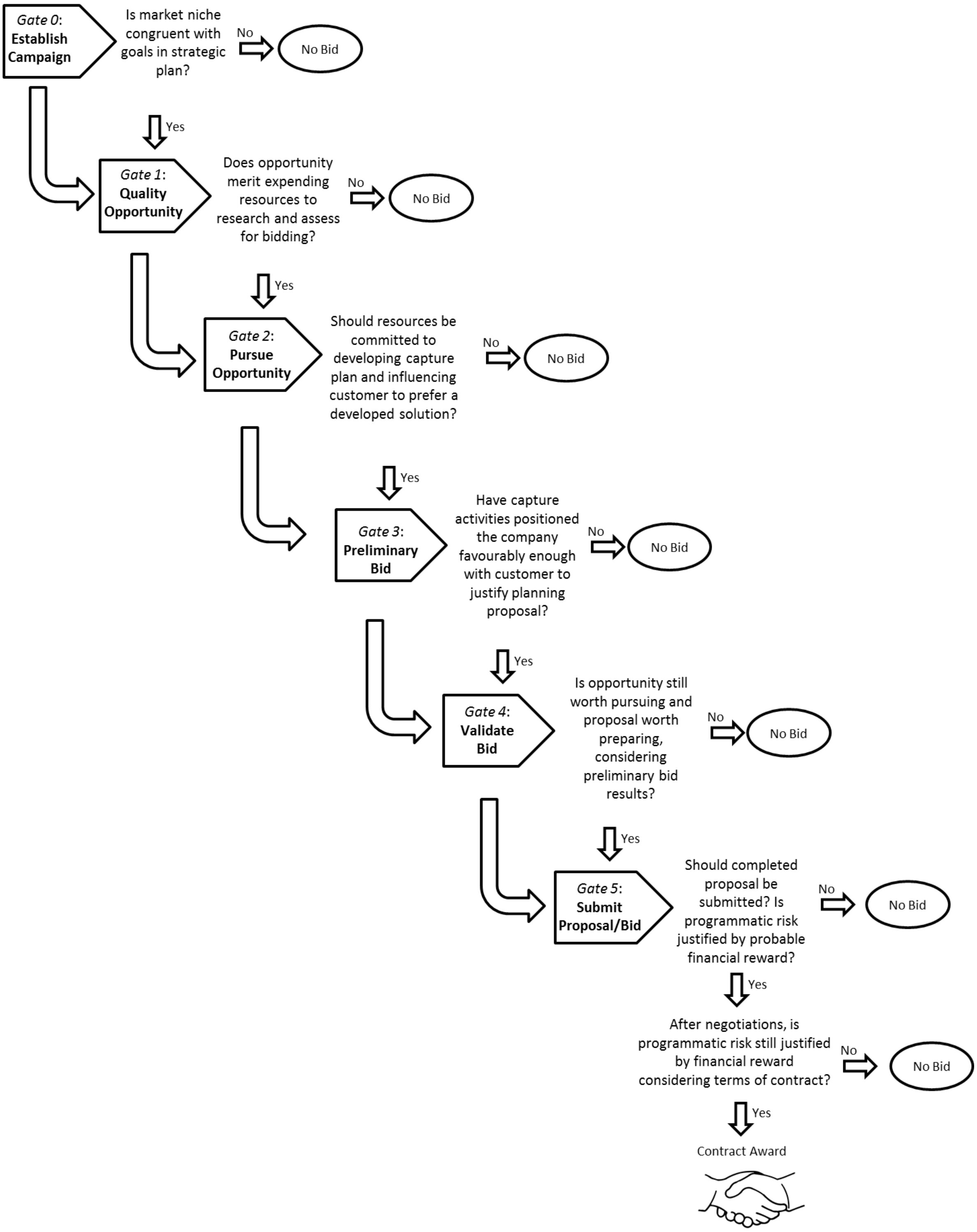


Figure 4-4 Bidding Process for CfA

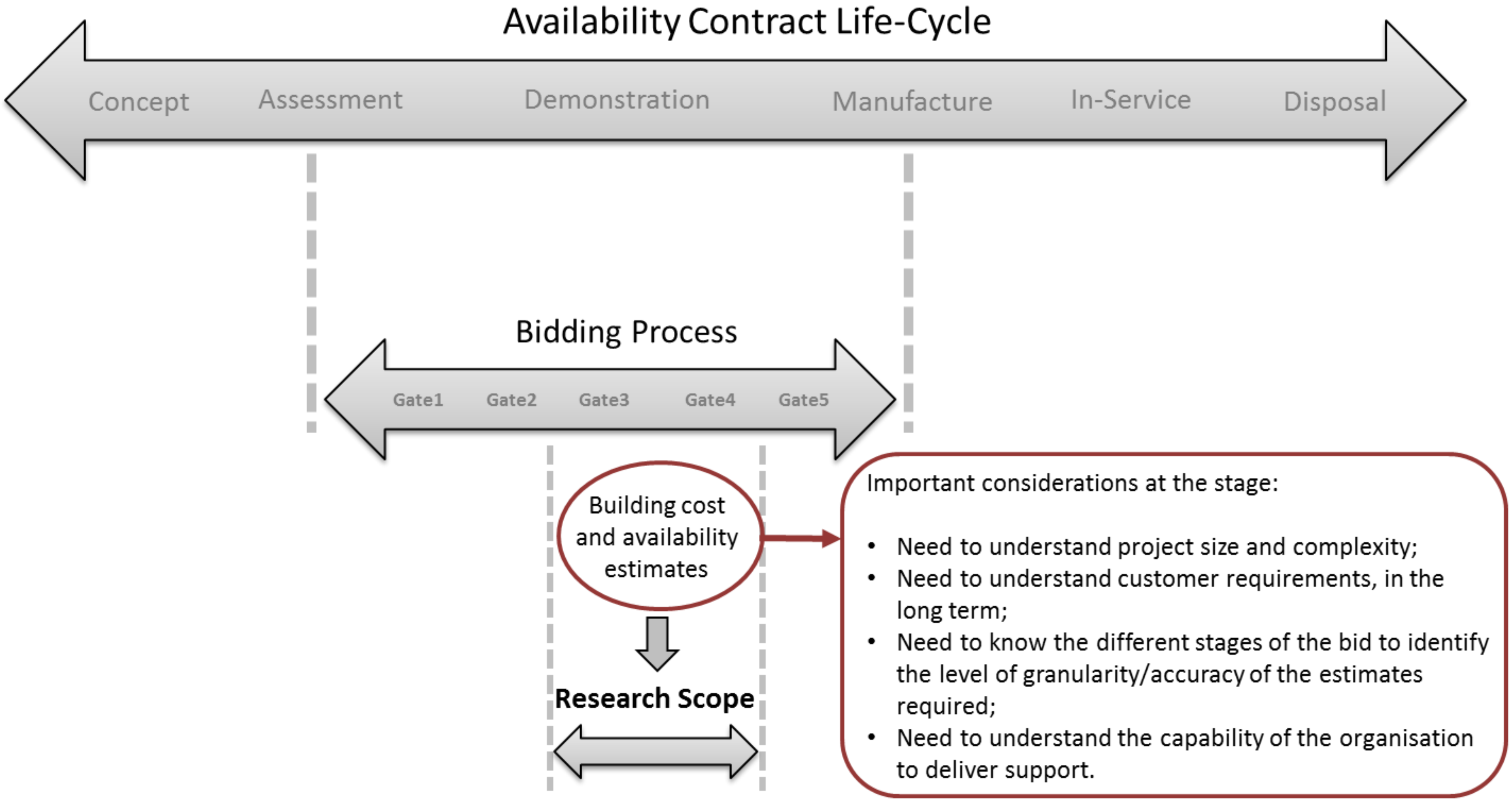
At the “*establish campaign”* gate, each contracting opportunity is studied to decide if it fits the strategic market of the company. It starts by identifying and analysing strategic market areas and customers, and developing marketing approaches aligned with the target customers’ expectations, to identify/gather opportunities for business. The next stage is the “*quality opportunity*” gate or “*interest*” gate. This gate aims to verify if the opportunity fits in the company strategic direction and capability and determines whether or not the opportunity is sufficiently defined and there is an approved customer project with a budget and an owner that fit with the organisation’ capabilities and objectives for further pursuit. This is also the stage to understand who are the potential competitors and if there is any interest/possibility to team with a competitor if necessary. The next stage is the “*pursuit”* gate that is used to determine if a formal capture should be initiated. The decision will be taken by assessing if a company is in a position to win the bid for the estimated cost of a solution. If yes, proceed to the capture planning phase to further plan and execute capture, e.g., to confirm/adjust initial win strategy as well as to assess competition to develop a realistic price-to-win (conceptual solution). The “*preliminary bid*” gate is the next phase and is used to verify/determine that company is positioned to win the contract and that capture preparations have been completed, before moving to an expensive proposal effort. Therefore, it is necessary at this stage to confirm/adjust win strategy, pricing, solution, win themes and discriminators. Management team has also to build initial cost estimates to see if it is within the estimated price-to-win region. Funding for all the remaining bidding phases has also to be adjusted. The “*bid validation*” gate occurs after the “*preliminary bid*” and aims to ensure that there is sufficient probability to win the contract and proposal readiness actions have been completed to develop a winning proposal. Also, it aims to confirm that there is sufficient business case and risk mitigation to justify proposal development. After ensuring that there are no impediments to make the deal, the process evolves to the “*proposal*” gate. This last gate aims to ensure conformance with company policies and quality standards, by verifying that final proposal meets standards (e.g. it is compliant, responsive and competitive), pricing is acceptable, risks have been adequately addressed, and all the necessary internal approvals have been obtained.

It also makes sure that the project management team is ready to begin delivery immediately upon contract award.

Defining leadership roles and responsibilities for pursuit decision gates is a critical success factor in the overall business development process. There are typically four leadership roles that have a direct involvement in the bidding process: executives, operations manager, business development manager and capture manager. The executives are the key stakeholders for the “preliminary bid”, “validate bid” and “submit proposal decision” review gates, as they prepare and conduct negotiations. They assist in developing the price-to-win strategy and signing off on final revisions to cost and technical volumes of proposal. The operations manager identifies potential opportunities, gathers intelligence about the customer and possible competitors, supports the business development manager by updating about the operational activities planning and performance estimates, assists the capture manager in defining the conceptual solution, assists in the process of estimating price-to-win targets and the preparing for the preliminary and final bid gate reviews, and assesses strategic fit and risks. The operations manager has a key role at the “preliminary bid” and “validate bid” review gates, as they conduct and lead the process of building preliminary and final cost and performance estimates. The business development manager collaborates with the capture manager in gathering the necessary information, developing solutions and estimating costs. He also monitors all the bidding preparation process and makes sure that it will be worth to the company’s business. In additionally, he provides general guidance of business and marketing development. The capture manager builds the bridge between the technical departments and the top level management departments. The main responsibilities are: determine the customer requirements and assess the competitive position of the company, determine and finalise win strategy, discriminators, price to win and solution, collaborate and assist the operations manager in all phases of operations and cost planning, and make sure that all aspects of the cost and technical volumes are consistent.

The scope of this research covers single and multiple source availability type contracts, and is focused at the bidding stage. More specifically, the research aims at improving and optimising the process of building cost and availability estimates during the “preliminary bid” and “validate bid” review gates as illustrated in Figure 4-5. Considering the information provided up to this stage, the bidding stage is one of the most (if not the most) important stages of the contracts life cycle, as it is where the total contract cost is built and agreed, upon commitment of achieving predefined levels of availability for the contract duration. It this therefore important for each supplier that decides to bid for a particular contract that: (1) understand the project size and complexity; (2) analyse and understand the customer; (3) have knowledge of the bidding process; (4) be aware of the market regulations and of possible competitors; (5) be aware of the capacity of the organisation in delivering a support solution on time and meeting all the requirements.

The next section identifies the practices and challenges faced by three large UK manufacturers that provide engineering support services to complex engineering systems worldwide, under the scope of PBC and in particular CfA, during the bidding stage.



Important considerations at the stage:

- Need to understand project size and complexity;
- Need to understand customer requirements, in the long term;
- Need to know the different stages of the bid to identify the level of granularity/accuracy of the estimates required;
- Need to understand the capability of the organisation to deliver support.

Figure 4-5 Research Scope within the Current Practices Identification

4.5 Building Cost and Availability Estimates during Bidding

This section presents three case studies which consist of three workshops made with project managers and cost engineers from three different organisations, which aimed to understand the current practices of each organisation in designing and implementing CfA, and in particular the bidding preparation process.

The three organisations interviewed are large multinational manufactures that provide through-life support services to complex engineering systems in sectors such as defence and aerospace. Due to confidentiality restrictions of each organisation in disclosing some information to the public domain, the level of analysis and detail is different in each case-study. However, all the organisations enumerated the main challenges experienced at the bidding stage of the contracts. The name of each organisation is also not provided to protect confidentiality and avoid any type of competitive advantage from competitors.

4.5.1 Case Study 1: Organisation 2

This information was disclosed by participant SH6 who is a systems engineer from Organisation 2, with extensive experience in CfA bids. He provided a top level understanding of the current practices in his organisation in designing CfA, and enumerated the main challenges. Organisation 2 is a multinational manufacturer which operates in different sectors such as security, marine and air, and provides a wide range of products and service under the scope of PBC (e.g. CfA) such as: threat analysis, data management/protection, spares, maintenance and training.

Organisation 2 includes a number of individual departments such as: commercial department, project management, engineering, procurement and business development. These independent departments work collaboratively to develop and deliver a product-service offer that is aligned to the customer needs and requirements.

At the top level are the commercial, project management and business development departments. They are the ones that lead new business activities and the bid preparation process.

The commercial and procurement departments are closely related; the primary distinction is that commercial is a customer facing department and procurement is the supplier facing.

The commercial and project management departments work very closely together (there are even people working simultaneously in both departments) to develop detailed cost estimates and statements of work (SOW), which define the scope of a specific work package that is required from the customer.

During the bid preparation, the SOW is distributed to the other departments (lower level departments such as the engineering department), each of which is provided with an estimate request form and a copy of the SOW. Once the other departments receive the statement of work document they decide which tasks are their responsibility and which ones are not, and send back to the ‘top level’ an estimate of man-hours, resources and time that they will allocate in relation to the SOW, and an estimate of the total cost of these activities; this will include the identification of any known risks and opportunities. Project managers working within the commercial department are then responsible for collating these estimates from all departments in order to create an overarching project estimate and plan. Each individual estimate will be reviewed and challenged as part of the bid preparation process in order to ensure that the final estimate is as accurate as possible and competitive. Historical data from legacy projects is used for comparison purposes, typically assessed based on expert opinion as there are no tolls available that support at this level of analysis. Even though there exist some software tools such as RED CUBE and OPUS 10, that can only be of assistance if there is a lot of detailed information to be inputted that is normally not available at the bidding stage. These tools are more appropriate to the in-service phase (where more detailed information becomes available) or to be used by the “lower level departments”.

Before any bid is submitted to a customer it has yet to go through a “request for bid approval” process as part of an internal life cycle management process. A panel of senior cross-departments subject matter experts lead by a member of the organisation leadership committee will determine if the bid is mature enough to be submitted.

The main challenges experienced by Organisation 2 in CfA planning are:

1. Contracting structures need to be more aligned with product lifecycles in order to enable the implementation of optimised through-life product strategies. This is not an easy problem to resolve because longer term contract structures need to build on accurate and reliable data; this in turn will require the development of long term predictive modeling capabilities that currently do not exist.
2. Project management within industry is often focused on the successful delivery of products/services in relation to agreed contractual requirements with a specific scope and duration that is considerably shorter than the “in-service support” phase of the product lifecycle; this is predominantly driven by customer requirements. As a result industry is forced to adopt a shorter term project perspective, when a clearly defined “through-life strategy” would provide more opportunity to optimise costs.
3. The risk of counterfeit parts entering the supply chain is increasing due to the impact of obsolescence, i.e. contractors are forced to use non-preferred suppliers in order to satisfy the demand for obsolete components.

Academic Challenges:

- Development of processes/tools adapted to the needs of management level decisions, of easy level of functioning, which could build quicker and robust estimates of cost and systems’ performance (e.g. availability);
- Development of processes/tools capable of mitigating challenge 1 and 2 (as identified above), and incorporating uncertainty analysis in the estimates.

4.5.2 Case Study 2: Organisation 4

Participants SH15, SH16, and SH17, from Organisation 4, participated in this workshop. These participants have an average of 15 years of experience in designing and managing CfA bids. Organisation 4 is a multinational manufacturer that provides different types of support services under the scope of PBC (e.g. CfA) such as maintenance, repair and overhaul, in sectors such as aeronautics and defence. The results from this workshop are divided in three different parts: (Part A) the bidding preparation process; (Part B) the contract deployment scenario; and (Part C) Building the cost and availability estimates during bidding. Part A provides details about the different stages of the bid, including number of people allocated to perform the different tasks and duration of each bidding phase. Part B gives an overview of how the customer requires the support during the in-service and how it is delivered to him. It is also explained how the availability is measured and what information is recorded for future analysis and planning. Part C explains how the cost and availability estimates are built, based on the information provided in part B about the process of measuring availability during the in-service. The most important cost drivers considered and the tools/models used to build the cost and availability estimates are also identified.

Part A) The Bidding Preparation Process:

The cost and performance (e.g. availability) estimates are normally built during review gates number 3 and 4, and there is a dedicated team of managers and engineers to conduct and lead the whole process. Depending on the size (cost value) and complexity of the contract, the number of elements of this team can vary. For a medium size bid for example (typically between £5M-£15M), the team normally includes: 1 bid manager, 1 business development manager, 1-2 sub-contracts manager, 1 obsolescence manager, 1 quality assurance, 1 information technology specialist, 1 engineering manager, 1 modelling analysis manager and 1-2 policy regulators and safety and test specialists.

Moreover, significant time is spent costing and writing the proposal. The solution development is usually a subset of the total bidding period and involves 3-4 people over a period of typically 2-3 weeks. It tends to be a relatively small part of the overall bid effort. The team will normally work on a bid for about 6-8 weeks but some major bids may take over 12 months.

In addition, there are review points throughout the bidding design process to assess the progress and to evaluate the feasibility of the contract. These review points involve senior managers from each internal department (e.g. engineering, finance and commercial), and the delivery teams on current contracts.

Part B) The Contract Deployment Scenario

When a contract is in place, there is a cooperative effort to monitor the system to assess for any requirement that affects its availability. Basically, when a part fails or an upgrade is needed, it is automatically communicated to the supplier (Organisation 4) to replace the part or install new parts according to the scheme presented in Figure 4-6. The requirement is first communicated to the contract management team - technical management - which in turn communicates the request to the Information and Technology (IT) department. The IT department passes the message onto the inventory management department (IM) which checks if the part(s) are available in the inventory and if yes, send them to the system for installation. Within this process, the availability of the system is measured not directly in the system operation records, but in the communication link between the IT and IM departments, according the rate of positive responses to the parts requirement.

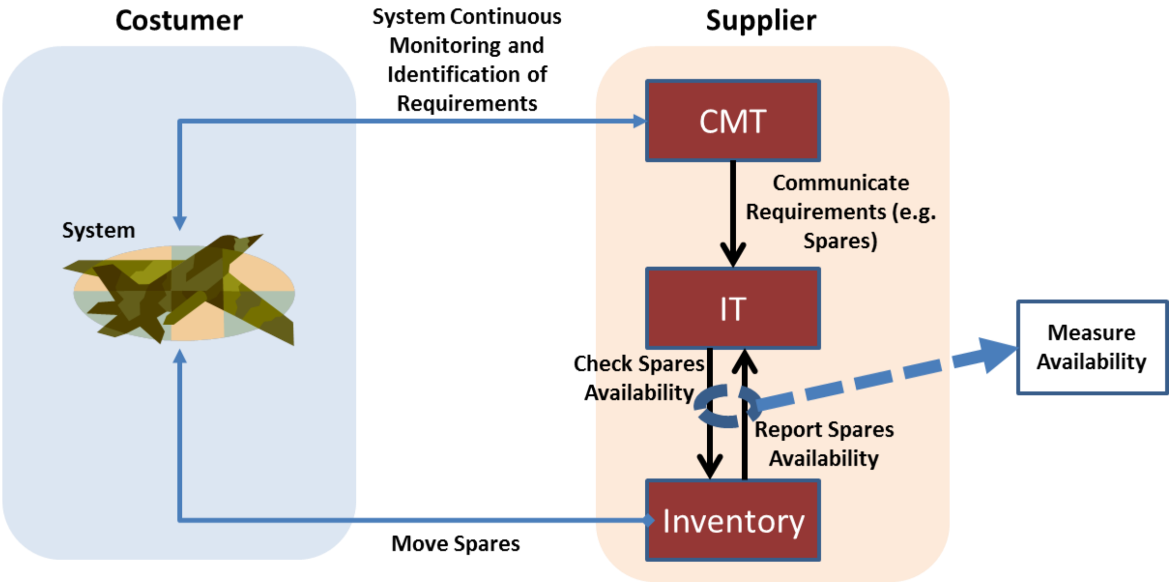


Figure 4-6 Current Practices Case Study 2: Contract Deployment Scheme

Under this process, relevant information is recorded and saved for future analysis when planning new projects such as:

- Level of availability achieved;
- Number of no-fault found (No-fault founds are the faults which cannot be correctly diagnosed or even detected under standard maintenance testing (Erkoyuncu *et al.*, 2016));
- Level of reliability (related to availability);
- Number of system operation hours;
- Expenditures with maintenance and manpower;

Part C) Building the Cost and Availability Estimates During Bidding

Based on the process adopted by the organisation to measure availability, there are four main attributes that impact on availability which are:

- Reliability (and any potential increase, either by design modification or changes such as improved system cooling);
- Repair turnaround time (including any transport delays and batching of repairs - this is all linked to the application of lean techniques);

- No fault found rates (any reduction may be from improved test software, better diagnosis, training);
- Spares (the more spares are available for use the better the availability but this may be a more expensive option compared with the application of lean techniques).

So, when considerations are made about availability (either to increase/decrease or estimate future scenarios), the assessment is performed on the effort (£) across those attributes and consequent impact on availability, in order to select the most cost effective option(s). Often, increasing the spares quantities or reliability is impractical or very expensive so the solution tends to be reducing the no fault found rates or application of lean techniques. However, this assessment is mainly done based on the opinion of the experts, which use their experience to compare with the performance from previous and similar projects to build the estimates. If the duration of the contract is relatively short (e.g. up to 5 years) and there is a good level of information about what will be the system requirements during the contract period, OPUS 10 tool is typically used to test different scenarios and estimate the impact on availability. For example, if the repair turn round time is reduced by 10 days, OPUS 10 can estimate what is the likely improvement on availability. Based on that, the total cost is then estimated considering the cost of each activity and resource included in the plan.

Organisation 4 recognised that the availability levels and cost of the different attributes that drove availability in the different CfA ran by the organisation in the past projects did not suffer much fluctuation (comparing project with the same level of complexity and duration). However, two challenges have been enumerated that are seen as areas for potential improvements in future projects such as:

1. Normally, there is a joint control over a number of attributes that impact on availability. This joint control varies in terms of percentage from project to project and that percentage is actually hard to assess and

quantify. This fact makes it difficult predict/assess the effectiveness of each party. For example, sometimes the lead time of the components (e.g. repair and transportation time) reduces only because of external changes in the joint logistics and policies. This fact may lead to a substantial increase of the level of availability without requiring any extra effort from the organisation. The opposite can also happen.

2. If the contract covers the support of a new system and no similar system has been supported before, or a system working under extreme environmental conditions, there is no robust method or tool to build the estimates as there is no historical data available for analysis.

4.5.3 Case Study 3: Organisation 1

This workshop was made with participant SH1, SH2, SH3, SH4 and SH8 from Organisation 1. These participants have an average of 20 years of experience in planning and monitoring CfA bids. Organisation 1 is a multinational engineering support services organisation, which has large experience in delivering complex and critical support to systems in different environments (e.g. air, land and sea), under the scope of PBC (e.g. CfA). Some of the services provided by this organisation cover IT support, operational training, maintenance & overhaul and transportation.

The outputs of this workshop were divided in part A and B that consisted of: (Part A) business process towards contracting negotiation; and (Part B) building the cost and availability estimates during bidding. Part A describes how organisation1 explores and identifies contracting opportunities for bidding, and Part B describes how the cost and availability are built, at the bidding stage.

A) Business Process Towards Contracting Negotiation

Typically, Organisation 1 performs a continuous assessment of the business of its potential customers, in order to identify possible opportunities for improvement and therefore suggesting a collaboration plan (e.g. negotiation of the adequate contract to provide the necessary support), even though when there is no current contract in place. If a contract is in progress, the supplier can also identify opportunities for improving the current strategy or a need to upgrade the system which is outside the current contract scope. Alternatively, the customer can also recognise a need for increasing its own capability and approach the supplier with an invitation to negotiate a contract to provide the necessary support (e.g. consultancy, training, maintenance, etc.). A contract can be agreed at different stages of the life cycle of the system, e.g., the contract can be negotiated while the system is already in service. The high level business model of Organisation 1 in the context of CfA is illustrated in Figure 4-7. The figure shows that opportunities for negotiating a contract can be identified either by the customer or the supplier.

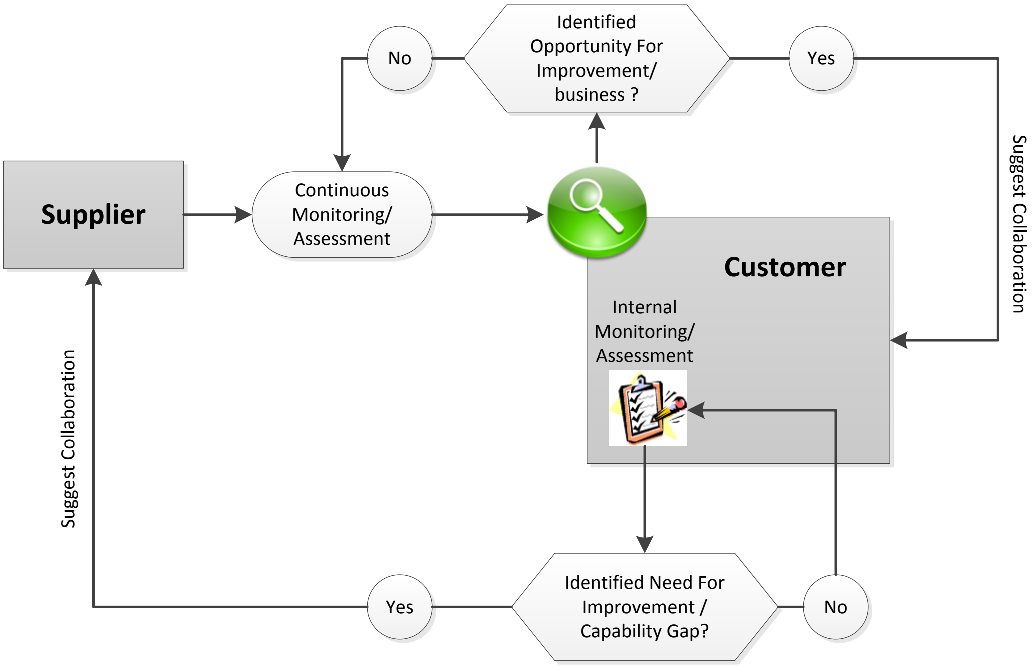


Figure 4-7 Current Practices Case Study 3: Business Strategy to Explore Contracting Opportunities

B) Building the Cost and Availability Estimates During Bidding

There are several independent departments inside the organisation that work together to build an estimate for the total contract cost and system availability. These estimates are typically built based in the experience of their subject matter experts and in a comparison with previous and similar projects. In some case, when there is a reasonable about of information about future support requirements, some tools such as OPUS 10 and RED CUBE are also used to assess “what-if” scenarios. There is also a dedicated modelling team and an internal department for consultancy that also cooperate in this process.

After building the first estimates, a sensitivity analysis process is performed with participation of cost engineers from all the internal departments involved in the bid, in order to assess the level of uncertainty of those estimates and try to reduce it in order to increase the confidence for bidding. Regardless of the technique that is applied, there are eight attributes that the company considers essential to be included in the analysis when estimating cost and availability during bidding which are: training, equipment, personnel, information, doctrines and concepts, organisation, infrastructure and logistics. These attributes are documented in literature (Pawel, 2013) and Organisation 1 recognises them as being the attributes with more impact in the cost and availability targets of the contracts. However, due to the complex nature of CfA that leads to a joint cooperation in the support delivery, these attributes are not fully controlled and influenced by the supplier. Thus, the organisation starts by differentiating these two concepts: “attribute control” and “attribute influence”. Attribute control refers to how much changes (%) can each party make (or is allowed to do) in each attribute. Attributes influence refers to the impact that each party has in the effectiveness of each attribute, e.g. within the percentage of control allocated to a party over an attribute, how much that party can influence in the effectiveness of that attribute. The organisation has an idea of how much control and influence they have, in average, over each attribute in CfA as indicated in Table 4-1. Obviously, these values are only indicative as they may vary according to the type of system, customer and contract. Also, the company is trying to increase their control over training to 60/70% and their influence over personnel to 60%, because they recognise that it will improve the quality of their services planning and delivery.

Table 4-1 Current Practices Case Study 3: Control and Influence of Organisation 1 over the Cost and Performance Attributes

Attribute	Current Control (%)	Current Influence (%)
Training	20-30	10
Equipment	70	80
Personnel	5	10-15
Information	50	Not Known
Doctrines and Concepts	0	5
Organisation	External: 0 Internal: 100	5
Infrastructure	90	90
Logistics	> 50	60

The main challenges experienced by Organisation 1 in CfA planning are:

1. There is a need to optimise what the organisation offers as a joined up solution. It is hard to assess the control and influence over each attribute and consequently it is hard to assess the impact of the investment (£) made in each attribute in the availability of the system. For example, in CfA the company typically controls 70% of influence over equipment but there aspects regarding to maintenance and ownership of assets that are under control of the customer(s). Therefore, even increasing the effort (£) on equipment is not a guarantee of higher availability as the 30% of customers’ influence on equipment can harm its availability.
2. The data managing process inside the organisation is not great and could be significantly improved. Also, the data provided by the customer is also typically not complete or obsolete, and therefore not reliable to include into analysis to produce estimates. In addition, the processes of

turning that data into valuable information and knowledge are obsolete as they still rely too much in the opinion of subject matter experts

3. Personnel culture is reported to be poor and driving personnel culture is challenging. Improve personnel culture is important increase their perception about the importance for reporting/registering relevant equipment fault details. However, the problem with poor data recording is common either because there are not aware of the importance of recording data properly or because they do not know exactly what type of data they should record and how to record.
4. Managing the customer requirements is challenging as they can change frequently during the contract. In the defence industry for example, the supplier is expected to be ready to deploy support effectively whether the situation is of conflict or not, which represents very different levels of support demand throughout the contract: “We recognise that suppliers will have to reshape itself, to improve productivity and to adjust to lower production levels once current major equipment projects have been completed, while at the same time retaining the specialist skills and systems engineering capabilities required to manage military capability on a through-life basis” (Defence, 2005). This fact can cause uncertainties at estimating the contract cost, as multiple and unpredictable events/scenarios can occur during the in-service that can impact the availability of the system such as: unscheduled maintenance actions (e.g. caused by, for example, adverse environment conditions), unexpected equipment usage rates, long lead times, etc.;

Academic Challenges:

- It would be useful to have a robust method or process to trade-off between cost and availability at the bidding stage, considering the limitations in terms of data availability that are associated to these contract stage. Such method/process would allow to estimating the level of availability for a particular investment (£) in the attributes, and/or estimate the cost impact of each attribute in the other attributes. At the moment, this analysis is typically made based on assumptions and experience of subject matter experts.

4.5.4 Comparison between Organisations and Summary of Identified Challenges

Although the description of each case study presents different levels of analysis to the way each company configures its business to negotiate and design CfA, they all highlight the fact that CfA implies a joint cooperation between customer and supplier to plan and deliver the support strategy. This joint cooperation brings difficulties to design an effective support plan that is aligned with the customers' expectations. Customers always expect more performance outcome from the suppliers for the lowest price.

Thus, all the three organisations reported that they commit a big effort to prepare their bids, in order to design the most effective support delivery plan that translate the lowest contract cost that proposes at achieving predefined levels of availability, according to their forecasting analysis. The accuracy of the forecasts is important for the suppliers to achieve the customers' expectations and to maintain a competitive position in the market, as well as to avoid any cost slippage and ensure his own profit. However, the process of building cost and availability estimates at the bidding stage is reported to be challenging, due to a number of factors that are recognised from all three organisations which are:

I. **There is a lack of understanding about the different attributes that impact the availability of the system, and the interrelationships between them:**

Understanding which attribute(s) has the highest impact on availability might be challenging, as well as understanding the interrelationships between different attributes. Typically, by investing more in an attribute different performance will be achieved in the other attributes in terms of their impact on availability. This fact increases the difficulty of assessing different investment (£) configurations across the attributes.

II. Estimating the optimal contract duration considering the life-cycle of the system involved:

As the equipment involved in the contracts can have much longer life-cycles that the contract itself, it is hard to establish/develop a through-life strategy for support delivery. In some cases, the contract covers the support of equipment that is already in-service; if a new supplier(s) wins the contract, he can have difficulty in assessing problems related to obsolescence or facing risk of counterfeit parts/components having been installed in the equipment in previous overhauls.

III. Balancing the shared responsibilities/control between customer and supplier over the support delivery:

The increasing share of responsibilities between customer and supplier(s) with regard to the support delivery, means that the total cost of the contract and the availability of the system wiil be impacted by different parties. Thus, each party is vulnerable to the effectiveness of a third party performance at executing tasks that impact its own performance or the overall system availability. This vulnerability increases as more parties are involved in the process (e.g. multiple source contracts). There is then a certain level of control from each party over each attribute that impacts on availability which is challenge to measure or assess. For example, an equipment can be operated by personnel from both customer and supplier or by personnel from different suppliers. This fact makes it difficult to assess the performance of each party's personnel through the overall availability of the system. Although in performance-based type contracts customer and supplier(s) try to build a good relationship in order to create a win-win situation, it is not evident that this approach will reduce the operational costs as the responsibility sharing factor is hard to be assessed.

IV. Scarcity of data for analysis:

There is a general issue of data scarcity for analysis at the bidding stage. As the understanding about the in-service phase is limited at this stage, it is hard to estimate detailed information about the operational conditions of the equipment such as daily/weekly/monthly usage rate, number of overhauls required or deployment scenarios. Moreover, the data related to the performance measured in previous comparable projects is typically limited and not complete or unappropriated. This fact is explained by a lack of personnel culture to report/register relevant data for analysis, and also because the process of managing data inside the organisations is typically not good.

V. Lack of standard processes to follow, to build cost and availability estimates:

Most of the tools to build cost/availability estimates are focused in the in-service phase and very few can be applied at the early stages. There are some tools that can be applied at the bidding stage such as OPUS and RED CUBE, but they require a lot of information to be input to produce satisfactory results, which is typically not available at this stage. Actually, these tools have been designed to perform detailed analysis of parameters such as stock quantities, number of working hours, suppliers location, etc, which requires an expensive effort of time and money to collect information, and limits the flexibility of the analysis. Moreover, these tools are based in pre-defined parameters for measuring availability and cost, and do not consider the interrelationships between different attributes that impact on availability. These tools are also very specific to a particular context which difficult its utilisation in other contexts (Datta and Roy, 2010). Literature is also not mature at supporting this type of analysis, and in particular for scenarios where the information available is limited. The few approaches available are very theoretical and do not focus on high level analysis (management level estimates).

4.6 Summary

CfA has been extensively applied in different industry sectors such as defence, automotive and aerospace, because customers recognise value in negotiating a fixed price contract that will ensure a pre-defined level of availability for their systems, during long periods of time. CfA is contextualised in a matrix of different contracting approaches that are classified according to the level of responsibility that is given to the supplier to ensure the through-life performance of complex engineering systems.

Three case studies with three multinational organisations with large experience in delivering support under the scope of PBC (e.g. CfA), enabled to better understand their current practices in identifying contracting opportunities, planning support, building cost and availability estimates and delivering support. The main focus of the case studies was on the bidding stage, and in particular in the process of building the cost and availability estimates, although they also cover other phases of the contracts, with different level of granularity.

The analysis of each case study concludes with identifying the main challenges and opportunities for improvement recognised by each participant in the correspondent organisation. In summary, the challenges and opportunities for improvement identified are:

- Although CfA is a promising approach towards ensuring benefit for both customer and suppliers, there are currently no robust methods to justify the value of this approach. This difficulty is mainly because of the complexity of assessing the sharing of responsibilities between customer and suppliers, over the support delivery; The development of models is encouraged to estimate the necessary effort (£) from each party in the different attributes that impact the effectiveness of the support delivery, in order to ensure certain level of availability. The models must also be prepared and able to produce results with the minimum of input information, as data is typically limited at the bidding stage;

- The bidding stage is perhaps the most critical phase of the contracts as it involves the planning of investment across different attributes impacting on the availability of the system, in order to achieve the most cost-effective solution, for the entire duration of the contract;
- Innovative processes must be developed and applied to assess the interrelationships between the different attributes that impact the cost and availability targets in CfA, to guarantee that the designed support plan will achieve the desired level of availability for the lowest cost.

The next chapter covers the first, second and third objectives of this research, identifying a list of attributes that impact on cost and availability in CfA, assessing the interrelationships between these attributes, and building a process to assess the impact of the attributes on cost and availability.

5 AN ARCHITECTURE TO IDENTIFY AND ASSESS THE ATTRIBUTES THAT IMPACT ON COST AND AVAILABILITY

5.1 Introduction

This part of the research focused on identifying the attributes that impact the cost and availability targets in CfA, aligned with the first objective of the research, assessing the interrelationships between attributes, aligned with the second objective of the research, and proposing a framework to assess the impact of the attributes on cost and availability, aligned with the third research objective.

The chapter is structured in the following way:

Section 5.2 presents the methodology adopted to perform the research. Section 5.3 describes the systematic process adopted to identify an extensive list of attributes that impact the cost and availability targets in CfA. Also, the interrelationships between attributes are qualitatively assessed based on the results of an on-line survey. Section 5.4 identifies a list of key performance indicators that build the link between attributes and performance (e.g. availability). Section 5.5 presents a conceptual solution to measure the interrelationships between attributes, and to assess the impact of the attributes on cost and availability in order to allow a trade-off analysis between these two elements. Finally, Section 5.6 presents a summary of the chapter contents and results.

5.2 Methodology

The first objective defined for this research was to identify the attributes that impact the cost and availability targets in CfA. They were considered as a baseline to conceptualise a solution to assess and measure the interrelationships between attributes and to trade-off between cost and availability by changing the investment in the different attributes. Understanding the type and nature of the attributes is important to then select the most appropriate method to build the analysis.

With this in mind, the study pursued two parallel approaches of identifying findings derived from both literature and stakeholders' narratives to establish the extent to which one set of findings reinforced and validated the other in order to identify new knowledge. This study was undertaken in three stages as illustrated in Figure 5-1.

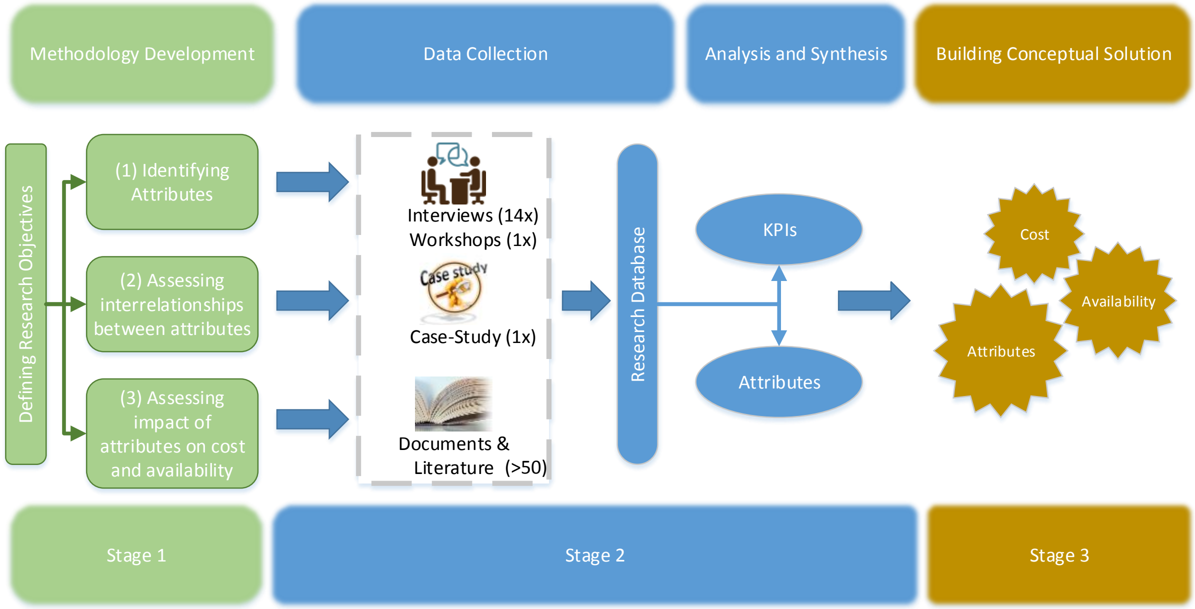


Figure 5-1 Methodology for Identifying and Assessing the Attributes that Impact on Availability

The focus in Stage 1 was on defining the aim and objectives for this part of the study, which focused on: (1) identifying the attributes that impact on cost and availability in CfA, in fulfilment of the first objective of the research; (2) identifying and assessing the interrelationships between attributes, in fulfilment of the second objective of the research; (3) building a process to measure the impact of each attribute on cost and availability, in fulfilment of the third objective of the research. These objectives are aligned with the first, second and third objectives of the research. This stage also included the identification of the relevant stakeholders to perform initial interviews to collect information. Participants SH1, SH2, and SH3 where selected to initiate the first interviews. They then helped to identify other relevant stakeholders and information (e.g. websites, reports, etc.).

Stage 2 covered all the process of collecting information from stakeholders and from relevant documents. A case study related to a CfA bid was also analysed to collect information. At the end of this process the project database included a mature list of attributes as well as a list of key performance indicators (KPIs). The KPIs were not included in the objectives of this PhD but throughout this study they were referred as being important towards measuring the availability level.

In Stage 3, all the information collected was analysed to build the conceptual framework that considers the relationship between attributes, KPIs, availability, and cost towards allowing a trade-off analysis between total contract cost and system availability, at the bidding stage.

The study is presented in a sequential order showing how it developed over time and how information was collected and validated, including the key stakeholders involved.

5.3 Building a List of Attributes

Two initial interviews with participants SH2 and SH3, of two hours each, resulted in a first list of attributes as presented in Table 5-1. This list was suggested by the participants, and was based on their experience considering the type of business of their organisation (within the context of CfA). The definition of each attribute was then further explored in literature (Kerr *et al.*, 2006; Pawel, 2013; Rodrigues *et al.*, 2015). These definitions were also validated with participant SH6, in a one hour interview, who confirmed their comprehensiveness.

Table 5-1 List of Attributes Impacting on Cost and Availability in CfA: A View of Practitioners

Attribute	Definition
Training	Includes the provision of the means to practice, develop and validate, within constraints, the practical application of a common doctrine, to deliver a certain capability
Equipment	Includes the provision of expendable and non-expendable equipment and support including maintenance, transportation, and infrastructures needed to outfit or equip an individual, group or organisation
Personnel	Includes the timely provision of sufficient capable and motivated personnel to deliver certain outputs, now and in the future
Information	The provision of a coherent development of data, information and knowledge requirements for capabilities and all processes designed to gather and handle data, information and knowledge. Data is defined as raw facts, without inherent meaning, used by humans and systems. Information is defined as data placed in context. Knowledge is information applied to a particular situation
Doctrine & Concepts	A concept is an expression of the capabilities that are likely to be used to accomplish an activity in the future. Doctrine is an expression of the principles by which people guide their actions and is a codification of how activity is conducted today. It is authoritative, but requires judgement in application
Organisation	Relates to the operational and non-operational organisational structures within the suppliers and any proposed enterprise relationship
Infrastructure	This includes the acquisition, development, management and disposal of all fixed, permanent buildings and structures, land, utilities and facility management services. It also includes estate development and structures that support personnel
Logistics	This is the science of planning and carrying out the operational movement and maintenance of systems and resources. In its most comprehensive sense, it relates to the aspects of operations which deal with: the design and development, acquisition, storage, transport, distribution, maintenance, evacuation and disposition of materiel; the transport of personnel; the acquisition, construction, maintenance, operation, and disposition of facilities; and the acquisition or furnishing of services, medical and health service support.
Interoperability	In addition to the other eight attributes, interoperability is included as an overarching theme that must be considered when any other attribute is being addressed. The ability of customer and suppliers to interact and cooperate in the delivery of services such as training, and operate effectively together in the execution of assigned operations and tasks. Interoperability is used in the literal sense and is not a compromise lying somewhere between integration and de-confliction.

Further investigation about these attributes was made in literature (Petrovic *et al.*, 2013) (mainly non-published documents), in events of interest such as symposiums and seminars, and interviewing participants SH7, SH9, SH10. Participant SH7 was suggested by participants SH2 and SH3 because of his level of experience in the topic. Participant SH9 was introduced during a through-life engineering conference, in Cranfield. Participant SH10 was identified during the literature review, and has considered these attributes is his own research. These three participants were interviewed in three separate sessions of one hour each, to investigate about the relevance of these attributes. Their opinion was unanimous, considering that the nine attributes presented in Table 5-1 can fully describe all the necessary elements that can ensure an effective support delivery in CfA.

Nonetheless, participants SH2 and SH3 outlined that typically the contract' requirements include a list of attributes that is different from the nine attributes described above, although they are closely related. They gave the example of maintenance and obsolescence management as very related to equipment, and transportation as very related to logistics. To better understand this situation, participants SH2 and SH3 provided a case study for analysis, which consisted of a bid proposal document for a CfA. The description of the case-study is presented in Section 5.3.1.

5.3.1 Case Study: CfA Bid Proposal

This case study consists of a high-level description of an availability contract' requirements, where Organisation 1 was involved. These requirements are based in an assessment of the “invitation to bid” document, which was given to the supplier Organisation 1 at the early stages of the bidding process. The contract was proposed to last for seven years, and had an estimated total cost of about £20 million. Under this contract the customer expected the supplier to remain responsible for the delivery of a type of complex systems (and all auxiliary equipment), in order to maintain a required level of availability for the customer. The supplier was as well responsible for the transportation of the system (to include all auxiliary components) to any required destination by the customer, and for maintenance. In particular, the contractor had to ensure that all necessary facilities, plant, machinery, equipment, fixtures and fittings that the supplier requires to perform the contract are properly maintained, overhauled and modified as necessary throughout the duration of the contract and thereafter into any potential extended period of contract duration.

The general areas of support expected to be covered by the supplier are:

- Logistics Management;
- Technical Support;
- Design Authority;
- Obsolescence Management;
- Health Checks;
- Safety Environment and Documentation Management;
- Software;
- Project Management, Meeting and Reports;
- Configuration Control;
- System Overhauls;
- Capability Improvements;
- Availability, Reliability and Maintainability;
- Test Facilities/Equipment.

These are the list of attributes that the customer recognised as impacting on the availability of the systems.

5.3.2 Attributes Categorisation

Analysing the case study presented in Section 5.3.1, it is actually possible to see that no reference is made to any of the attributes presented in Table 5-1. However, participants SH2 and SH3 referred that there is a link between the attributes presented in Table 5-1 and the ones highlighted in the case study presented in Section 5.3.1, and suggested to consider a categorisation approach for those attributes, building a list of “main-attributes” and “sub-attributes”. This list was built as presented in Figure 5-2. The figure also considers cost and availability as the main targets in CfA, as they are the main topics of concern within the scope of this PhD.

However, there was no knowledge about how to make a categorisation of this attributes by building the link between main and sub attributes, and how to establish a link between attributes within the same level (e.g. link between main-attributes and link between sub-attributes). Also, this list of sub-attributes was not considered as exhaustive yet as it was built based on one case study only.

In order to extend this list of sub-attributes and also to categorise each sub-attribute identified per main-attribute, an extended review of the literate was performed as well as a number of interviews to other stakeholders.

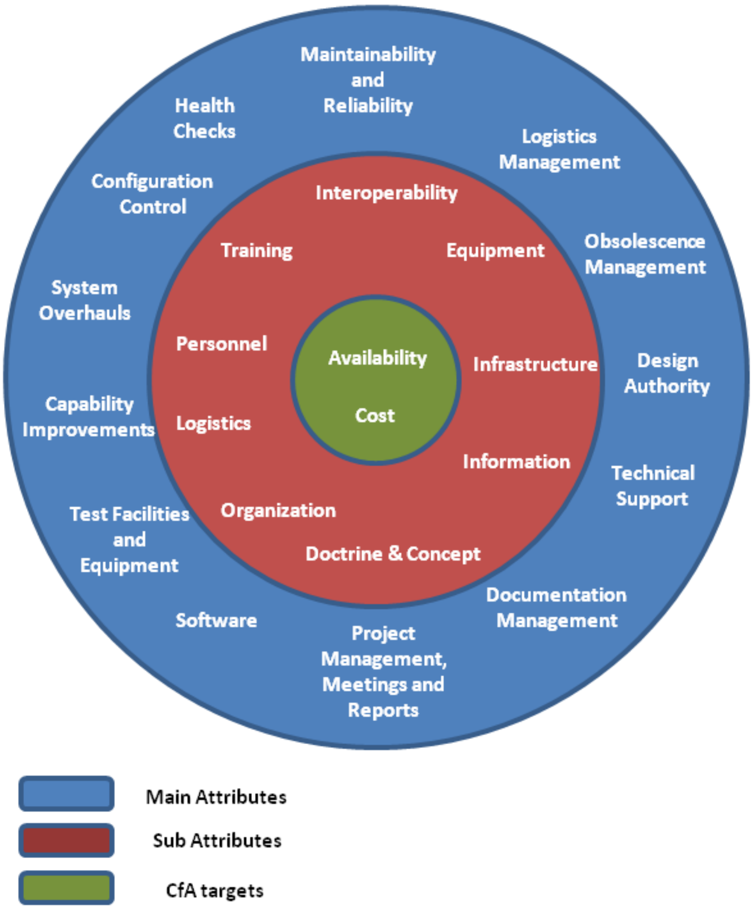


Figure 5-2 Main-Attributes and Sub-Attributes Impacting on Cost and Availability in CfA: Empirical Results

The literature review started with an initial search for articles that related to the attributes defined in Table 5-1. The search was performed in SCOPUS platform using the keywords: “attribute name” AND (“through-life planning” OR “engineering” OR “performance-based contracting” OR “availability contract” OR “contracting for availability”). Filters were also activated to select only peer reviewed documents such as journal papers and conference papers, in order to ensure reliable information sources. The review of these documents resulted in a new list of sub-attributes as presented in Table 5-2. In this list the attributes are already categorised and it was validated by participants SH1, SH2, and SH3, in a two hours interview. They considered the categorisation valid but the list of sub-attributes not yet exhaustive as it should include more attributes specific to the context of CfA, and in particular covering complex engineering systems.

The search for relevant literature continued, now using *google scholar* for searching and the keywords: “contracting for availability”, “cost attributes”, “availability/performance attributes”, “cost drivers”, and “availability/performance drivers”. The word “driver” was identified as very closely related to “attribute” and therefore it was also included in the search. Unpublished documents such as “white reports” were also considered for review. These type of documents were very useful as they contained technical information that could not be found in peer reviewed articles, and in particular related to the attributes impacting the cost and availability targets in CfA.

Among the documents reviewed, some internal reports from Organisation 5 were found that proposed a categorisation of attributes, considering the same main-attributes as presented in Table 5-1. This categorisation is shown in the list presented in Table 5-3. In this list some of the sub-attributes matched with the ones presented in Table 5-2 and some others were new.

Table 5-2 Main-Attributes and Sub-Attributes Impacting on Cost and Availability in CfA: Literature Review Results

Main Attributes	Sub-attributes	References
Training	Delivery methods	(Ford and Schmidt, 2000; Kozlowski *et al.*, 2001; Brown, 2001; Aragón-Sánchez *et al.*, 2003; Arthur Jr. *et al.*, 2003; Davis and Yi, 2004; Aguinis and Pierce, 2008; Keith and Frese, 2008; Aguinis and Kraiger, 2009; Bulut and Culha, 2010; Ehrhardt *et al.*, 2011; Martins and Soares, 2012; Sun, Hsu and Wang, 2012; Brunetto, Farr-Wharton and Shacklock, 2012; Dhar, 2015)
	Number of facilities	
	Quality of facilities	
	Frequency	
	Attendance	
	Quality of trainers and trainees	
Personnel	Loyalty and trust	(Barkdull, 1976; Knapik, *et al.*, 1983; Knapik, 1989; Songer and LaPorte, 2000; Knapik *et al.*, 2001; Kozlowski *et al.*, 2001; Grant, *et al.*, 2007; Aguinis and Kraiger, 2009; Bulut and Culha, 2010; Ehrhardt *et al.*, 2011; Brunetto *et al.*, 2012; Nouri and Parker, 2013; Hill *et al.*, 2014; Hodgetts, 2014; Casey *et al.*, 2014; Gill *et al.*, 2014; Green *et al.*, 2014; Gubata *et al.*, 2014)
	Well-being	
	Perceived accessibility to training	
	Perceived benefits from training	
	Retirement	
	Organisational commitment	
	Interpersonal skills	
Organisation	Management	(Garvin, 1993; Brandes *et al.* 2004; Grant *et al.* 2007; Brunetto, Farr-Wharton and Shacklock, 2012; Nouri and Parker, 2013; Hill *et al.*, 2014)
	Structure	
	Carrier growth opportunities	
	Methodologies	
Logistics	Design changes	(Dial, 1971; Jin, 2007; Widen, 2009; Yang *et al.* 2010; Thiagarajan *et al.*, 2011; Zou, 2013; Chen, 2014; Liang *et al.*, 2014; Mkandawire *et al.*, 2014; Squires and Hoffman, 2014)
	Training	
	Transportation	
	Maintenance planning	
	Maintenance scheduling	
	Technology integration	
Infrastructure	Size	(Klose and Drexl, 2005; Hodgetts, 2014)
	Quality	
	Location	
Information	Communication	(Barker and Camarata, 1998)
	Data collection and storage	
	Data sharing	
Equipment	Design	(Barkdull, 1976; Arshad *et al.*, 2014; Hodgetts, 2014; Mkandawire *et al.*, 2014; Martorell *et al.*, 2015)
	Type	
	Failure rate	
	Performance	
	Complexity	
Concepts and Doctrine	Development of individuals, teams, organisations, and society	(Garvin, 1993; Widen, 2009; Correll, 2014; Coticchia and Moro, 2014; Hodgetts, 2014; Paris, 2014; Patalano, 2014)
	Industrial performance, profitability, and competitiveness	
	Innovation/modernisation	
	Responsibility to protect and deliver humanity interventions	
	Research and defence diplomacy	
	Policies (e.g. Business strategy change)	
Interoperability	Interoperability	(Dial, 1971; Pope *et al.*, 1999; Davis and Yi, 2004; Klose and Drexl, 2005; Jin, 2007; Yang *et al.*, 2010; Jimenez and Rodriguez, 2012; Arshad *et al.*, 2014; Mkandawire *et al.*, 2014; Martorell *et al.*, 2015)

Up to this point, more information was found in unpublished documents than in peer reviewed papers, about the attributes that impact cost and availability in CfA. Although there is always a question of whether or not unpublished documents such as internal reports from industry organisations, presentations, or “white papers” can be seen as trustable, they can at least be a starting point for study and discussion, when there is limited peer reviewed literature about the topic. Also, it has been identified that unpublished documents tend to provide a list of attributes more specific to the context of complex systems and CfA, whereas in the published literature the attributes are more generic.

Table 5-3 Main-Attributes and Sub-Attributes Impacting on Cost and Availability in CfA: Results from Unpublished Material

Main-Attributes	Sub-attributes	
Training	Single service training	Individual training
	Joint training	Synthetic training
	Multinational training	Life training
	Collective training	
Personnel	Individual training	Vocational and career development
	Professional category	Carrier expectations/plans
Organisation	People relationships	Business organisation
	People carrier structure	Organisation reviews
Logistics	Procedures and mechanisms	Maintenance management
	Design and development	Supplying of services, medical, and health service
	Storage	Training management
	Transport and Distribution	Structures
	Disposal	Sustainability
Infrastructure	Requirements	Work-related buildings
	Operational expeditionary infrastructure	Storage
	Housing	
Information	Information management	Information categorisation
	Information sharing	Streaming
	Information drawn from all resources relating to a capability	
Equipment	Deployable equipment	Equipment cost
	Non-deployable equipment	Software

	Operational equipment	Hardware
	Non-operational equipment	Obsolescence
Concepts and Doctrine	Provenance	Innovation
	Authority	Alternative solutions
	Timescale	Research analysis and experimentation
	Realism	Policies
	Doctrine hierarchy	
Interoperability	Requirements	

The search for more attributes (sub-attributes) continued with two semi-structure interviews with participants SH9 and SH12 respectively. These interviews were face-to-face and had an average duration of 3 hours each. Participant SH12 mentioned attributes that were already included in Table 5-1, Table 5-2 and Table 5-3, whereas participant SH9 suggested to consider the Integrated Logistic Support elements (ILS) and the Human Factors (HF) as sub-attributes, and provided some references from literature (Booher, 2003; Morrow, 2008; Ministry of Defence, 2014; Defence Equipment and Support Engineering Group, 2015; Jitwasinkul *et al.*, 2016). These two concepts were referred to be widely as applied in the context of performance-based contracts (e.g. CfA), and their definition was well established in literature. The UK Acquisition System Guidance website, administrated by Organisation 5, was also suggested as a trustworthy source of information to research about the ILS and HF. The website contains a large amount of unpublished material such as lecture notes and reports (these resources are in a non-referable format but are available at: https://www.aof.mod.uk/index.htm), produced by subject matter experts from the defence context. Among these sources the following definitions are provided:

ILS is a disciplined approach to managing through-life cost (TLC) that affects both the customer and its supplier(s), in the context of defence. Its aim is to optimise the TLC by minimising the support system required for products (e.g. CfA), through influencing their design for supportability and determining the optimum support requirements. The end result is supportable and supported products (contracts) at an optimised cost. The ILS elements consist of:

I. **Supply Support:** is responsible for the timely positioning, distribution and replenishment of spares, repair parts and special or consumable supplies.

II. **Technical Information:** is the information necessary to install, operate, maintain, repair and support the product through-life.

III. **Maintenance Planning:** establishes the maintenance concepts and requirements for products using analysis tools and methodologies such as: failure mode and effects analysis, reliability centred maintenance, and level of repair analysis.

IV. **Reliability and Maintainability:** these are vital characteristics of CfA products. They affect the sustained delivery of the required performance in the field and are major drivers of the cost of equipment ownership through-life. They must be designed and built into a system during development and manufacture, if high levels of sustainability are to be achieved in-service.

V. **Facilities:** are the physical infrastructures required to integrate, operate and maintain products.

VI. **Packaging, Handling, Storage and Transportation (PHS&T):** the management of PHS&T ensures that all products and support items are packaged, handled, stored and transported properly and in conformance with appropriate legislation - particularly for hazardous materials.

VII. **Training and Training Equipment:** trained and qualified operators and maintainers are required to support products in service. Good training reduces TLC and increases system efficiency, safety capability and availability. The provision of training and training equipment impacts system effectiveness through: higher safety, increased efficiency, greater availability, lower whole life costs, and more capability (by consideration of the effectiveness of both operational and support functions).

VIII. **Disposal:** considers the efficient, effective and safe disposal of products, spares and consumables, throughout the product life. Disposal needs to consider the possibilities of re-deployment, sale, waste disposal, environmental impacts and the possible disposal of recovered material by sale.

IX. **Software Support:** is an intrinsic aspect of the support for any system with software content. Software Support is managed and controlled to ensure that equipment fit, form and function is not compromised.

X. **In-Service Monitoring:** the comparison of anticipated and actual performance and in-service costs permits decisions to be made which allow changes in the support strategy. This allows TLC to be managed by improving the design and/or supportability characteristics as appropriate.

XI. **Whole Life Cost:** also known as TLC, whole life cost identifies the system or product cost across all stages of acquisition: research and development, design, manufacture, operation support, and disposal or recycling.

XII. **Obsolescence:** is defined as the loss, or impending loss of the manufacture or supply of items, or shortages of raw materials. The rate of technological innovation coupled with the challenging in-service lives of complex materiel, mean that it is almost inevitable that obsolescence will impact on all products at some stage.

XIII. **Configuration Management:** applied over the life of a product, provides control and visibility of the product’s functional and physical attributes. Configuration management provides verifiable evidence that the product is capable of meeting requirements and is identified in sufficient detail as an aid to supportability throughout the lifecycle.

Human Factors is a multidisciplinary field incorporating contributions from the human sciences such as occupational and organisational psychology, sociology, anthropology, physiology, ergonomics and anthropometry. HF relates primarily to the science of understanding the properties of human capability at the individual, team and collective levels, and includes:

I. **Manpower:** this domain concerns the numbers of men and women required and potentially available to operate and maintain the system under consideration. From an HF integration perspective, there is a need to ensure that systems can be operated, maintained, and supported safely and efficiently with the minimum manpower, taking account of all conditions (emergency and operational) throughout the lifecycle of the system. Manning is the process of allocating appropriate personnel to a specified task or set of tasks. The process of developing the "manpower solution" requires prior analysis of the task and skill requirements, and consideration of appropriate accommodation, skills available and associated equipment. The purpose is to ensure that the right people are available to perform the required tasks at the right time having received the right training;

II. **Personnel:** concerns the required human physical, sensory and psychological characteristics, and required qualifications and experience to be able to operate and maintain the system under consideration. Physical characteristics include: gender, body size (anthropometry), strength, fitness and health. Sensory characteristics include: vision (including colour perception), hearing and dexterity. Psychological characteristics include: intelligence, literacy, numeracy and other mental aptitudes, ability to assimilate the training required (for the candidate's chosen trade) and the ability to work in a team. A clear understanding of the required characteristics of the users is fundamental to effective system design.

III. **Training:** is concerned with the training that is required to develop the knowledge, skills and abilities needed by personnel to operate and maintain systems to a specified level of effectiveness under the full range of operating conditions. Training builds cohesion and teamwork, and ranges from individual proficiency training to the conduct of complex training exercises. Training also enables personnel to continue to operate in the confusion and stress scenarios beyond a predefined (raw) capability. Training must be provided for individual operators, users and maintainers and sub-teams in order to support the delivery of the operational capability. Collective (team) training plays a critical role in enabling the Services to meet their objectives of increased operational effectiveness with fewer personnel.

IV. **Human Factors Engineering:** addresses the widest range of HF integration considerations and those of most central concern to the design of products. The considerations in this domain are often those that most directly affect personnel performing their jobs and tasks, and which can impact performance. The range of human factors engineering considerations that arise during procurement include the following domains: workspace and workstation specification and design; design of user-equipment interfaces and role of human factors style guides; use of automation; layout of operational, rest and transit areas and equipment; and design of the working environment in normal and abnormal working conditions.

V. **System Safety:** is concerned with the capability of the system to be operated and maintained without risk of injury or death to personnel. Adverse conditions may occur when the system is functioning in a normal or an abnormal manner. Every design decision may impact on system safety to a greater or lesser degree and may affect the risks to humans from damage, equipment malfunction or operator error. These risks must be continually assessed for the full range of interacting factors: design of equipment interfaces; workspace and compartment layout; movements of human and equipment; environmental conditions; operational duties; recreational activities; maintenance tasks. The safety management system is typically the focus for integrating the results of HF integration activities related to system safety. The HF integration programme must help to ensure that safety risks and safety mitigations are continuously addressed and entered into the safety case.

VI. **Health Hazards:** this domain is concerned with the conditions inherent in the operation or use of a system or equipment that may cause injury, illness, disability, or even death, or reduce the performance of personnel. Health hazards can occur in many forms. Health may be affected by the basic operation of equipment (e.g. repetitive strain injury and muscular strain), exposure to extreme environmental conditions, exposure to environmental emissions or materials, and by unhygienic working environment and/or living accommodations (for example, bacterial infection in galleys or washrooms). The types of health hazards that need to be considered are: noise (continuous or impulse sound); vibration (continuous or impulse vibration); toxicity (materials or fumes); electrical exposure; mechanical exposure (any moving parts which could entrap or injure); nuclear, biological or chemical exposure; musculoskeletal impact (for example, heavy lifting, repetitive movement, G-forces, shock, recoil); temperature extremes (heat/cold from the equipment or the environment in which it is being operated); optical injury (for example, exposure to equipment such as light sources that may cause ocular burns); electro-magnetic radiation (for example, magnetic fields, microwaves).

VII. **Social and Organisational:** this domain is concerned with the development of sociotechnical systems and improving organisational performance through the creation of suitable structures, social environments and processes. This domain has been specifically developed in response to changes in the following operational contexts: network enables capability, distributes operations, agile operations, and joint operations. There is a need for considering a broad range of social and organisational factors in system design, development and operation. Moreover, they must be considered across three key areas: organisational configuration, social environment, and ways of working.

Participant SH9 also suggested that these attributes could be seen as sub-attributes of the ones presented in Table 5-1. He acknowledged that although some ILS and HF have the same name as the attributes presented in Table 5-1 (e.g. training and personnel), their definitions and scope are different. A full “digestion” and validation of these new attributes was made in a workshop with participants SH1, SH2, and SH3, followed by two semi-structured interviews with participants SH2 and SH3. They acknowledged that, based on their experience from previous/recent CfA where that have been involved, all the attributes identified up to this stage were relevant to the context of CfA, although the level of relevance depends on the type of contract and system considered. They also suggested a new list of attributes that links ILS elements and HF to the attributes of Table 5-1, as presented in Table 5-4. In this compilation the participants still added some new “sub-attributes” to the list based on their experience.

Table 5-4 Main-Attributes and Sub-Attributes Impacting on Cost and Availability in CfA: Final List

Training Attributes						
Course Continuous Monitoring & Development	Training Facilities	Maintenance Planning	Reliability & Maintainability	Training & Training Equipment		
Training Development	Training Administration	Whole-Life Costs	Manpower	Personnel	Training Aids & Documentation	
Training Needs Analysis	Training Personnel	Human Factors Engineering	System Safety	Health Hazards	Interoperability	
Equipment Attributes						
Interoperability	Post Design Services	Technical Information	Maintenance Planning	Reliability & Maintainability		
Equipment Purchase	Equipment Support Facilities	Packaging, Handling, Storage & Transportation	Training & Training Equipment	Health Hazard		
Installation & Setting to Work	Engineering Support	Software Support	In-Service Monitoring	Whole-Life Costs		
Inventory Costs	Health and Safety	Obsolescence	Configuration Management	Obsolescence Contingency		
Technology Refresh	Project Management	Human Factors Engineering	System Safety	Training	Disposal	Repair & Overhaul
Personnel Attributes						
Interoperability	Number of Leading Hands Required	Maintenance Planning	Training & Training Equipment	Whole-Life Costs		
Social & Organisation	Number of Able Hands Required	Manpower	Personnel	Training		
Number of Chief Procurement Officers Required	Project Team Required	Human Factors Engineering	System Safety	Health Hazards	Number of Procurement Officers Required	
Information Attributes						
Supporting Documentation	Health Hazards	Maintenance Planning	Technical Information	Supply Support	Configuration Management	
Interoperability	Social & Organisation	Reliability & Maintainability	Packaging, Handling, Storage & Transportation	Software Support	Training	
Plans & Associated Documentation	Supporting Information Technology Infrastructure	In-Service Monitoring	Whole-Life Costs	System Safety	Obsolescence	
Concepts & Doctrine Attributes						
Human Factors Engineering	Training	Training & Training Equipment	Manpower	Interoperability	Personnel	
Organisation Attributes						
Interoperability	Social & Organisation	Manpower	Personnel	Training		
Infrastructure Attributes						
Facilities	Whole-Life Costs	Interoperability	Facilities			
Logistics Attributes						
Interoperability	Obsolescence	Supply Support	Maintenance Planning	Reliability & Maintainability		
In-Service Monitoring	Configuration Management	Packaging, Handling, Storage & Transportation	Disposal	Software Support	Whole-Life Costs	

At this stage, the list of attributes was already considered to be comprehensive, covering almost all the attributes that can impact availability and cost in CfA, according to the opinion of the stakeholders involved (SH1, SH2, SH3, SH6, SH7, SH9, SH10, SH11 and SH12) and based on the results of the literature review. Due to the quantity and diversity of attributes identified, additional validation was targeted as well as a preliminary assessment of the relationships between sub-attributes and main attributes. To achieve this aim, an on-line survey was designed and launched to be accessible by people from different suppliers, customers and consultancy organisations from different industry domains, that are involved in CfA at different levels (e.g. designing, negotiating, delivering, etc.). The consultancy organisations refer to those organisations that aim at supporting either customer and/or supplier in all the processes related to CfA (e.g. design/evaluate bid proposals, plan support, monitor support delivery, etc.). The targeted people in this survey were those with management level responsibilities in the process of planning and delivering CfA solutions. Actually, the reason for selecting the survey technique was to easily reach a diverse sample of people that is directly involved in the design and deployment of CfA solutions, in a daily basis, and therefore have the experience and knowledge to provide valuable insights about subject of study. This approach also allowed to get insights from other stakeholders than the ones presented in Table 2-8, minimising the risk of bias and increasing confidence in the conclusions of the study.

Thus, the survey aimed at:

1. Validating the list of attributes and their categorisation;
2. Assess the impact of each sub-attribute in the related main-attributes.

The description of the survey and its results is presented in the next section.

5.3.3 The Impact of each Sub-Attribute in the Related Main-Attributes

The survey contained a default list of attributes and sub-attributes and the respondents were challenged to select those that they considered to have a higher impact on the effectiveness of each main-attribute. The respondents of the survey were also asked to suggest some other attributes that they considered relevant.

Due to the large number of sub-attributes previously identified, not all could be included in the survey. Thus, the attributes presented in Table 5-1 were presented as main-attributes, and the ILS and HF were suggested as sub-attributes. The reason for selecting the ILS and the HF was because they appear to be better understood by the practitioners and because there was a clear definition for each of those in literature. These definitions could not be included in the survey due to limitation on the survey size, but references were provided to guide the respondent to those definitions, in case they need. Nevertheless, the sample of people targeted to respond to this survey was assumed to have a good understanding about these set of attributes from their job experience. Also, to ensure that the targeted people would be reached by this survey, the study had the cooperation of the UKCeB, which is a non-profitable organisation chaired by the UK secretary of state, and that promotes/facilitates the sharing of information between major contracting organisations in UK in different areas of operation, and with strong focus on PBC business (e.g. CfA). This organisation sent the survey to a list of people whose profile matched with the target audience, and let it available on-line for one month.

In total, 13 people responded to this survey. Each respondent provided information about job role, business sector and years of experience, as shows in Table 5-5.

Table 5-5 On-line Survey: Respondents Details

Position in the CfA business	Job Role/Business Sector	Years of Experience
Customer	Defence	35
Consultant	Cross Sectors	30+
Supplier	Defence and Aerospace	25+
Consultant	Cross Sectors	25
Supplier	Defence	15+
Consultant	Cross Sectors	41
Supplier	Aerospace	30
Customer	Defence	4
Customer	Defence	29

Consultant	Cross Sectors	20+
Supplier	Defence, Aerospace and Transportation	20+
Customer	Defence	28
Customer	Defence	15

The size of the sample and the identification/selection of the appropriated population for sampling are generally referred in literature as the two most important parameters to consider when preparing an on-line survey (Draugalis, Coons and Plaza, 2008). However, it was hard to assess if thirteen responses was enough to ensure the quality of the results, and in particular when we do not know the size of the population of study, as most of the approaches proposed to define an appropriate sample size are based in the population size (Kadam and Bhalerao, 2010). However, there are a lot of other factors that must be considered at the time of defining the sample size such as: adjustments for ineligibles and nonresponses, expense of the design given the sample size, and credibility (Henry, 1990), which make the process complex and subjective.

In qualitative surveys, as is the case in this survey, the sample should be of at least ten elements, and can have more than forty, depending on how accurate the survey results are expected to be (Hardon *et al.*, 2004). But it is also referred in literature that this accuracy can be driven more for the quality of the data collected than for the size of the sample (Degu and Yigzaw, 2006). Although in this survey the sample size was a variable out of control for the researcher, the quality of the data collected was considered to be high, as each respondent spent an average of thirty minutes responding to the survey, which demonstrates commitment and responsibility in the responses, and they had an average of thirty years of experience in their jobs which gives them the ability to provide valid and meaningful insights and responses.

Throughout the analysis of the survey results, the level of impact/association between attributes will be considered based on the percentage of respondents that recognised that impact. However, as no rule has been identified in literature to quantify the impact of each sub-attribute on the main-attributes based on the number of participants recognising that impact, the following criteria was assumed, as adapted from a 4 point likert scale to rate impact (Bierman *et al.*, 2016):

- If between 0 and 24% of the respondents recognised impact of A in B - being A and B a sub and main attribute respectively - than A has no impact on B.
- If between 25 and 49% of the respondents recognised impact of A in B, than A has slight impact on B.
- If between 50 and 74% of the respondents recognised impact of A in B, than A has considerable impact on B.
- If between 75 and 100% of the respondents recognised impact of A in B, than A has great impact on B.

The results of the survey are presented in Figure 5-3 using a fishbone diagram (Levinson, 2006), where each “bone” corresponds to each main-attribute, and indicates the number/percentage of respondents recognising impact of each sub-attribute in that main attribute. The sub-attributes considered are listed on the left of the figure and differentiated with different colours As there are some ILS and HF with the same name as the main-attributes considered (the ones from Table 5-1), the main-attributes are written in italic style and marked with “*” for differentiating, e.g. “*attribute**”. Upon analysis of the results presented in Figure 5-3, it is possible to see that “training & training equipment”, “manpower”, “personnel”, “training”, “human factors & engineering” and “system safety” have a great impact on *Training**. Other sub-attributes such as “maintenance planning”, “reliability & maintainability” and “health hazards” have also considerable impact on *Training**. Moreover, the respondents highlighted that *Training** must include operator, maintainer and logistics training, and that time and quality are important aspects to be considered towards an effective training delivery. These five aspects might be considered as new sub-attributes, or *Training** could be broken-down into more subcategories in order to address these new elements. The respondents also suggested “technical complexity”, “technical experience”, “technical knowledge”, “training development” and “logistics training” to include in the sub-attributes list for *Training**.

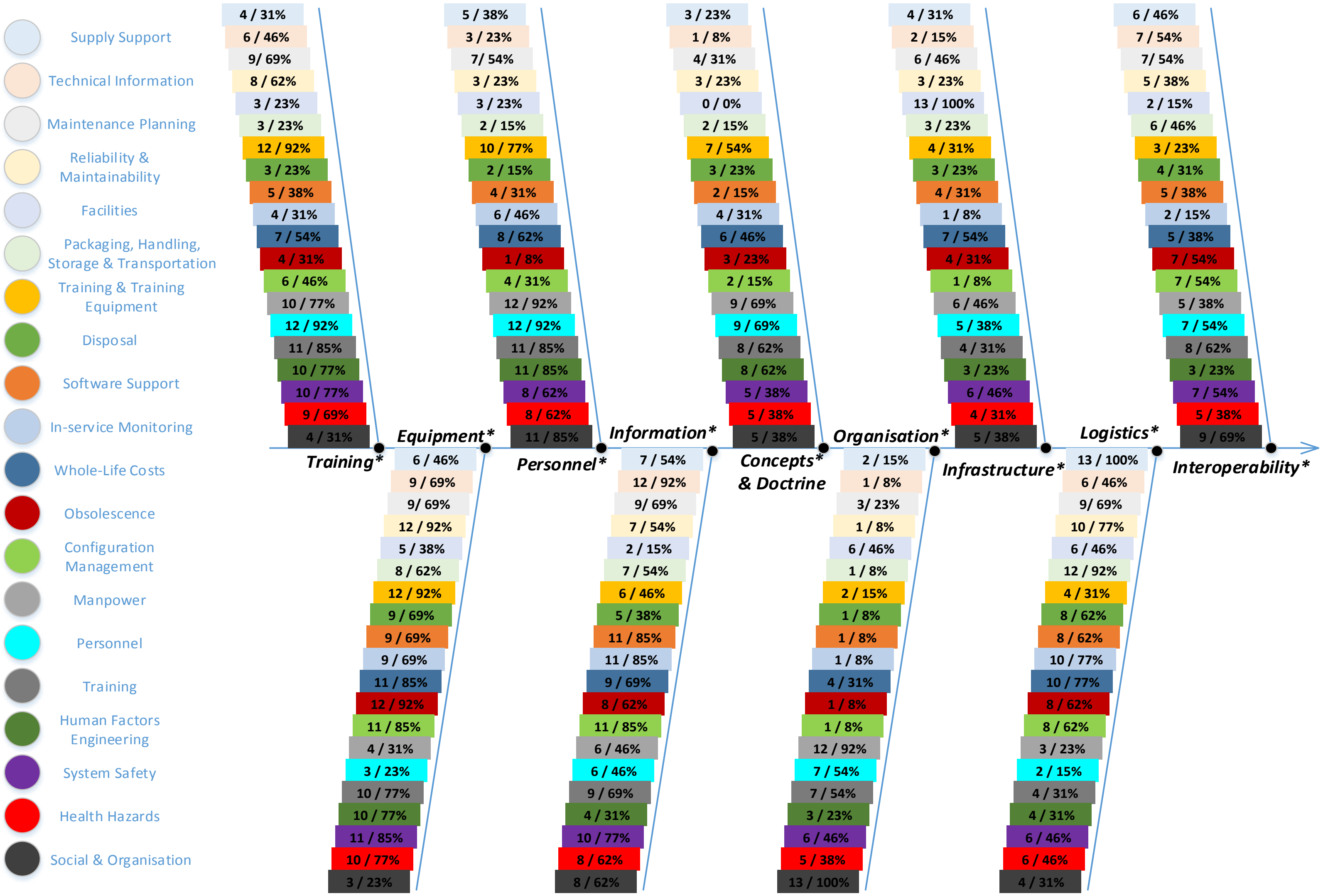


Figure 5-3 Survey Results

For *Equipment**, the attributes with greater impact are “reliability & maintainability”, “training & training equipment”, “whole-life costs”, “obsolescence”, “configuration management”, “training”, “human factors engineering”, “systems safety”, and “health hazards”. Also, apart from “manpower” that has only slight impact, and “personnel” and “social & organisation” that have no impact, all the other attributes have considerable impact on *Equipment**. Moreover, the respondents suggested three new sub-attributes to consider as impacting on *Equipment** which are: “health & usage monitor systems”, “support & test equipment”, and “complexity”.

For *Personnel**, the attributes with greater impact are “training & training equipment”, “manpower”, “personnel”, “training”, “human factors engineering” and “social & organisation”. In contrast, “technical information”, “reliability & maintainability”, “facilities”, packaging, handling, storage & transportation”, “disposal”, and “obsolescence” have no impact. The respondents also suggested to consider the following sub-attributes as impacting on *Personnel**: “supplier personnel”, “contractor personnel”, “trust”, “number of people”, “experience”, and “knowledge & skills”.

For *Information**, the attributes with greater impact are “technical information”, “software support”, “in-service monitoring”, and “configuration management”. Moreover most of the other attributes have considerable impact and only “facilities” has no impact. The respondents referred that “information sharing” and “quality of exchange information between customer and supplier” are actually the two most important sub-attributes of *Information**, and gave some examples of types of information that are important to be shared between customer and supplier such as: availability, configurations, locations, economic life, costs to operate, etc. Also, they suggested to include as sub-attributes: “modelling & analysis”, “information assuring”, “software and hardware robustness”, “planning”, and “information accessibility”.

There is no sub-attribute, from the list provided, that has a great impact on *Concepts and Doctrine**. There are however some sub-attributes that have a considerable impact such as “training & training equipment”, “manpower”, “personnel”, “training”, “human factors engineering”. Moreover, “facilities” have no impact at all. The respondents suggested to consider “operational requirements” as a sub-attribute in this category as it defines how to contract effectively according to the operational needs.

For *Organisation**, only “manpower” and “social & organisation” have a great impact, being this least unanimous between all the respondents. All the other attributes have slight or no impact, except “personnel” and “training” that have between slight to considerable impact. The respondents also suggested to include aspects related to the joint support delivery such as: “attribute control”, “attribute influence”, “risk” and “equipment ownership”, as having a great impact on *Organisation**.

For *Infrastructure**, only “facilities” has a great impact, and it is unanimous between all the respondents. Moreover, all the other attributes have slight or no impact, except “whole-life costs” that has between slight to considerable impact. The respondents also suggested “nature”, “dimension” and “portability” as sub-attributes of great impact on *Infrastructure**.

For *Logistics**, the attributes with more impact are “supply support”, “reliability & maintainability”, “packaging, handling, storage and transportation”, “in-service monitoring”, and “whole-life costs”. Moreover, it is of highlight that there is no attributes with no impact. Also, the respondents suggested some more sub-attributes that impact on *Logistics** such as: “level of supplier responsibility over the support delivery”, “supplier support efficiency”, “business efficiency”, “planning”, “speed and agility” and “materials vulnerability”.

For *Interoperability**, there are no attributes of great impact on it. Rather, all the attributes seem to have a slight to considerable impact, which show a moderate but balanced impact. However, the respondents suggested that the following sub-attributes may perhaps have a great impact: “level of cooperation between customer and supplier”, “information asymmetry between customer and supplier” and “flexibility”.

The results of this survey are limited to the understanding of the thirteen people that responded. Although this is not large sample, it is multi-disciplinary and includes the view of the different parts of a CfA - customer and supplier. It is important to refer that not all the respondents answered to all the questions because of their limited understanding about specific attributes. Thus, four people responded about *training**, six responded about *equipment**, four responded about *personnel**, five responded about *information**, two responded about *concepts and doctrine**, two responded about *organisation**, three responded about *infrastructure**, three responded about *logistics**, and three responded about *interoperability**.

The analysis of these results led to the following conclusions:

1. There is less understanding about concepts and doctrine, organisation, infrastructure, logistics and interoperability;
2. The list of the main-attributes presented is well accepted as none of the respondents argued against any; This means that the scope of the definitions presented in Table 5-1 can cover the full list of requirements in CfA;
3. Some new attributes were suggested which reinforced the idea that it is hard to build an exhaustive list of sub-attributes because the scope of CfA is extensive and different people can suggest different attributes according to their experience. Nonetheless, it was acknowledged by the different stakeholders involved in this process that the list of attributes identified cover a comprehensive list of support requirements in CfA.

In the several interviews performed in this research and literature reviewed, one topic was introduced and highlighted as important to be considered when assessing for the impact of each attribute/sub-attribute on availability, called “key performance indicators” (KPIs). Participant SH2 and SH3 define KPIs as the means that both customer and supplier have to judge how well the customer is performing. In other words, they are the variables of a function that measures availability, under the contract specifications. Next section presents the results of the research towards identifying different KPIs for measuring availability.

5.4 Identifying the Key Performance Indicators for Measuring Availability

The search for KPIs in the context of CfA covered two interviews and one case study.

The case study was the same presented in Section 5.3.1. Some additional documents were provided about that CfA bid proposal, from where the following KPIs were identified:

- Mean time between failures;
- Number of days that the system is unable to perform as required under high availability demand;
- Number of days that the system is unable to perform as required under critical availability demand;

The word *critical* used above refers to a higher level of availability demand than *serious*. A further interview was then performed with participants SH1, SH2, and SH3, to identify some additional attributes based on their experience from previous CfA where they have been involved. From this interview, the following list of KPIs was identified:

- Mean time between failure;
- Ability to support;
- Ability to deploy;
- Ability to recover.

In this list, *ability to support* refers to the capacity of the supplier in identifying any support need and find appropriate solution, or answering positively to any support requirement, *ability to deploy* refers to the ability of the supplier in delivering each support activity on time and with success, and *ability to recover* refers to the ability of the supplier in performing repair and overhaul activities. This list was actually very similar to the case study analysis. A further interview was then performed with participants SH14, SH15 and SH15, to validate these results. The participants agreed with the list of KPIs presented and also suggested the following:

- Reliability;
- Repair Turn Round Time;
- No Fault Found Rates;
- Number of Inventory Spares.

This final list of KPIs was considered complete enough to cover the scope of any CfA, in the opinion of the stakeholders involved in this process.

The challenge now consisted of building a process to estimate the necessary investment in each attribute and sub-attribute in order to achieve the required level of performance in each KPI and consequently on availability, during the entire duration of the contract. This challenge was aligned with the objectives 2 and 3 of the PhD, and a conceptual solution to mitigate this challenge is discussed in the next section.

5.5 Designing a Framework to Trade-Off Cost and Availability at the Bidding Stage of CfA

This section proposes an innovative framework to assess the interrelationships between attributes and to assess how the investment in each attribute/sub-attribute impacts on availability and cost. It consists of a systematic process that considers the main attributes, sub attributes and KPIs, towards performing a trade-off analysis between the total cost of the support activities and the level of availability of the system, at the bidding stage of CfA. The framework considers the breakdown structure defined for each attribute in Table 5-4. Consequently, each sub-attribute has a direct impact on the related main attribute(s) and each main attribute has a direct impact on each KPI. Thus, for each sub-attribute within the breakdown structure of each main attribute, an effort will be committed towards lifting the performance of that main-attribute. Similarly, the performance of each main attribute will lift the level of each KPI. The KPIs will then be the variables of the function that measures availability, e.g. in theory, the higher the performance of the KPIs, the higher the level of availability.

The interrelationships between attributes are also considered at each level of analysis, e.g. the impact of each sub-attribute in other sub-attributes and the impact of each main attribute in other main attributes. This type of impact is very important to be considered as many examples were identified during the interaction with practitioners. For example, in the case of the sub-attributes ‘training hours’ and ‘equipment maintenance’, both measured in time. Participant SH2 stressed that by investing more in training hours there will be, most likely, less need for maintenance hours to achieve the same level of availability. The assessment of these relationships is considered as a trade-off analysis.

The proposed framework is presented in Table 5-4 and consists of three different phases of assessment. Phase 1 consists of assessing the impact of each sub-attribute on the related main attribute(s) and the interrelationships between sub-attributes. Phase 2 consists of assessing the impact of each main attribute in the KPIs and the interrelationships between main attributes. Phase 3 consists in assessing the impact of each KPI on availability. Each phase is explained in detail in the next sub-sections.

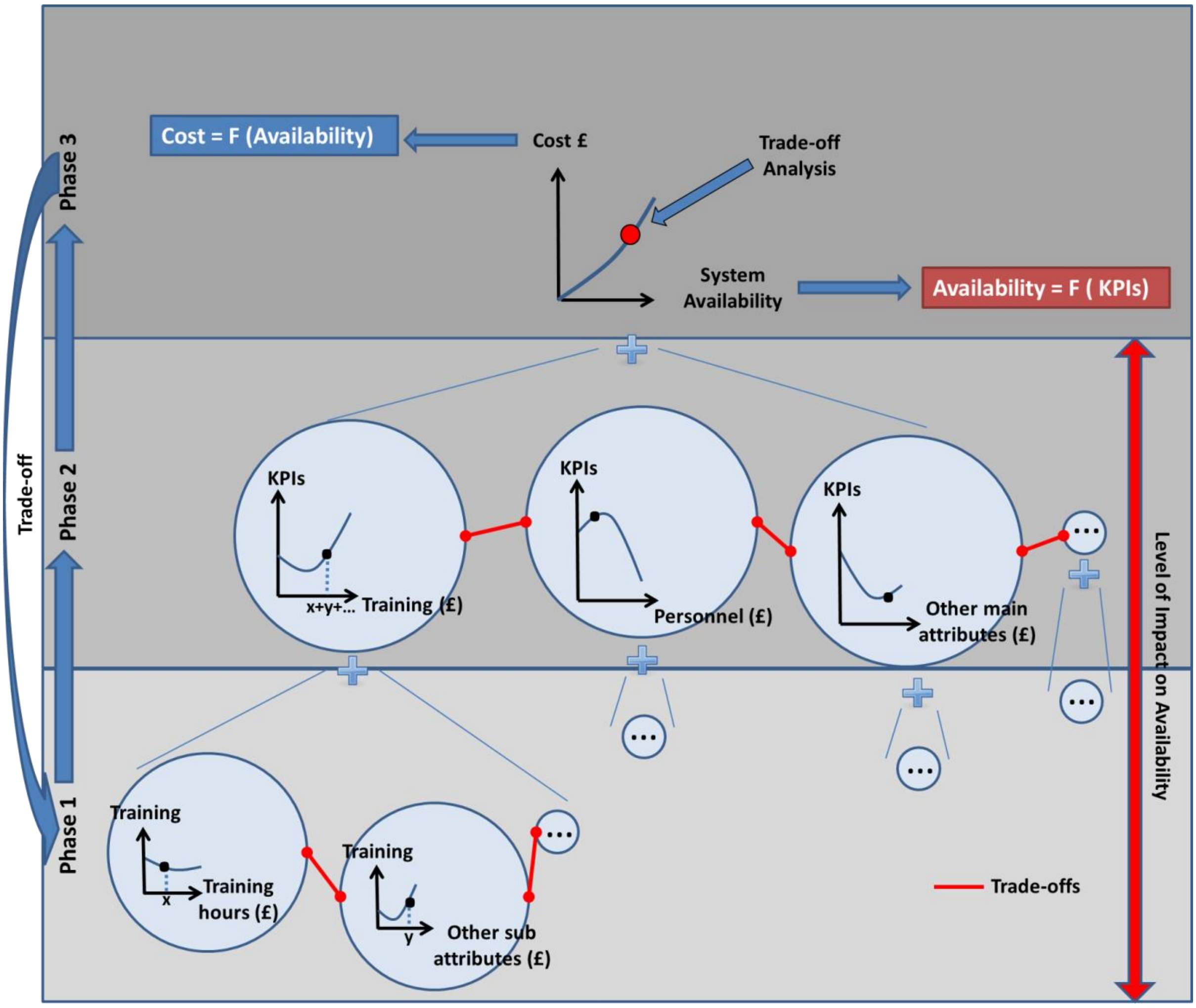


Figure 5-4 A Framework to Trade-Off between Cost and Availability in CfA

5.5.1 Phase 1: Measuring the Impact of each Sub-Attribute

The first parameter to be defined is the effort in each sub-attribute. This effort must be considered in the appropriate currency, for example, time or cost. If the currency selected is other than money, then there should be a clear formula to translate that currency to cost, in order to enable a further cost assessment.

The effort in each sub-attribute will impact in the effectiveness of each related main attribute(s) through a mathematical function. Similarly, each sub-attribute will impact in the other sub-attributes also through a mathematical function.

These functions should be generated by applying modelling techniques as the ones identified in Section 3.4.3.

5.5.2 Phase 2: Measuring the Impact of each Main-Attribute

Each main-attribute will perform according to the level of effort in each related sub-attribute. This performance will then impact on each KPI through a mathematical function. Also, each main attribute will have an impact in other main attributes which should also be assessed by means of a mathematical function. Once more, these mathematical functions should be built using modelling techniques as the ones identified in the literature review section.

The KPIs will then be variables of a mathematical function that estimates availability. This function should be agreed between the customer and supplier, according to the customer expectations.

5.5.3 Phase 3: Building the Total Cost and Availability Estimates

During the process of identifying the main and sub attributes, most of the participants highlighted that customers value when the design of the support solution is performed and presented across the attributes presented in Table 5-1 (even though those attributes are not typically included in the contract requirements). Thus, this conceptual framework considers a way of presenting the cost analysis across the main attributes.

Firstly, for each solution representing the effort in each sub-attribute, that effort must be translated to cost using the appropriate formula. Then, the cost of all sub-attributes associated to each main-attribute are added up in order to estimate the total effort in that main-attribute. This process is repeated for each main attribute. Thus, if any change is required in the effort in an attribute, that change should be made directly in the related sub-attributes until achieving the desired result.

In terms of availability, the effectiveness of each main attribute will enable a certain level of performance in each KPI. Pursuant to, the level of availability is calculated/estimated by running the availability formula considering the estimated level of each KPI. If any change is required in the level of availability estimated, the level of each KPI has to be changed until achieving the desired level of availability and consequently, the effort in each attribute (and therefore in the associated sub-attributes) must be revised until ensuring that KPIs level.

The actual trade-off analysis between cost and availability can now be performed by changing the investment across the different sub-attributes and observing how the cost of each main attribute varies as well as the level of availability. This trade-off can be repeated as many times as needed to get an acceptable balance between cost and availability that guarantees to the contractor a competitive and robust bid estimate. This acceptance will be based on a criteria of affordability and value for money, defined by the parties involved in the negotiation.

The validation of the framework was made qualitatively, by inquiring of participants SH 1, SH2, SH3, SH6, SH7, SH8 and SH9. This validation covered:

- One structured interview with participants SH1, SH2, and SH3, and other with participants SH2, SH3, SH7, of two hours duration each, where the proposed framework was presented. They recognised that this framework “reflects exactly what they need”, considers the right attributes and performs the type of analysis required, at the bidding stage. They highlighted that this framework can be a step further in terms of quality of the estimates, as the current processes do not consider these many relationships.
- One interview with participant SH9, of three hours duration, where the framework was presented with focus on the interrelationships between attributes and sub-attributes. The participant agreed that, for performing an effective trade-off analysis between cost and availability, all of the

relationships considered in the framework have to be considered, although he highlighted that it is a complex process, as these relationships may vary considerably from one contract to another; He suggested to make a good assessment of these relationships in literature, to ensure a quality implementation of this framework in a practical application;

- One interview with participant SH6, of two hours duration, where the framework was presented as well as some ideas for further implementation. The feedback of the participant was aligned with the opinion of the other participants in the other interviews, and he also suggested to consider uncertainty analysis in the estimates in order to analyse it more realistic. He highlighted that cost and availability estimates at the bidding stage should not be as single numbers but rather an interval that could give to the project manager(s) an idea of the best and worst scenario of the total project cost and system availability.

Moreover, all the participants encouraged the development and implementation of this framework in a practical application (e.g. simulation model), and recognised that such application would significantly improve the current processes of building the cost and availability estimates at the bidding stage, by producing more realistic estimates and increasing the confidence of the bid managers in those estimates through the possibility of making a trade-off analysis/assessment between cost and availability.

5.6 Summary

From the challenges identified across the industry interaction, there was a need to identify and validate a complete list of attributes that impact on cost and availability in CfA. This list would help the parties involved in a CfA to understand what impacts on availability in order to better plan the investment (£) across those attributes and optimise contracts cost. In this study, many attributes were identified, in an extensive literature review and interaction with practitioners from different organisation involved in CfA. However, it has been concluded that is it hard to define a standard list of attributes as they might vary according to the contracts' specifications and type of system considered. Therefore, a categorisation process is proposed to divide the attributes in main and sub attributes, where the main-attributes would be standard for all type of CfA, and the sub-attributes would be dynamic and selected according to the contract specifications. Four different lists of sub-attributes are presented (Figure 5-2, Table 5-2, Table 5-3 and Table 5-4), to give guidance in future contracts planning. Also, an assessment of the interrelationships between the attributes is presented based on the results of an on-line survey, where thirteen subject matter experts with an average of thirty years of experience in PBC planning and delivery gave their opinion.

In addition, a conceptual framework is presented to assess the impact of the attributes on availability and cost, considering all the interrelationships between attributes in order to allow trade-off analysis between cost and availability, at the bidding stage. A further implementation of this framework is presented in the next two chapters of this thesis.

6 COST AND AVAILABILITY TRADE-OFF AND ESTIMATION MODEL FOR CfA BIDS MODEL (CATECAB)

6.1 Introduction

This chapter focuses on developing the conceptual framework to trade-off cost and availability presented in Chapter 5, to a concrete mathematical model that was implemented in a simulation platform. This model is aligned with the fourth objective of this research.

The main output of this chapter is the model that was called Cost and Availability Trade-off and Estimation during Bidding (CATECAB). The CATECAB applies three different techniques: multiple regression analysis (Yang *et al.*, 2013), Monte-Carlo simulation, and bootstrapping re-sampling (Betterton and Cox III, 2012; Marin-Garcia and Bonavia, 2015). The multiple regression analysis is applied to build the mathematical functions that relate cost, availability and time, and a mixed Monte Carlo and bootstrapping re-sampling approach is used to mitigate data scarcity scenarios at the bidding stage, as reported in the current practices identification chapter.

The chapter is structured as follows:

Section 6.2 describes the methodology adopted for developing of the model. Then in Section 6.3, the notations applied throughout the model description and some important definitions are presented. A detailed description of the CATECAB is then presented starting with the inputs and outputs in Section 6.4, and moving to of the modelling process is Section 6.5 and subsequent sub-sections. Finally, Section 6.6 summarises the specifications of the CATECAB model and its context of application.

6.2 Methodology

The methodology designed for this research is illustrated in Figure 6-1. It consists of two main phases, with iterative processes performed within each phase and a detailed validation of all the results. The description of each phase is presented in the next two sub-sections.

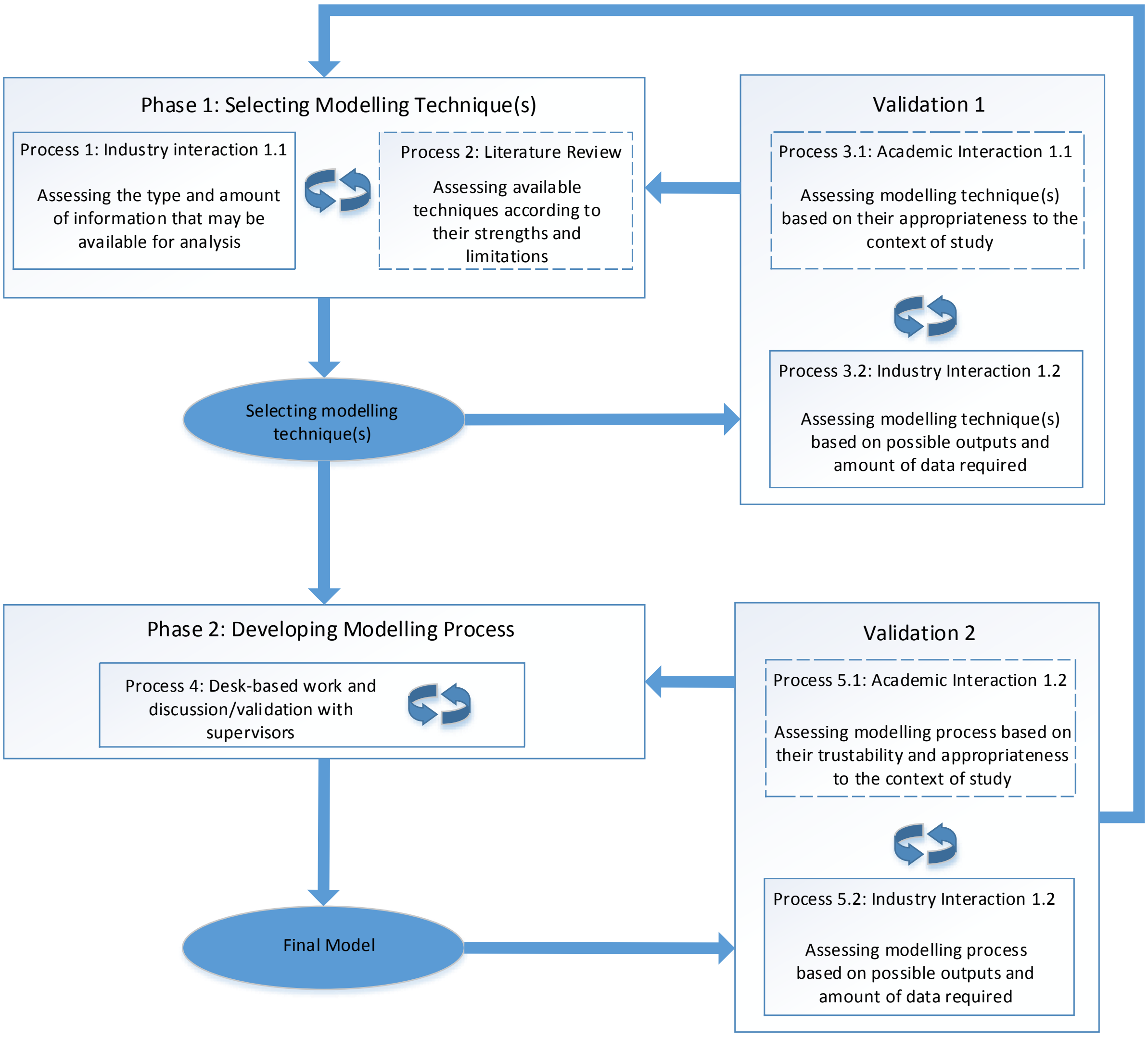


Figure 6-1 CATECAB Development Methodology

6.2.1 Phase 1: Selecting the Modelling Techniques

The first phase of this study consisted of assessing the literature and approaching the industry stakeholders in order to select the appropriate technique(s) to develop the modelling process. Three main processes were carried out during this phase: process 1 and 2 that progressed in parallel to collect information about modelling techniques and existent data, and process 3 to validate the results. Each process described below.

Process 1 - Interacting with Industry: Two structured interviews were performed with participants SH1, SH2 and SH3, with an average duration of two hours, to understand the amount of information that is typically available during the bidding stage as well as the amount and type of information that is available in their company databases, from previous projects. Subsequently, two additional interviews were performed, one with participants SH4 and SH5 and another with participant SH7 with the same aim. The information collected was also validated and enriched in informal conversations with other people involved in CfA projects that participated in the NASA Langley Uncertainty Quantification symposium in London, 2015.

Process 2 - Literature Review: the literature was reviewed according to the processes described in Chapter 3, and different techniques were identified and assessed in terms of their strengths and limitations according to different parameters of interest such as applicability and type/amount of input information required. The results of process 1 and process 2 were assessed together in order to select adequate modelling techniques to develop the model. In total, three techniques were proposed by the researcher based on the literature review results and based on the results from the industry interaction in terms of data constraints and expectation from the model. The three techniques proposed were: (1) neural networks; (2) fuzzy logic; (3) regression analysis. The acceptance of each of these techniques by the academic community and the industry stakeholders is highlighted in the description of the next processes.

Process 3.1 - Academic Validation: one structured interview with participant SH21 and several brainstorming sessions with participant SH24 and the academic supervisors were performed in order to validate the appropriateness of the modelling techniques suggested. They accepted that all three techniques suggested are powerful and could produce valuable results, but highlighted that they would have to be assessed in terms of data requirements, and those requirements would have to be validated with the industry stakeholders in terms of feasibility/availability.

Process 3.2 - Industry Validation: participants SH1, SH2, SH3 and SH8 were involved in the process of selecting the modelling techniques. These participants were selected based on their involvement in the definition of the research scope and objectives. Each technique identified in literature was presented to them to perform a collaborative selection of the most appropriate to this research. Thus, for each technique, the researcher explained to them what would be the type and amount of information required for that technique to produce certain type of outputs.

The first technique presented was *neural networks*. What they liked the most in this approach was the fact that it considers all the attributes in a dynamic network. However, they recognised that this approach is supported by complex algorithms which would maybe make difficult their understanding and a wider acceptance by other industry stakeholders.

The second technique presented was *fuzzy logic*. This technique was initially very well accepted by these participants, and in particular because of the logic of the approach that was easy to understand, and because of the dynamic nature of the outputs that it produces that were also possible to visualise (e.g. they could visualise the dynamic impact on cost and availability of any investment change in an attribute). However, when the research moved into the development phase, this approach revealed to be unfeasible because of the requirements in terms of data availability. The participants recognised that the type and amount of data required for analysis would not be possible to gather at the bidding stage.

Thus, *regression analysis* was suggested as an alternative modelling approach. This approach requires less input information than the other two approaches suggested, and can produce similar results to the fuzzy logic approach, if further developed as a simulation model. The participants recognised to be possible to provide the type and amount of information required by the regression analysis approach and liked the fact that this approach is well known by many industry practitioners which facilitate its acceptance by other industry stakeholders and makes it easier to identify case-studies for validation.

Consequently, regression analysis was the selected approach to develop the model, being recognised by the industry stakeholders as the most appropriate from the three suggested by the researcher, considering the following parameters: process modelling complexity, data availability/constraints, and expected outputs.

6.2.2 Phase 2: Developing Modelling Process

The actual model was developed in a desk-based effort over two months. During this process, several brainstorming sessions were performed with the academic supervisors to update the model development and to address suggestions and corrections. The validation of the final modelling process was performed based on feedback from academic and industrial experts, performed according to the processes 4.1 and 4.2 respectively, which consisted of:

Process 4.1 - Academic Validation: the academic community contributed towards the validation of the modelling process. It received feedback in the human factors integration symposium, held at Bristol in 2016, from a wide audience of experts in PBC and supportability, with strong academic background, in one seminar at Cranfield University, from fifteen researchers from different areas of expertise such as manufacturing process and aerospace engineering. Additionally, five brainstorming sessions with participant SH24, of one hour duration each, and some informal conversations with research colleagues from the TES centre, at Cranfield, reinforced the confidence about the modelling approach developed.

Process 4.2 - Industry Validation: the industry stakeholders validated the model throughout its development in order to ensure that was aligned with their expectations and initial plan. This validation covered: (1) three interviews of 2 hours each with participants SH1, SH2 and SH3; (2) one interview of three hours with participant SH3; (3) one interview of 1.5 hours with participants SH5, SH13 and SH17; (4) one interview of 3 hours with participants SH14, SH15 and SH16; (5) one interview of 1 hour with participant SH18.

The feedback loop in Figure 6-1 from Phase 2 to Phase 1 corresponds to the change of modelling approach from *fuzzy logic* to *regression analysis*, which forced to a reassessment within Phase 1.

6.3 CATECAB Notation and Definitions

The following notation and definitions are applied throughout this chapter:

Table 6-1 CATECAB Notation and Definitions

Availability (AV)	Availability of the system
System (S)	The element whose availability dictates the performance of the contract (e.g. equipment, platform, etc.)
Attribute (A)	Any element that impacts the availability of the system
Main-attribute (MA)	All *A* that have a breakdown structured composed by other *A*
Sub-attribute (SA)	All *A* that are part of a breakdown structured of another *A*
Investment (I)	Money effort
N	Total number of attributes that impact the availability of *S*
A_i	*i*-th attribute

MA_i	*i*-th main-attribute
SA_i	*i*-th sub-attribute
$I(A_i)$	Investment in A_i
$I_s(A_i)$	Investment in A_i in a particular *S*
$I(SA_i, MA_j)$	Investment in SA_i associated to MA_j
$C(SA_i, MA_j)$	Coefficient of association of SA_i to MA_j. $C(SA_i, MA_j) \epsilon [0,100]$
$MI_s(I_s(A_i))$	Required investment in each A_j ϵ S, when the investment in A_i is equal to $\mathrm{I}_s(A_i)$, j≠i. $MI_s \epsilon \mathbb{R}_0^{+(Ns-1)}$
$AV_s(I_s(A))$	Level of availability (in %) of the system when the investment in each A ϵ S is equal to $\mathrm{I}_s(A)$
CD	Contract duration

6.4 CATECAB Inputs and Outputs

The following information needs to be provided to the model to produce the appropriate results:

1. The list of all A for a particular S of study;
2. The historical information about $\mathrm{I}_{S_j}(S)$ and $AV_{S_j}(\mathrm{I}_{S_j}(A))$, for at least three comparable $S_{j_{j \,\epsilon\, \{0,1,\dots\}}}$.

The following outputs can be generated by the model when appropriately fulfilled with the required input information:

1. $\mathrm{MI}_s(\mathrm{I}_s(A_i))$ for a given $\mathrm{I}_s(A_i)$;
2. $AV_s(\mathrm{I}_s(A))$.

The list of inputs and outputs is sequentially described in Figure 6-2.

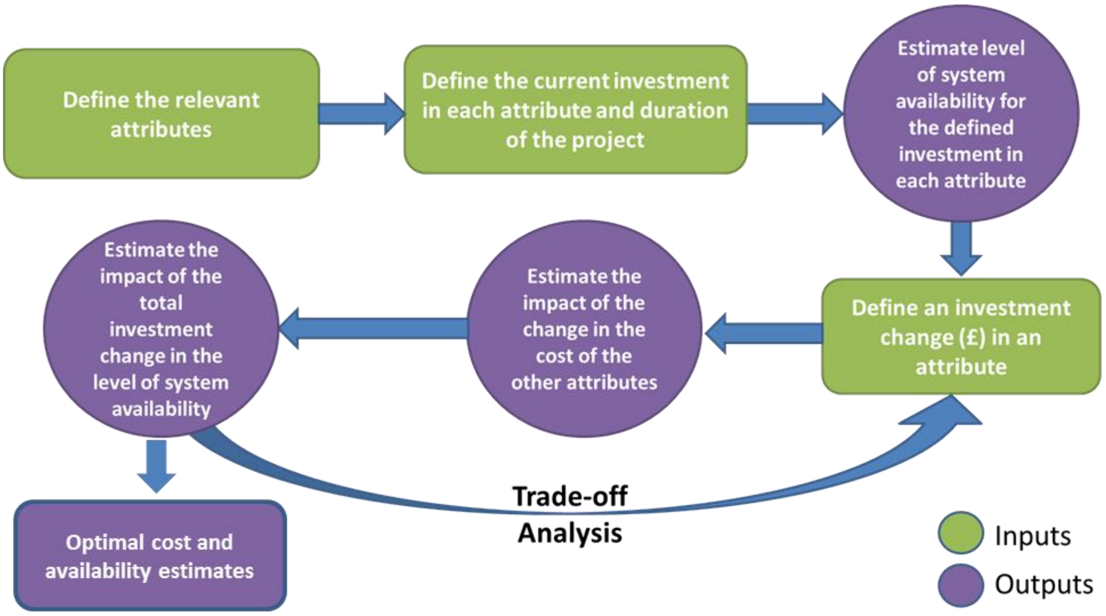


Figure 6-2 CATECAB Inputs and Outputs: Overview.

6.5 CATECAB Modelling Process

The CATECAB modelling process is described in Figure 6-3. This process was designed in a desk-based work, considering the conceptual framework presented in Section 5, and discussing ideas with the academic supervisors.

The process starts with a decision point that guides to path-1 or path-2 according to the type of analysis required to the attributes. There are two types of analysis possible: analysis through attributes' categorisation or analysis where all the attributes are at the same level. This categorisation is according to the scheme presented in Chapter 5.

Path-1 corresponds to the categorisation analysis and is for scenarios where the attributes are categorised in main-attributes and sub-attributes. The categorisation of the attributes is appropriate for scenarios where there is a large number of attributes and it is useful to make a high level analysis of the problem considering only few attributes (typically the most relevant). These most relevant attributes are then considered as the main-attributes and the other attributes are considered as part of the breakdown structure of each main attribute (e.g. the attribute training can be broken-down into trainers, facilities, documentation, etc.).

Path-2 corresponds to the non-categorisation analysis and is for scenarios where all the attributes are considered to be at the same level for the purpose of analysis. This is appropriate for scenarios where the number of attributes is reduced.

Regardless the path selected (path-1 or path-2), the type of outputs that can be achieved with the CATECAB model are equivalent, corresponding to cost and availability estimates for a contract.

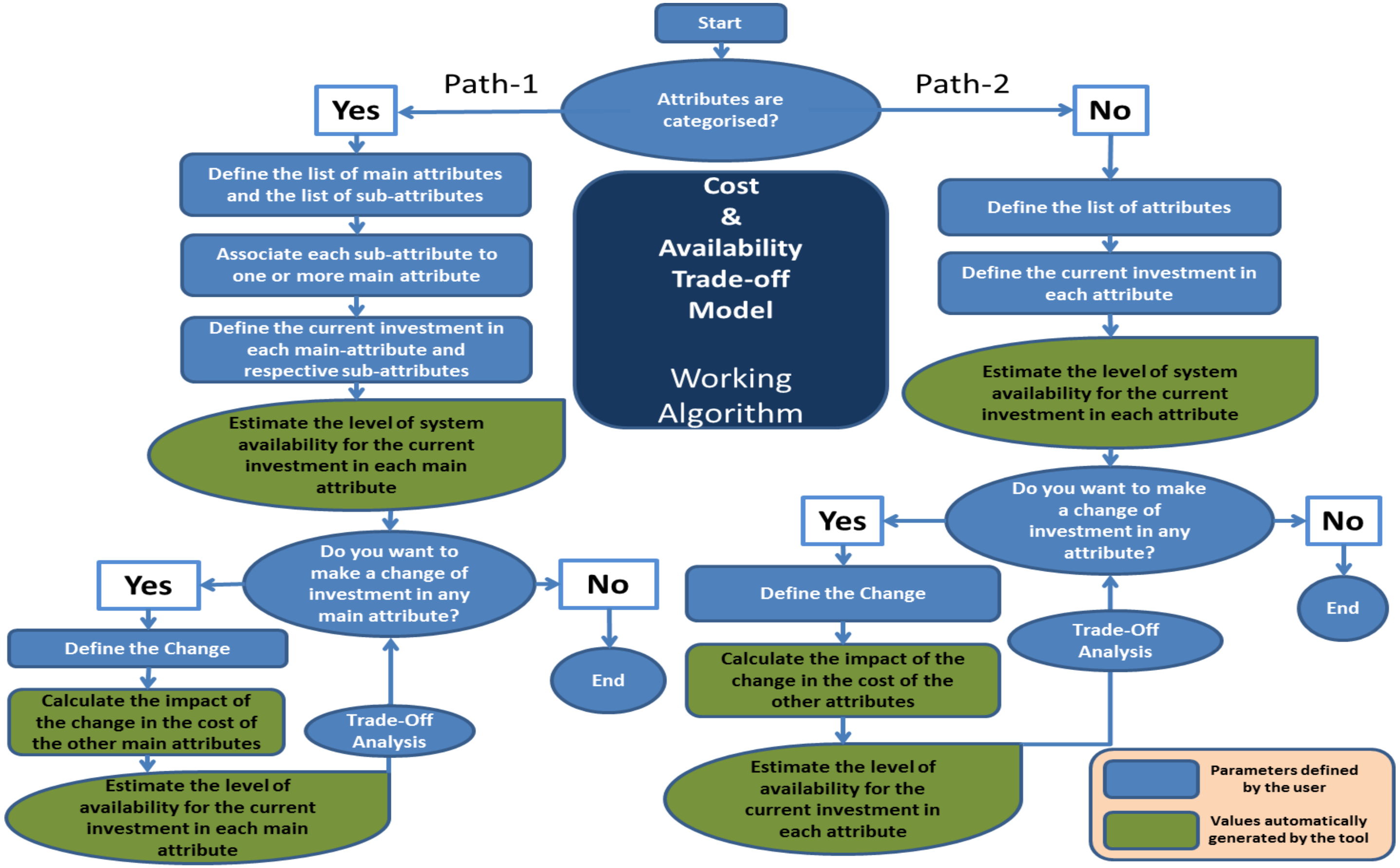


Figure 6-3 Process for Cost and Availability Trade-Off and Estimation

6.5.1 Defining the Investment in the Attributes

In Path-2, the allocation of budget per attribute follows a straight process, being the investment defined directly in each attribute. For Path-1, the process is slightly more complex and works as follows: first, the list of attributes and respective sub-attributes needs to be defined. Then, the investment is defined in each sub-attribute within each main attribute. The total investment (£) per main attribute is then calculated by adding up the cost of each associated sub-attribute as illustrated in Figure 6-4. The process is sequentially described from step 1 to 4, using the notation defined in Table 6-1.

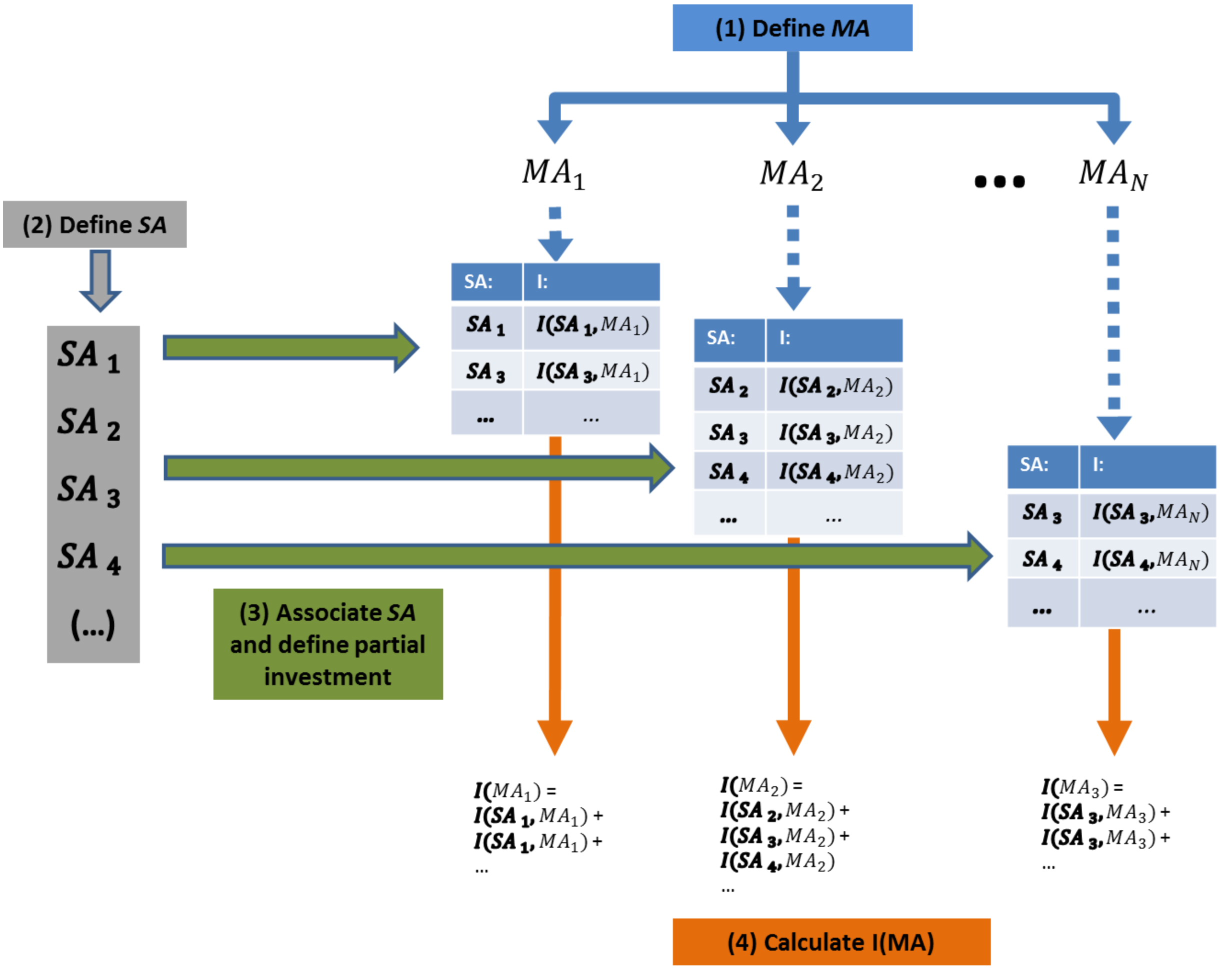


Figure 6-4 Process to Define the Investment in the Attributes for Path-1

6.5.2 Building the Cost and Availability Estimates

The cost and availability estimates are built using multi-linear regression equations. This approach is able to explain the relationship between one continuous dependent variable and two or more independent variables. The reason for selecting a linear approach is the high uncertainty about the relationship between the variables, and because at the early stages of the bidding process only a high level guidance is necessary and therefore this approach was believed to be suitable. This technique was selected based on the literature review results about modelling techniques for TES design and implementation in PBC, presented in Chapter 3. These equations explain how cost and availability vary in function of a number of variables such as: contract duration, attributes cost and system availability. The contract duration was considered as a variable, as from the current practices review it was identified that it has a big impact on cost and availability. The equation to build the regression analysis was extracted from relevant literature (Sykes, 1988; Humpage, 2000; Williams *et al.*, 2013), and is described as follows:

$$\hat{y} = \alpha_1 v_1 + \ldots + \alpha_n v_n + \beta \tag{6-1}$$

Where:

- $\hat{y}$ is the value of the predicted variable (e.g. cost or availability);
- β is constant;
- n is the number of variables affecting the estimates;
- v_i is the i-th variable;
- α_i is the regression coefficient of the variable v_i;

Each coefficient α_i represents the expected change in $\hat{y}$ for each unit of change in v_i, when the other variables are held fixed. As higher is the absolute value of α_i, higher is the contribution of v_i to $\hat{y}$. The parameters α and β are calculated based in a regression process applied to the list of inputs described in Section Figure 6-2. With that, the model estimates $\hat{y}$ so that $\sum(y_i - \hat{y})^2$ is minimal, where $(y_i - \hat{y}) = \varepsilon_i$ is the i-th error of the estimate. In fact, $y = \hat{y} \pm \epsilon$ where ϵ is the cumulative error of the estimated function. The lower the value of ϵ is, greater the quality of the approximate function $\hat{y}$ will be. The dimension of ϵ can be assessed by a coefficient of determination R^2 (Koksalan *et al.*, 1999).

6.5.3 Building Analysis through the Main-Attributes

When the attributes are categorised (Path-1), the aim is to present all the estimates based on the investment per main-attribute. However, all the calculations to estimate cost and availability are based in the total investment per sub-attribute. Therefore, it is necessary to establish a process to relate those estimates with the investment per main-attribute, which are the attributes of interest for analysis.

Let us first outline the two types of estimates that this model produces:

- Availability estimates: the level of availability of the system(s) that will be supported under a CfA agreement, considering the contract duration and certain investment in the different attributes that impact on availability.
- Cost estimates: the cost estimates cover the cost impact estimate of an investment change (£) in an attribute in the other attributes and the total contract cost.

To assess the level of availability based on the investment per main-attribute, the following process is applied in the following sequential order:

1. Define the investment in each sub-attribute within the breakdown structure of each main-attribute *I(SA,MA)*;
2. Calculate the total investment per main-attribute *I(MA)*;
3. Calculate the total investment per sub-attribute *I(SA)*;
4. Estimate the level of availability based in the total investment per sub-attribute *AV(I(SA))*;
5. Present the availability estimate and the cost per main-attribute as calculated in (4) and (2) respectively.

Steps 1, 2 and 3 proceed according to the process described in Section 6.5.1 and Step 4 proceeds by applying Equation (6-1). In this way, the trade-off analysis can be performed across the main-attribute even though the availability estimates are a consequence of the cost of each sub-attribute.

For the cost impact estimates in each main-attribute, all the process works based on the cost impact in the sub-attributes that make the breakdown structure of that main-attribute, which then is reflected on to the cost of that main-attribute. It is however a complex process because it has to deal with the fact that the same sub-attribute can be associated to more than one main-attribute.

To describe how the process works let us assume that $I^*(MA_i)$ is an investment change made in $I(MA_i)$, and we want to estimate $I^*(MA_j)$, which is the cost of MA_j as consequence of the change $I(MA_i)$ to $I^*(MA_i)$, being $i \neq j$.

The process works sequentially as follows:

1. Update $I(SA)$ for all $SA \in MA_i$ according to each investment change $I^*(SA, MA_i)$;
2. For each $SA \in MA_j : SA \notin MA_i$, estimate $I^*(SA)$ using Equation (6-1) and considering the variable CD. $I^*(SA)$ is therefore the new investment in SA as consequence of $I^*(SA, MA_i)$;
3. Once $I(SA)$ is updated for all $SA \in MA_j$ (e.g. $I^*(SA)$), $I^*(SA, MA_j)$ is calculated for all $SA \in MA_j$ such that:

$$I^*(SA, MA_j) = I^*(SA) * C\big(SA, MA_j\big) \tag{6-2}$$

Where,

$$C\big(SA, MA_j\big) = \frac{I(SA)}{I(SA, MA_j)} = constant \tag{6-3}$$

$C(SA, MA_j)$ is constant as it depends on the initial investments $I(SA)$ and $I(SA, MA)$ defined for the project.

This process can be repeated for each main-attribute in the project. Once the cost of each main-attribute is updated, the level of availability is also updated through the process described before. During this process, it is assumed that the value of CD is held fixed.

6.5.4 Guidance in the Investment Change

Regarding to the second decision point in the process defined in Figure 6-3, an investment change is typically made to find the most effective solution according to the cost and availability targets of the contract. This process is the so called trade-off analysis. This change can be made in a trial and error basis or it can be assisted by guidance from the model.

The model guides in this decision by assessing the regression coefficient of each attribute when Equation (6-1) is applied to estimate availability, in order to identify the attribute with more impact on availability. The regression coefficient reflects the level of impact of each variable of the equation in the predictable variable which in this case is the level of impact of each attribute on availability. The regression coefficient will be assessed in absolute value. Typically, the attribute with higher impact on availability is preferable to be selected for an investment change.

When the attributes are categorised (path-1), the fact that the availability is estimated based on the cost per sub-attribute brings difficulty to the design of this type of guidance across the main-attributes. To enable this task, similar process to the cost impact assessment across main-attributes is applied, as presented in Section 6.5.3, and works as follows:

1. Read α_{SA} for all SA in the project, being α_{SA} the regression coefficient associated to SA in the availability equation;
2. For all SA in each MA, calculate:

$$\alpha_{SA,MA} = C(SA, MA_j) * \alpha_{SA} \qquad \textbf{(6-4)}$$

being $\alpha_{SA,MA}$ the weight of α_{SA} relating to MA.

3. Calculate α_{MA} such that:

$$\alpha_{MA} = \sum_{SA \in MA} \alpha_{SA,MA} \qquad \textbf{(6-5)}$$

where α_{MA} is the regression coefficient associated to MA in the availability equation. The highest impact on availability will be recognised to the MA whose α_{MA} has the highest absolute value.

6.5.5 Trade-Off Analysis

The trade-off analysis is typically considered as the identification of the right balance between total cost and availability but it can also be the trade-off between the investment in two different attributes or sub-attributes and availability. For example, by investing more in a certain attribute it may be possible to achieve the same level of availability with less investment in other attributes, which may signify to achieve the same or higher level of availability for a lower total contract cost. These trade-offs are intended to be performed manually on a trial and error basis. Thus, an investment change in an attribute can be defined as many times as necessary until achieving a satisfactory solution.

For the case of path-2, an investment in an attribute can be suggested (following guidance as presented in Section 6.5.4, if needed) and the most likely impact of the investment change in the cost of the other attributes and on availability is estimated using a regression equation such as Equation (6-1).

For the case of path-1, one main-attribute can be selected to make an investment change (e.g. following guidance as presented in Section 6.5.4), and the process of defining that investment change and estimating the impact of that change in the cost of the other main-attributes and on availability is performed as described in Section 6.5.3.

6.5.6 Sample Size

The ideal number of comparable project data that must be provided to fulfil the second input condition defined in Section 6.4, is not unanimous in literature. Some authors state that it should be at least thirty times (e.g. thirty projects) the number of explanatory variables (Pedhazur, 1997) while others say that ten times would be enough (Stevens, 2009). Ideally, it should be the number that minimises the cumulative error ϵ. The minimum number that the CATECAB model requires is three projects' data, although it is advisable to use twenty times the number of attributes, if possible, to ensure better quality estimates. Thus, for the simplest case of a project with four attributes defined, eighty comparable projects' data would be ideal. Typically, the higher is the size of the sample, better will be the accuracy of the estimates. Small sample size can produce non-significant regression coefficients which in turn will harm the results (Lin *et al.*, 2010). However, obtaining large data samples is challenging according to the findings obtained from the industrial interaction.

In one interview with participant SH21 of two hours duration, aimed at validation the modelling process, the participant suggested to apply bootstrapping resampling technique or Monte-Carlo simulation in order of generate an extended data sample. This participant has more than 15 years of experience in modelling, so his opinion was considered very trustable. In a further telephone interview with participant SH18, aimed also at validating the modelling process of the CATECAB model, the participant also suggested to apply bootstrapping technique and Monte-Carlo simulation to generate extended data samples. A further investigation was performed in literature which confirmed the valuable use of these approaches towards extending data samples, without losing too much of pattern of the original data.

Thus, and to ensure that the CATECAB estimates would be built based on input samples of information with enough size to ensure quality estimates, a bootstrapping resampling technique combined with Monte-Carlo simulation was applied to create an extended dataset.

This extended dataset is built in such a way that it preserves the pattern of the original data and does not significantly change the relationships between the different attributes, for the purpose of analysis. The suggested approach also guarantees that the normality condition of the data required to apply the regression analysis technique (Williams *et al.*, 2013). The bootstrapping resampling and Monte-Carlo techniques applied are described in Section 6.5.7.

6.5.7 Extending the Sample Size

The mixed bootstrapping re-sampling and Monte-Carlo simulation approach applied to extend the data samples works as follows:

Let us denote the investment in the *ith* attribute in the *jth* project by $d_{j,i}$. For each dataset $\left[d_{j,i}\right]_{i=0,..,\mathrm{k}-1}$ of a project *j*, a range of $\left[d_{j,i} - a_i * \left(d_{j,i}\right), d_{j,i} + b_i * (d_{j,i})\right]_{a_i,b_i \,\epsilon\, \mathbb{R}_0^+}$ is first considered. Here, a_i and b_i represent an upper and lower degree of variation of each sample value. This can also be seen as an uncertainty range for each sample value that can be measured, for example, with existent tools such as those presented in (Ho *et al.*, 2005; Erkoyuncu *et al.*, 2013; Abdo and Flaus, 2016).

After having these uncertainty ranges defined for each dataset provided, *N* new datasets can be artificially generated, with no limit for the value of *N.*

These new datasets are obtained by generating random numbers within the specified range, by applying a mixed Monte-Carlo and bootstrapping re-sampling technique as illustrated in Figure 6-5.

All the data corresponding to an attribute *i*, considering each group of artificial datasets generated from an original dataset $[d_{j,i}]_{i=0,..,k-1}$, is normal distributed within the uncertainty range defined for $d_{j,i}$.

In the example illustrated in Figure 6-5, three attributes and *k* data sets are considered which can be, for example, *k* different contracts. Also, a fixed uncertainty range of [-10%, +10%] of the original value is considered for each attribute.

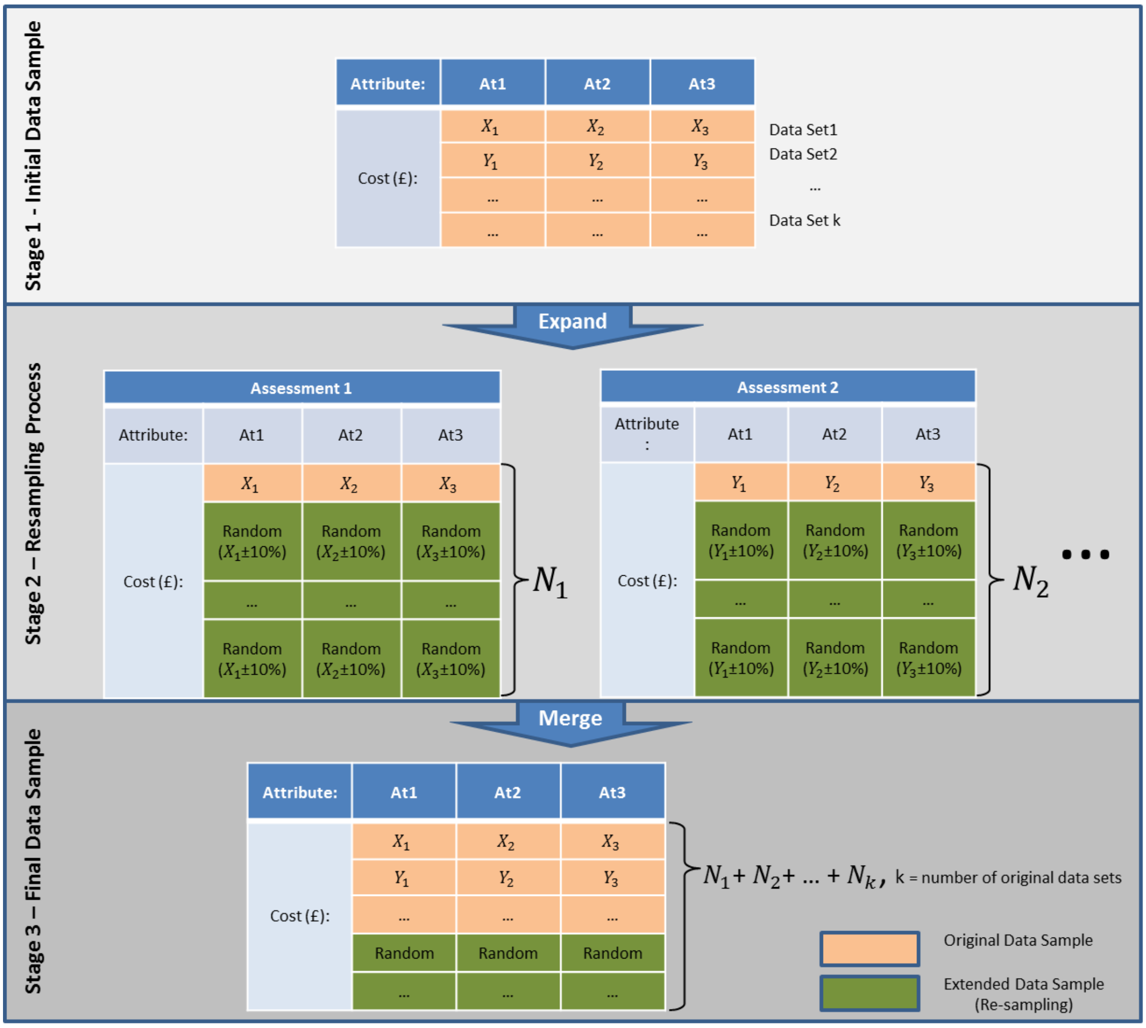


Figure 6-5 Bootstrapping Re-Sampling and Monte-Carlo Simulation Process

The figure is organised in three stages. The first stage shows *k* different datasets (corresponding to *k* different comparable contracts) and each dataset contains the investment made in each of three attributes. The second stage illustrates the process of creating new datasets from the original ones. Each original dataset is assessed independently to create N_i new datasets by applying the mixed Monte-Carlo and bootstrapping resampling technique. Finally, at the third stage all the datasets are merged together to create the final extended data sample.

This approach was initially validated in a two-hour interview with participant SH24 who acknowledge that this approach “has potential” and can produce extended data samples without losing too much of pattern of the original data sample, which was the purpose that it was developed for. Moreover, further validation of the approach was made as presented in Chapter 8, and in particular through case studies.

6.6 Summary

Although suppliers increasingly seek to improve their competitive position in the market in the context of CfA projects, they have to improve their ability of building the cost and availability estimates at the bidding stage. Also, they have to improve the ability of allocating the budget across the different attributes that impact on availability in order to achieve certain level of availability for the lowest cost.

Currently, the project managers find it challenge to accomplish these tasks because there is a lack of knowledge and tools to support in the process, and because of limited data scenarios at the bidding stage the difficulty the analysis.

This chapter presents the CATECAB model, which is an innovative simulation model that calculates cost and availability estimates under data scarcity scenarios, and allows to perform trade-off between total contract cost and system availability targets. The CATECAB model is targeted to be used by project managers, at the bidding stage of CfA projects. The process consists of understanding how cost and availability depend on each other, by applying a multiple regression analysis technique to assess the historical investment in different comparable projects towards estimate the total cost and availability for a specific contract. A mixed Monte-Carlo simulation and bootstrapping and re-sampling approach is also applied to generate bigger data samples for analysis, mitigating data scarcity scenarios.

The innovation offered by the CATECAB model consists of:

1. A systematic process to define the attributes that impact the availability of the system for a particular CfA;
2. The modelling process to build availability estimates;
3. Guidance on what information must be collected from each project to provide better estimates for future projects;
4. A systematic process to measure the interrelationships between the attributes that impact on availability, in terms of cost;
5. The process to trade-off between total contract cost and systems availability;

Further application and validation of the CATECAB model in real-world scenarios using CfA case studies is presented in Chapter 8.

7 COST AND AVAILABILITY ESTIMATION AND OPTIMISATION FOR CfA BIDS MODEL (CAEOCAB)

This Chapter presents the Cost and Availability Estimation and Optimisation for CfA Bids (CAEOCAB) model, which aims to estimate the optimal investment in defined attributes, to achieve predefined targets of cost and availability, for a certain CfA duration. The model is aligned with the fifth objective of this research.

The proposed model will allow to find the best allocation of the budget across the attributes that impact the availability of the systems, by applying an Enhanced Multi-Objective Genetic Algorithm (EMOGA) to optimise the trade-off analysis in the CATECAB model presented in Chapter 6. This model addresses the industrial challenges identified in Chapter 4 related to the lack of tools for supporting decision-making at the bidding stage of CfA, and the research gap identified in Chapter 3 related to the lack of research focused on the bidding stage of CfA.

The Chapter is organised in the following way:

Section 7.1 describes the methodology adopted for developing of the model. Section 7.2 presents the CAEOCAB model development, starting from the notations applied and important definitions in Section 7.2.1, moving to the description of the EMOGA in Section 7.2.2, and describing the modelling process in Section 7.2.3. Finally, Section 7.3 summarises to the aim and specifications of the CEOCAB model, and its context of application.

7.1 Methodology

The methodology designed for this research is illustrated in Figure 7-1. It consists of three main phases, with iterative processes performed within each phase and a systematic validation of all the results. The description of each phase is presented in the next three sub-sections.

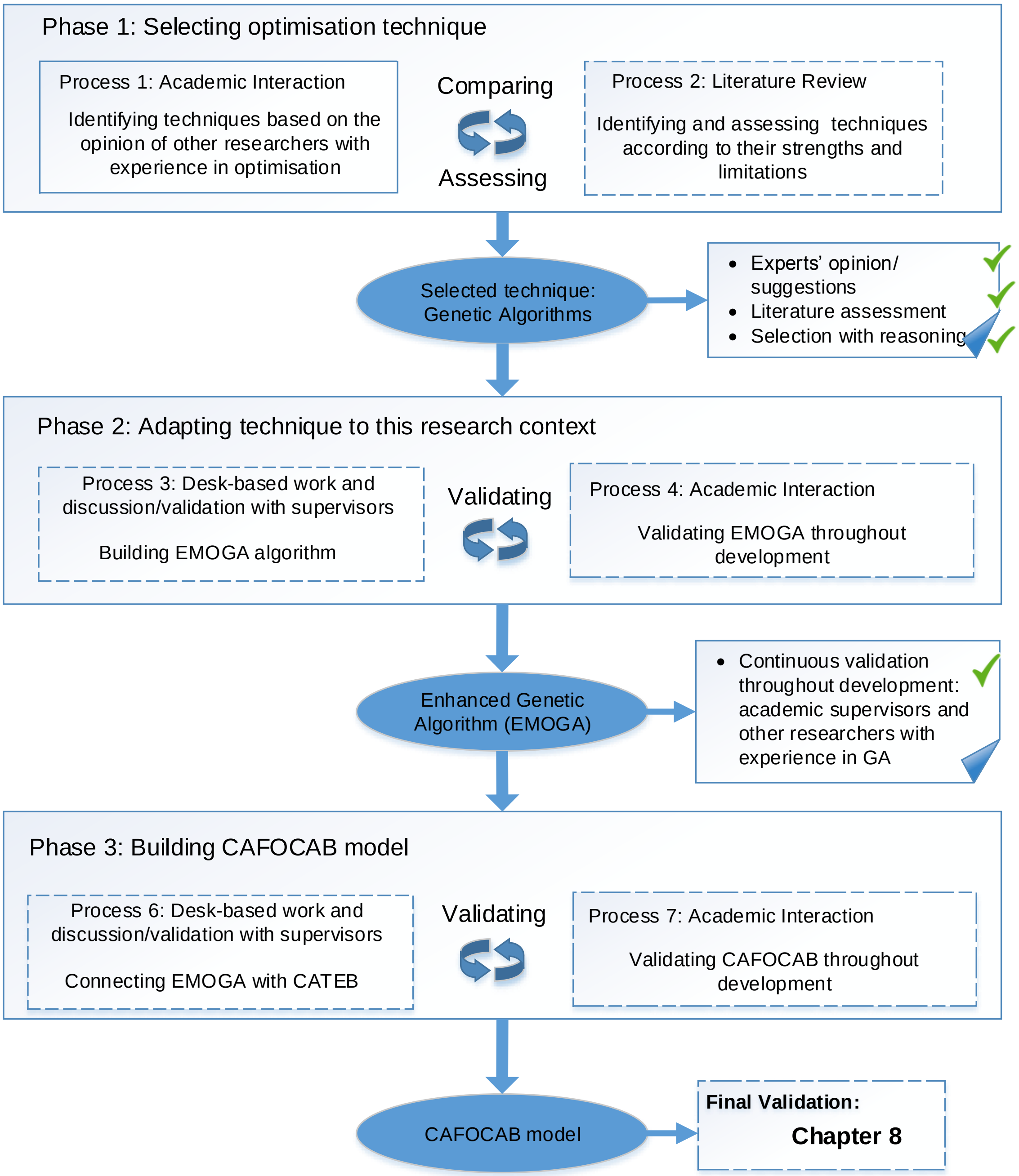


Figure 7-1 CAEOCAB Development Methodology

7.1.1 Phase 1: Selecting Optimisation Techniques

The first phase of this study consisted of assessing the literature and approaching the industry stakeholders in order to select the appropriate technique(s) to develop the optimisation process. Two main processes were carried out during this phase: process 1 consisted of interviewing other researchers with experience in optimisation to suggest effective optimisation approaches/techniques; and process 2 consisted of comparing the suggestions made by the researchers with the results from the literature review to assess strengths and limitations of those approaches/techniques. Details about each process are presented below.

Process 1 - Academic Interaction: One telephone interview was made with participant SH18, of one hour duration, aiming at discussing approaches and techniques for optimisation. Participant SH18 was chosen for this interview because he has more than twenty years of experience in modelling and optimisation. He recommended to look at genetic algorithms (GA). He highlighted that during his carrier he developed various applications to optimise supply chain management, using the GA approach and achieving successful results. He suggested that GA is a powerful optimisation approach to develop industrial application, according to his experience. In further conversations with participants SH21 and SH24, they also agreed with the relevance and capacity of the GA technique.

Process 2 - Literature Review: In the literature review results presented in Section 3.4.4, different optimisation algorithms are reviewed and GA is actually identified as the most powerful and widely applied, as it presents the best ratio between complexity of the algorithm and computational time required to find the optimal solution.

With the insights received from the experts, and the literature review results confirming the advantages and value of the GA approach, it was selected to be applied in this research.

7.1.2 Phase 2: Developing an Advanced Genetic Algorithm

After deciding about the optimisation technique that would be applied, an assessment was made about the variables that would be optimised and about the possible optimisation targets, in order to design/adapt/develop the adequate GA. Phase 2 covered the design and development of an enhanced GA (process 3), and the validation of algorithm throughout the development (process 4). Details about each process are presented below.

Process 3 - Development: The first question that was raised during the development of the optimisation process was to understand what had to be optimised. This research is mainly focused on cost and availability, although contract's duration has also been identified, during the study, as an important variable that impacts both cost and availability. Thus, the optimisation process considers the following variables: contract duration, cost and availability.

If more than one variable have to be optimised, the algorithm has to account with a balanced comparison between variables, as they all have different scales of measurement. Thus, and enhanced multi-objective genetic algorithm (EMOGA) was developed that considers a balanced comparison between the variables by normalising them according to the process described in Section 7.2.2.

Process 4 - Academic Interaction: The development of the EMOGA was continuously monitored, validated and updated with the academic supervisors, and with participant SH24. This participant has experience with GA and provided important ideas, references and comments during the development of the EMOGA, and also validated the final algorithm. A review of literature in GA was also carried out to support the development of the algorithm.

7.1.3 Phase 3: Building the CAEOCAB Model

Phase 3 (and last) consisted of the implementation of the EMOGA algorithm in the CATECAB model, in order to create the final CAEOCAB model. This phase covered the development of the CAEOCAB model (process 5) and the continuous validation throughout the development (process 6), which was made with the academic supervisors on a weekly basis.

The final validation of the CAEOCAB model, which assesses its accuracy and innovation, is presented in Chapter 8.

7.2 CAEOCAB Development

The next subsections describe the developed CAEOCAB model that aims to optimise cost and availability estimates at the bidding stage of CfA. The chapter starts with a description of the mathematical terms that are applied in the description of the methods and algorithms. Then, an enhanced multi-objective genetic algorithm (EMOGA) is introduced and described, which is further applied in the development of the CAEOCAB.

7.2.1 Model Notation and Problem Statement

The notation used throughout this chapter is as follows:

Support contract

i, j, k	Indices for contracts, attributes and sub-attributes respectively
D	Finite set of *m* attributes, D = $\{D_i\}_{j=1}^{m}$
mD	Finite set of n sub-attributes, mD = $\{mD_i\}_{k=1}^{n}$
sD	Finite set of *l* sub-attributes, sD = $\{sD_i\}_{k=1}^{l}$
t_i	Duration of the *i*-th contract
c_i	Total cost of the *i*-th contract
c_j	Total investment in the *j*-th attribute

s_i	A feasible investment in each attribute in contract *i*
$c_i(s)$	c_i when s_i is verified
$a_i(s,t)$	a_i during a period of time t_i when s_i is verified
Tr	Cost and availability trade-off rate (=cost/availability)

Genetic algorithm

N	Population size
$I_{p,gx}$	Individual *p* in generation g_x
F	Fitness function
$f_{I_{p,gx}}$	The fitness of $I_{p,gx}$

Other Specifications

$\blacksquare^*$	Optimal value or solution
$\blacksquare'$	Testing value: the different numbers or set of numbers evaluated in the search process; the best $\blacksquare'$ is the $\blacksquare^*$.
<>	Tuple
C,A,T	Generic functions

The CATECAB model presented in Chapter 6 defined a base for development of the CAEOCAB model. CATECAB estimate c_i, c_j, c_k, and a_i at the bidding stage of CfA, which was considered a step forward toward improving the current process of building these estimates, as no other model was identified in literature and across the industry interaction to accomplish that task.

However, the CATECAB does not consider optimisation and all the estimates are made on a trial and error basis. The CAEOCAB model presented in this chapter applies an enhanced multi-objective genetic algorithm (EMOGA) that searches for the optimal investment in the different attributes that impact the availability of the system, according to a total contract cost and total system availability targets for a particular contract duration. It also suggests the optimal duration of the contract to better achieve those targets. The EMOGA algorithm and the CAEOCAB model are presented in the next sections.

7.2.2 Enhanced Multi-Objective Genetic Algorithm (EMOGA) to build Cost, Availability and Time Estimates

Genetic algorithms have been extensively applied in many optimisation problems as they have proven to be robust and fast in searching for optimal solutions (Konak *et al.*, 2006). Although the core idea of this approach is unchangeable, there are a number of variations suggested by many authors that aim to produce better results when applied to a particular problem (Zbigniew, 1996). In this work we start from the genetic algorithm proposed in (Bosse *et al.*, 2016), developed to model availability and cost for IT services, and improve the evaluation point of the algorithm in order to produce better results in the context of availability and cost estimation in CfA bids. The flowchart of the developed algorithm, called EMOGA, is presented in Figure 7-2. As mention before, the innovation of the EMOGA is at the evaluation point, where the fitness of each individual is calculated. This approach considers the lowest fitness as being the best. The other stages of the algorithm apply general rules of genetic algorithm which can be found in for example (Bosse *et al.*, 2016; Zbigniew, 1996).

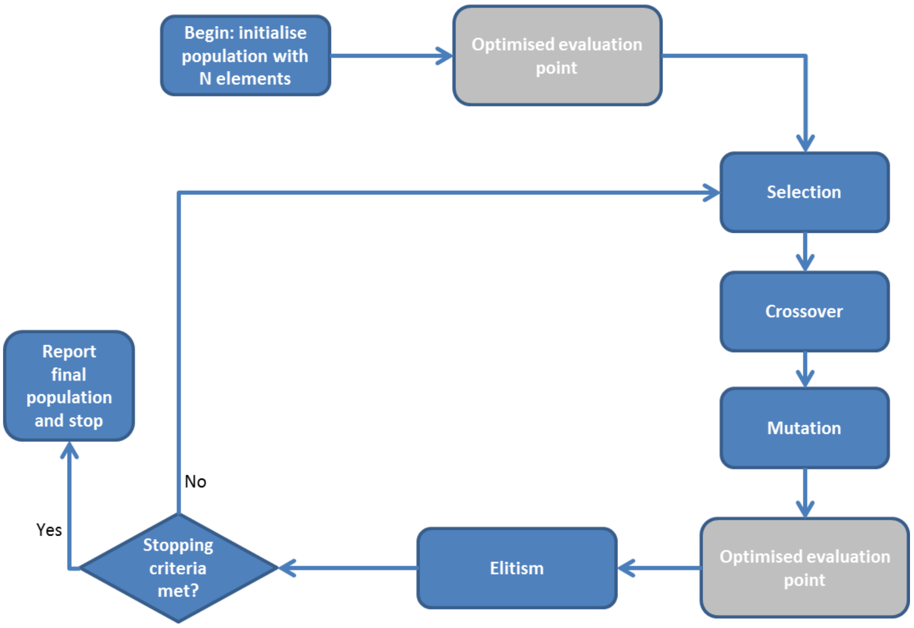


Figure 7-2 Flowchart of the EMOGA Algorithm

The process starts with a population of *N* elements that correspond to *N* samples of cost, availability and time. Each element of the population is submitted to an initial evaluation to calculate its “fitness”. Then, they pass through the process of selection, crossover and mutation to create a “stronger” generation that is then submitted to a new fitness evaluation. The population is then submitted to an elitism test to ensure that the best member of current generation is not worse than the best member of the previous generation. From this point the stopping criteria is applied to see if the “generation with the optimal solution” has been achieved or if the overall process will be repeated from the selection point. The stopping criterion in this problem is typically defined by a pre-defined number of generations.

The aim of the developed EMOGA is to calculate an optimal solution $<s^*, c_i{}^*, a_i{}^*>$ according to $<c_i,\ a_i>$ targets. These targets can have two possible configurations:

a) Specific total contract cost and total system availability targets;
b) Best trade-off between cost and availability.

The second target refers to the highest availability for the lowest cost. For each case, the optimisation process works differently in order to improve the effectiveness of the results. The reason for considering these two different targets is for increasing the flexibility of the estimates. For some projects the targets can be defined in terms of specific total programme cost and total system availability whereas in some others achieving the best trade-off between cost and availability may be more useful (Demeulemeester, 1995; Jin *et al.*, 2015; Rogerson, 2003). The variable contract duration t_i can also be considered in the targets in the conditions described in the following sections. Next subsections explain how each case is modelled with the appropriate algorithm.

7.2.2.1 Target 1: Specific Total Contract Cost and System Availability

It has been assumed that, for a particular contract bid *i* with duration t_i, the aim is to achieve a_i and c_i. Here, t_i will also be considered as a target to calculate the optimal duration for the contract. If t_i cannot be changed, then all the variables *t* must be removed from the next equations. Thus, we want to calculate c_i^*,a_i^* and t_i^* that minimise:

$$\begin{cases} C = |c_i^* - c_i| \\ A = |a_i^* - a_i| \\ T = |t_i^* - t_i| \end{cases} \tag{7-1}$$

Here, c_i^* is a function of s^*, and a_i^* is a function of s^* and *t*. Thus, the fitness of each individual could be intuitively considered as:

$$f = |c_i' - c_i| + |a_i' - a_i| + |t_i' - t_i| \tag{7-2}$$

However, either cost, availability or time have different units of measurement, which normally vary in different scales, e.g. time normally varies within a few years range, availability is limited to a range of 100 units, and cost can range in a scale of millions or billions .Thus, if we simply consider the fitness of each individual as in Equation (7-2), that will lead us to a biased comparison between the individuals, through their fitness.

Let us consider a practical example to describe the issue. Let us assume that, for a particular contract *i*, $c_i = 1000£$, a_i = 95, and $t_i = 10$ and that we have two different solutions $< s_1, t_1 >$ and $< s_2, t_2 >$ from individuals *p* and *q* respectively at iteration g_x, such that $t_1 = 9$, $c_i(s_1) = 3000£$, $a_i(s_1, t_1) = 90$, $t_2 = 9$, $c_i(s_2) = 2000£$ and $a_i(s_2, t_2) = 50$. In these conditions, $f_{I_{p,g_x}}(s_1, t_1)$ = 3091 and $f_{I_{q,g_x}}$ (s_2, t_2) = 2051 and therefore, the solution $< s_2, t_2 >$ would be preferable as $f_{I_{q,g_x}}(s_1, t_1) < f_{I_{p,g_x}}(s_2, t_2)$ (the lowest fitness is the best). However, because of the difference of magnitude between the variables cost, time and availability, the comparison between the solutions through *f* is not balanced, as the variable cost has higher impact in *f* than the other variables. In order to mitigate this issue, each function in (7-1) needs to be normalised. The optimised evaluation point proposed in Figure 7-2 applies an innovative normalisation process for this context. The proposed method consists of measuring the output of each function in (7-1) in terms of percentage, considering the total range of each measurement through Equation (7-3).

$$p(x', x_i, r_x) = \frac{|x' - x_i|}{max(|x_g - x_i|, |x_l - x_i|)} \tag{7-3}$$

Here, *p* is the normalised value in percentage (represents the common currency), x' is the testing value, x_i is the target value, x_g is the greatest value of the range and x_l is the least value of the range. In the ideal case, *p* = 0. Thus, the total normalised fitness of each individual will be a sum of three percentage measurements as described in Equation (7-4).

$$f = p(c_i(s'), c_i, r_c) + p(a_i(s', t'), a_i, r_a) + p(t', t_i, r_t) \tag{7-4}$$

Continuing the example above, consider now that c_i ϵ [0, 5000], a_i ϵ [0,100], and t_i ϵ [5, 15]. We have that:

$$p(c_i(s_1), c_i, 4000) = \frac{|3000-1000|}{4000} = 50\ (\%) \tag{7-5}$$

$$p(a_i(s_1, t_1), a_i, 95) = \frac{|90-95|}{95} = 5\ (\%) \tag{7-6}$$

$$p(t_1', t_i, 5) = \frac{|9-10|}{5} = 20\ (\%) \tag{7-7}$$

$$p(c_i(s_2), c_i, 4000) = \frac{|2000-1000|}{4000} = 25\ (\%) \tag{7-8}$$

$$p(a_i(s_2, t_2), a_i, 95) = \frac{|50-95|}{95} = 47\ (\%) \tag{7-9}$$

$$p(t_2', t_i, 5) = \frac{|9-10|}{5} = 20\ (\%) \tag{7-10}$$

By adding (7-5), (7-6) and (7-7), and (7-8), (7-9) and (7-10) respectively, we have that $f(s_1, t_1) = 75\%$ and $f(s_2, t_2) = 92\%$, so $< s_1, t_1 >$ is actually the best solution of the two, presenting a global $< c^*, a^*, t^* >$ much more close to the target. These calculations are illustrated in Figure 7-3. The left column of the figure illustrates solution 1 and the right column solution 2. The method to obtain the partial values of cost, availability and time is illustrated in the first 3 boxes of each column using the correspondent scale, and last box of each column shows the sum of all values in the common currency (%).

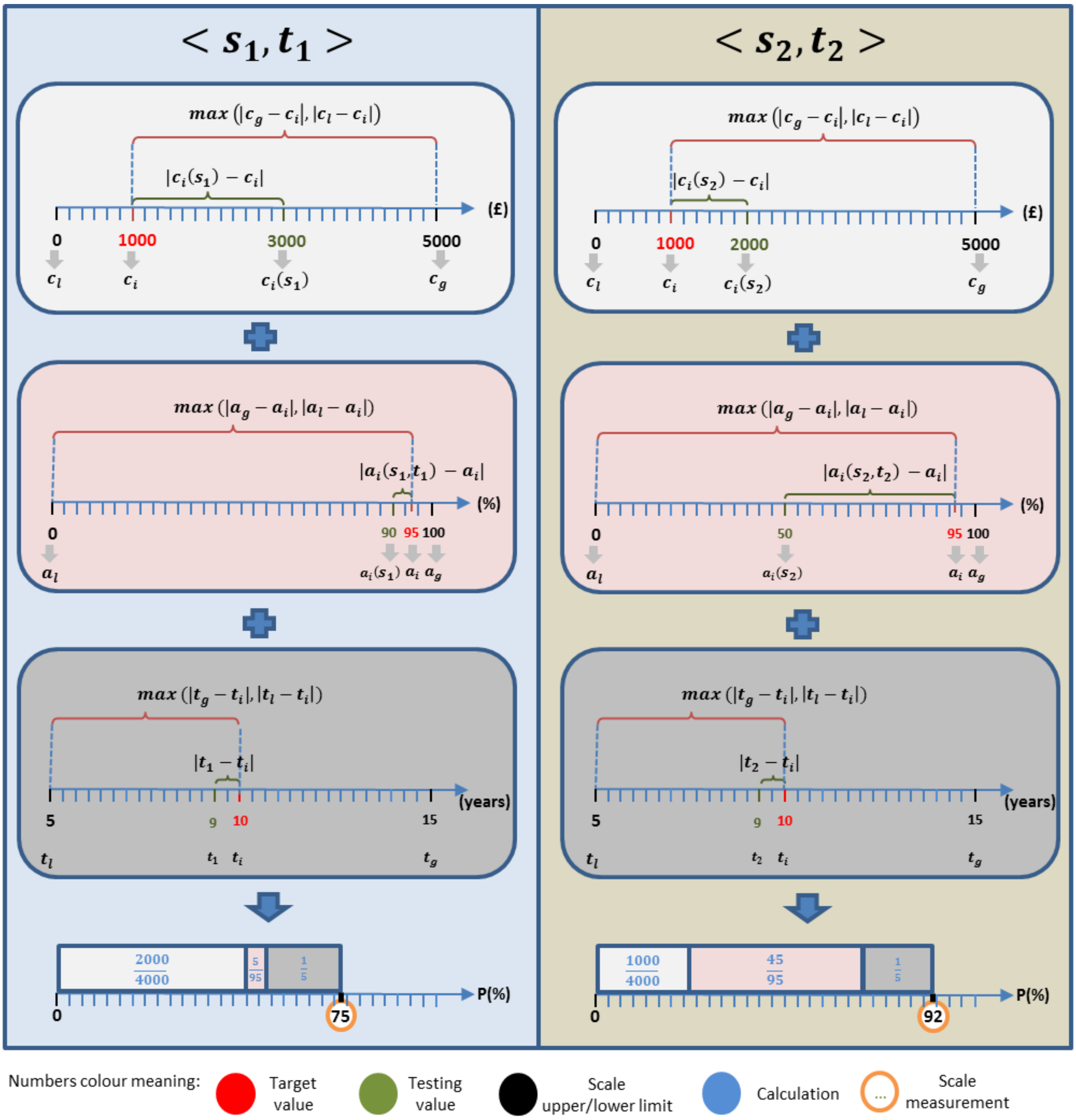


Figure 7-3 Comparison between Solutions using the Percentage Method

As we can see in Figure 7-3, the cumulative percentage (the sum of the percentages related to the availability, cost and time figures) of $< s_1, t_1 >$ is much lower than $< s_2, t_2 >$ (75% < 92%), so the first is preferable. This process is used at the “optimised evaluation point” of the EMOGA algorithm to calculate the fitness of each individual of the population, ensuring that all the variables (cost, availability and time) will have the same level of impact on *f*.

7.2.2.2 Target 2: Best Trade-Off between Cost and Availability

Trade-off analysis consists of determining the effect of decreasing the effort in one or more attributes and simultaneously increasing the effort in one or more other attributes, to achieve a certain balance between them (Yoe, 2002). During bidding, the goal of trading cost and availability is typically to decrease the total cost and increase availability, which is challenging as they normally vary in the same direction (Caldwell & Settle, 2011). The suggested approach to find the maximum availability and minimum cost is measured with the following Equation (7-11).

$$minimise\ tr = \frac{Cost}{Availability} \tag{7-11}$$

Actually, by pushing the levels of availability to the maximum and the cost to the minimum, the minimum value of *tr* is achieved as illustrated in Figure 7-4.

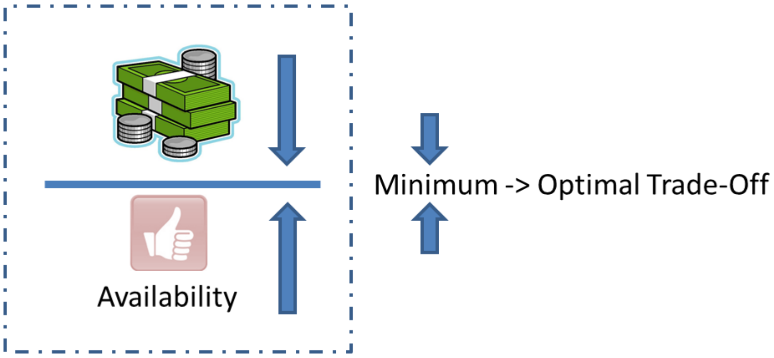


Figure 7-4 Optimising Cost and Availability Trade-off

Considering t_i as a target, the total fitness of each individual could be given by:

$$f = \frac{c_i{}'}{a_i{}'} + |t_i{}' - t_i| = tr' + |t_i{}' - t_i| \tag{7-12}$$

However, there is the same problem of bias as in equation (7-2) and normalisation has to be applied. As there are no specific cost and availability targets at this time, the normalised fitness function needs to be adapted in the following form:

$$f = \frac{tr'}{tr_g - tr_l} + p(t_i(s'), t_i, r_t) \tag{7-13}$$

where,

$$tr_l = \frac{minimum(c')}{maximum(a')} \tag{7-14}$$

and

$$tr_g = \frac{maximum(c')}{minimum(a')} \tag{7-15}$$

7.2.3 CAEOCAB Description

The “manual trade-off” approach suggested in the CATECAB model can sometimes be time-consuming and the optimal solution can actually never be found if the necessary number of trials are not performed. The proposed CAEOCAB model aims to optimise those results by introducing the EMOGA algorithm in the model. This new model searches for the optimal financial investment in different attributes to achieve pre-defined cost and availability targets. It also calculates the optimal duration of the contracts to better achieve those targets. The CAEOCAB model applies the same techniques and process as the CATECAB model to build extended data samples of cost, availability and contract duration, based on an initial database of data from at least three comparable CfA that have been completed in the past, and uses that data to build the mathematical function that relate cost, availability and time, by applying multiple regression analysis. Then, the EMOGA algorithm is applied to explore different combinations of <$s^*, c_i{}^*, a_i{}^*, t_i{}^*$ >, within a specific range of values for each variable, to achieve a pre-defined target of total contract cost and system availability, for a certain contract duration. The summary of the combined modelling techniques applied in the CAEOCAB model is presented in Figure 7-5.

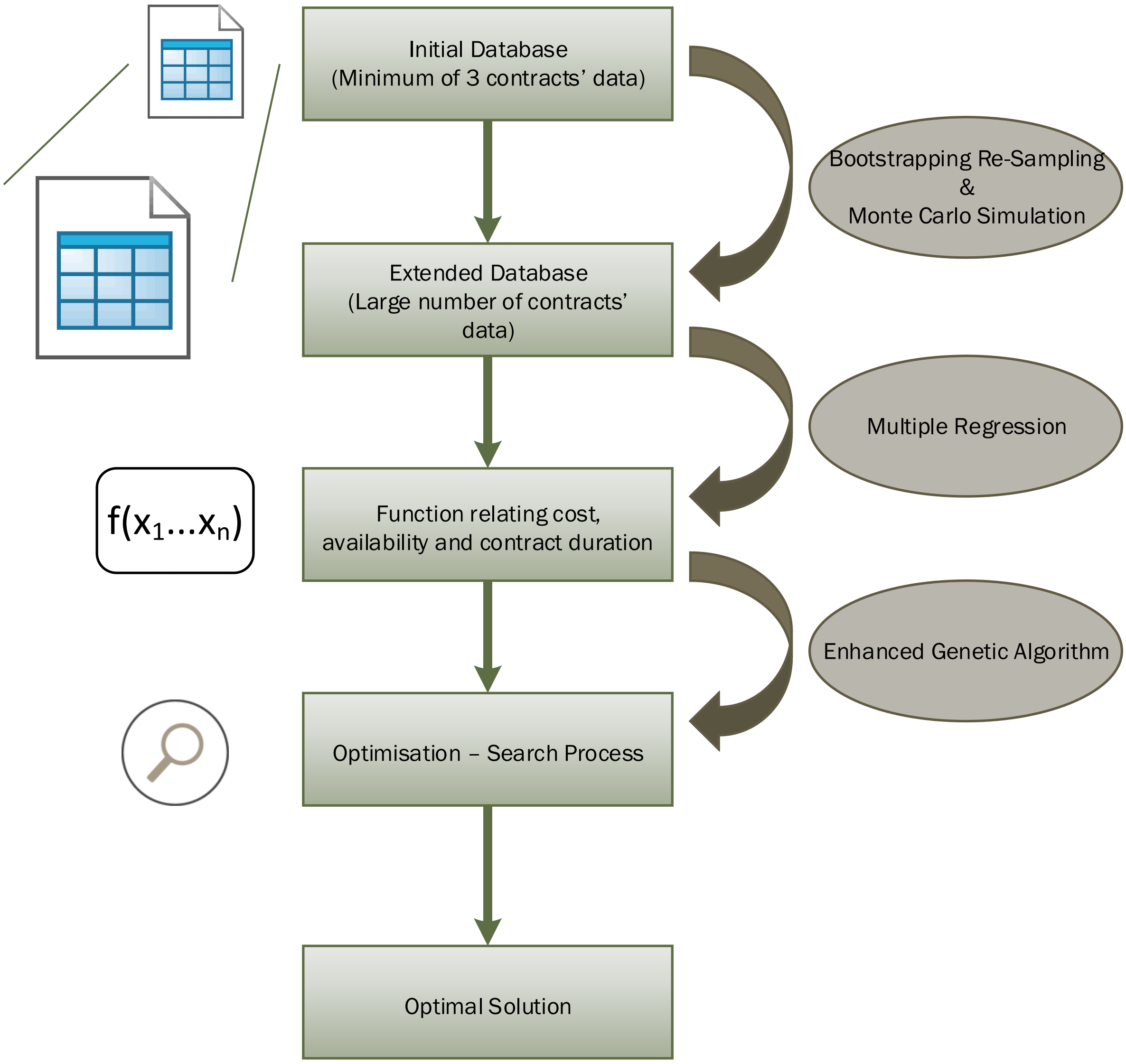


Figure 7-5 Modelling Techniques Applied in the CAEOCAB Model

The proposed CAEOCAB model is composed by five main stages as described in Figure 7-6. The process was designed in a desk-based work, with continuous monitoring and validation of the academic supervisors. Each stage of the model is explained in the next subsections.

To facilitate the interpretation and application of the model, it was implemented as a user-friendly simulation model using visual studio platform and visual basic coding. The reason for using visual studio platform was the fact that it is freeware and the applications developed in this platform can be converted in simple executable files easy to compile and share. This would facilitate the sharing of the model with the stakeholders for validation and wider use in industry.

Screenshots of the software are used to support the explanation of the modelling process.

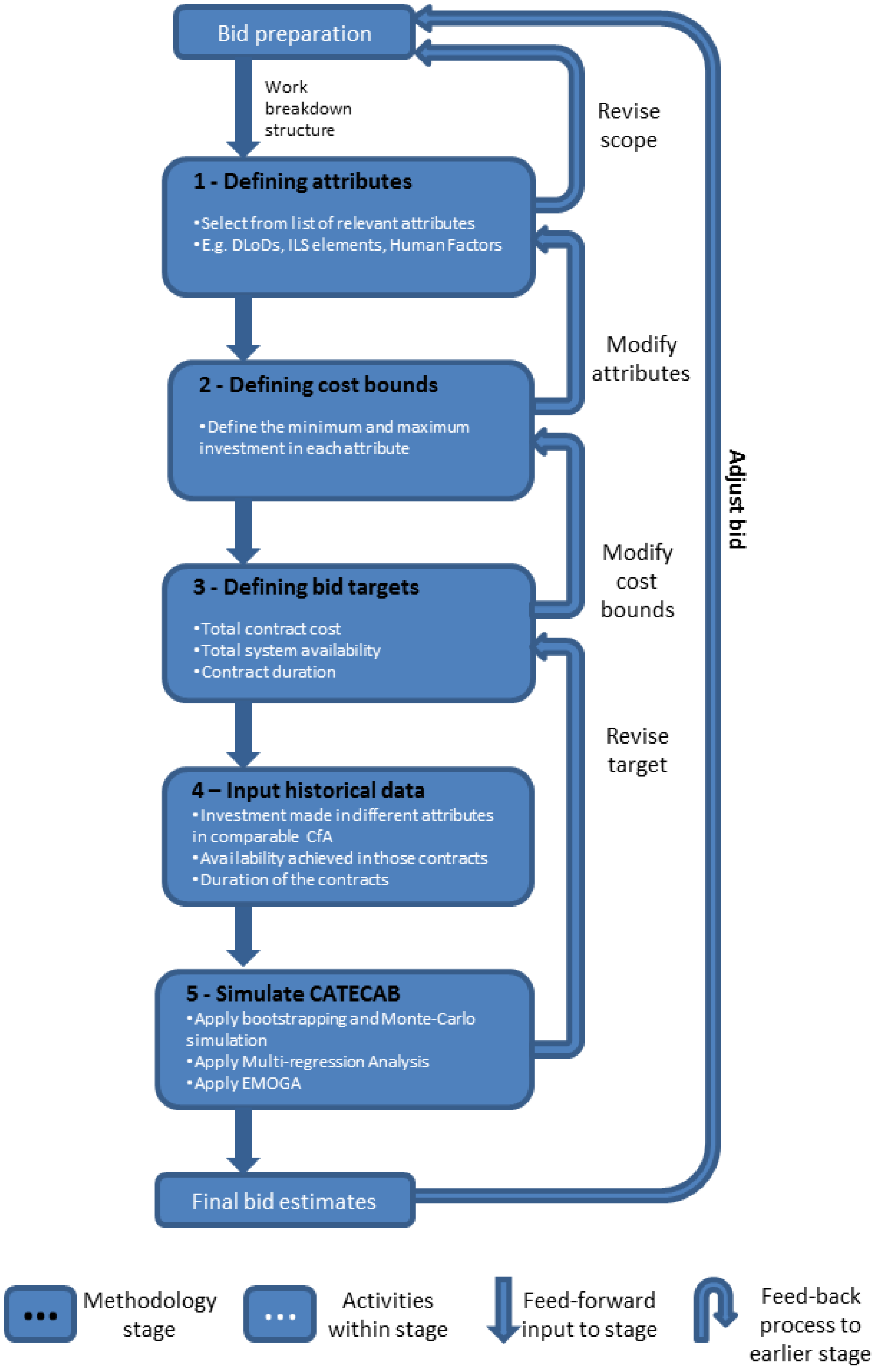


Figure 7-6 CAEOCAB: Modelling Process

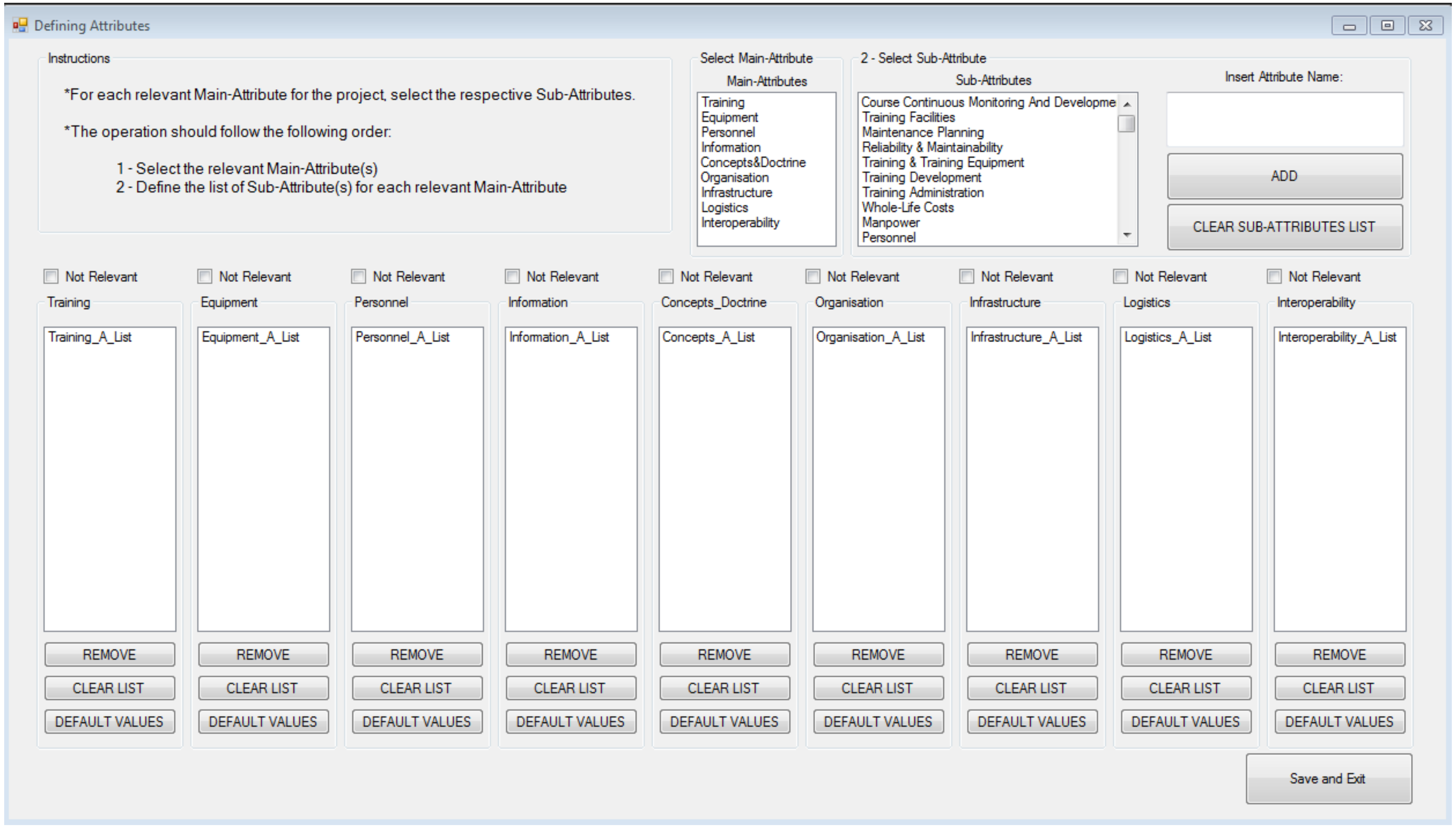
7.2.3.1 Step 1: Defining Attributes

The attributes can be considered categorised or non-categorised, as shown in Figure 7-7 and Figure 7-8 respectively.

In the categorisation approach, as described in Figure 7-7, there are on the top right hand side a pre-defined list of main-attributes mD and a pre-defined list of sub-attributes sD which are according to those presented in Table 5-4. For each main-attribute considered, a number of sub-attributes are selected using the option “ADD” and will appear in the respective list box. Options “REMOVE”, “CLEAR LIST” and “DEFAULT VALUES” are also available, where the “REMOVE” option removes a single selected sub-attribute, the “CLEAR LIST” option deletes all the attributes in the list, and the “DEFAULT VALUES” option populates each list according to the categorisation scheme presented in Table 5-4.

In the process illustrated in Figure 7-8, there is a pre-defined list of attributes D on the left hand side that covers all of those identified in Chapter 5. From that list the relevant attributes are selected using the “ADD” and “REMOVE” options, and are listed in the list box on the right hand side.

The criteria to select the attributes and/or sub-attributes should be according to their level of impact in the availability of the system. The classification in main and sub-attributes is optional and helps to analyse the problem at different levels, as presented in Figure 6-3.

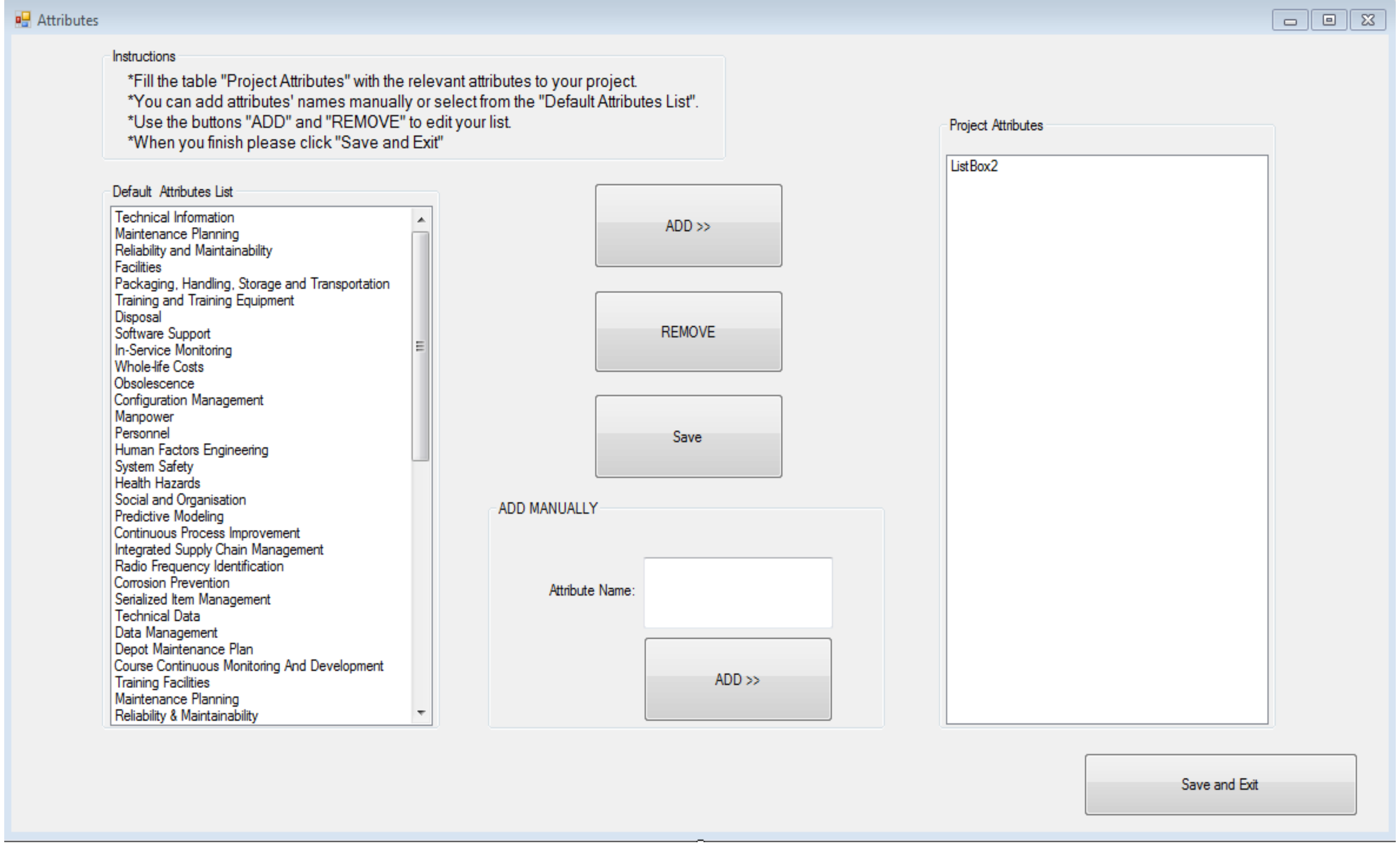


*For each relevant Main-Attribute for the project, select the respective Sub-Attributes.

*The operation should follow the following order:

1 - Select the relevant Main-Attribute(s)
2 - Define the list of Sub-Attribute(s) for each relevant Main-Attribute

Figure 7-7 CAEOCAB: Defining Attributes with Categorisation Approach



*Fill the table "Project Attributes" with the relevant attributes to your project.
*You can add attributes' names manually or select from the "Default Attributes List".
*Use the buttons "ADD" and "REMOVE" to edit your list.
*When you finish please click "Save and Exit"

Technical Information
Maintenance Planning
Reliability and Maintainability
Facilities
Packaging, Handling, Storage and Transportation
Training and Training Equipment
Disposal
Software Support
In-Service Monitoring
Whole-life Costs
Obsolescence
Configuration Management
Manpower
Personnel
Human Factors Engineering
System Safety
Health Hazards
Social and Organisation
Predictive Modeling
Continuous Process Improvement
Integrated Supply Chain Management
Radio Frequency Identification
Corrosion Prevention
Serialized Item Management
Technical Data
Data Management
Depot Maintenance Plan
Course Continuous Monitoring And Development
Training Facilities
Maintenance Planning
Reliability & Maintainability

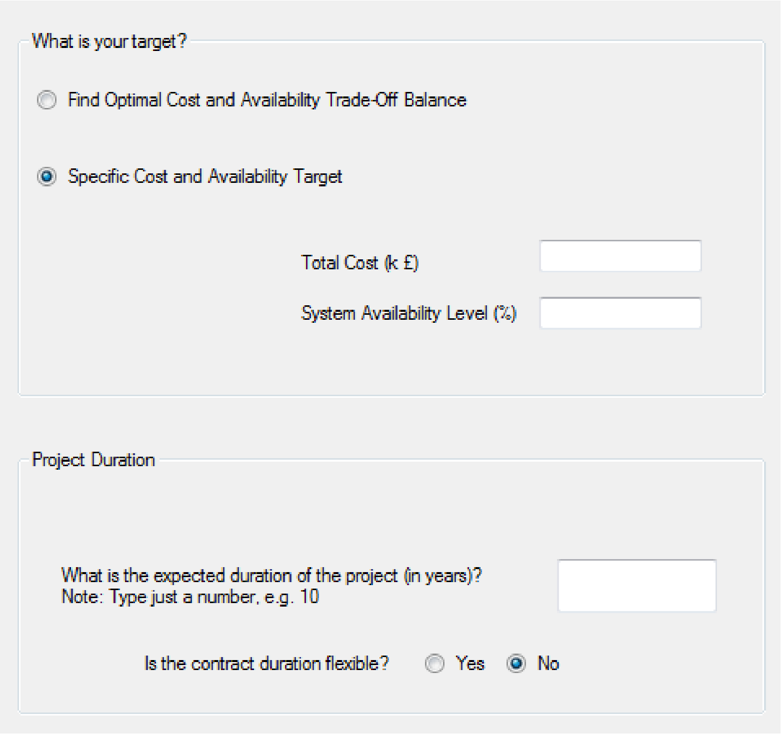
Figure 7-8 CAEOCAB: Defining Attributes with no Categorisation

7.2.3.2 Step 2: Defining Cost Bounds

For each $j \in D$ or $k \in sD$, a minimum and maximum bounds to the investment (£) that can be allocated has to be defined. This assessment can be made according to some budget constraints or project specifications, or it can also be the result of an uncertainty quantification process that was made previously for each attribute/sub-attribute (see, for instance, Erkoyuncu, 2014). The search process for the optimal solution will then be made within each range defined.

7.2.3.3 Step 3: Defining Bid Targets

The targets for the bid can be defined in two different ways as described in Section 7.2.2.1 and Section 7.2.2.2, and is illustrated in Figure 7-9. The search process for the optimal solution will consider each case with the appropriate approach as described in Section 7.2.2.


What is your target?

○ Find Optimal Cost and Availability Trade-Off Balance

● Specific Cost and Availability Target

Total Cost (k £)

System Availability Level (%)

Project Duration

What is the expected duration of the project (in years)?
Note: Type just a number, e.g. 10

Is the contract duration flexible? ○ Yes ● No

Figure 7-9 CAEOCAB: Defining Target

7.2.3.4 Step 4: Input Historical Data

There is a database that has to be filled with data related to comparable CfA that have been completed in the past. This data consists of the investment (£) made in different attributes that impact the system's availability in those contracts, duration of the contracts, and level of availability achieved. This information is the baseline to build the mathematical equations that produce the estimates. The reliability and robustness of the CAEOCAB outputs are very much impacted by the number of projects' data provided in the initial database and their degree of similarity with the project in analysis. The minimum number of projects' data suggested is three (based on the description provided in Section 6.5.7) although there is no limit to the maximum number.

7.2.3.5 Step 5: Simulate the CAEOCAB

When steps 1-4 are completed, the results are built in the following way:

1. The historical samples are resampled by applying the mixed Monte-Carlo and bootstrapping resampling technique to build an extended data set and thus create the necessary conditions to apply the multiple regression analysis;
2. The multiple regression analysis is applied to the extended data set to build the mathematical equation(s) that calculate the cost, availability and time estimates;

The EMOGA algorithm is applied to the equation(s) calculated in II to find the optimal cost, availability and time estimates according to the pre-defined targets.

7.3 Summary

This Chapter presents the CAEOCAB model, which aims to calculate the optimal investment (£) in a number of attributes that impact the availability targets in a CfA, according to pre-defined targets of total contract cost and system availability.

The development of the model covers two phases: First, an enhanced multi-objective genetic algorithm (EMOGA) is presented that searches for optimal solutions of cost, availability and time. Then, the EMOGA is integrated in the CATECAB model presented in Chapter 6, to identify the most effective allocation of the budget across the attributes and the optimal contract duration, to achieve pre-defined availability targets. The combination of the EMOGA and the CATECAB makes the CAEOCAB.

The innovation of the CAEOCAB model consists of:

(1) An enhanced genetic algorithm (GA) for optimising cost, availability and time estimates (EMOGA);
(2) The modelling process to build the cost and availability estimates;
(3) Guidance on how the budget should be allocated across the attributes to achieve certain level of availability for the lower cost;
(4) Guidance on what should be the ideal duration of the contract to better achieve the cost and availability targets.

The CAEOCAB models is to be applied at the bidding stage of CfA projects, and to support decision-making at the management level. The development of this model was in fulfilment of the fifth objective of this research.

This final validation of the CATECAB and CAEOCAB models is presented in the next chapter, which completes the full achievement of all the objectives of this research.

8 VERIFICATION AND VALIDATION

8.1 Introduction

This chapter presents the results of the verification and validation (V&V) of the CATECAB model presented in Chapter 6 and the CAEOCAB model presented in Chapter 7. This stage of the research was considered of extreme importance as the models are aimed to be used to support decision-making in major CfA projects (e.g. some million pounds) at the bidding stage.

The objectives defined for this V&V process were:

1. To ensure that the models were built following a structured methodology;
2. To ensure that all the techniques used to develop the models were applied correctly;
3. To ensure that the data on which the models are based is accurate, and from documented and valid sources;
4. To ensure that the models are innovative and will bring a valuable aid to support and improve the current practices;
5. To ensure that the models meet the specification and the purpose they were designed to meet;
6. To ensure that the models meet the stakeholders' requirements for flexibility and usability;
7. To ensure that the models meet the stakeholders' requirements for the type of outputs/estimates produced;
8. To ensure that the models perform accurately under various scenarios.

These objectives are aligned with the validation square framework that addresses the main issues of V&V in applied research and engineering (Seepersad *et al.*, 2006), and have been distributed by the verification and validation phases, according to a defined criteria. Thus, the verification phase aimed at ensuring that: (1) the models fit within the scope of this research, and fulfil the research objectives; (2) the researcher acquired the necessary knowledge and experience to carry out the work; (3) the construction of the models followed a structured methodology process; (4) the equations of the models as well as the overall mathematical process are logical and produce the expected type of results; (5) the models complexity is aligned with the initial expectations of the possible users; (6) the data on which the models are based is accurate, and from documented and valid sources. A detailed description of the verification process is presented in Section 8.2.

The validation phase aimed at: (1) ensuring that the models are innovative and useful; (2) ensuring that there is no other model/tool operating at the same level of analysis and producing the same type of outputs; (3) determining the extent to which the models will produce realistic outputs, by providing judgements from experts on the sustainability and validity of the models for use as credible tools for assisting decision making at the bidding stage of CfA. The process sought to acquire robust and appropriate data from “real-word” case studies, to run the models and make a sanity check of their outputs, based on the opinion of the experts that were involved in those particular case studies. The use of case studies to validate the models had the primary aim of ensuring that their accuracy would be judged based on evidences from real contracts. A detailed description of the validation process is presented in Section 8.3.

The methodology adopted to perform the V&V of the models is described in Figure 8-1. The process starts with the verification, where each model was implemented in a software platform to facilitate the overall V&V process. The implementation of the models in a software platform enabled to build them as simulation models, which facilitated the demonstration to the stakeholders and their interpretation and assessment. During the implementation of the models in the software it was possible to verify if the equations and algorithms were performing as required, by applying techniques such as unit tests and exhaustive search. After the verification is complete, the validation process started. This validation covered a total of twenty one case studies - each case study was related to a particular CfA - that were grouped in four multiple case study scenarios, two in the maritime domain and other two in the aviation domain. Each model was evaluated with two multiple case study scenarios, in both domains, and the results were assessed by project managers that were involved in the bidding process of the contracts of each scenario.

A detailed description of each V&V phases is presented in the next sections.

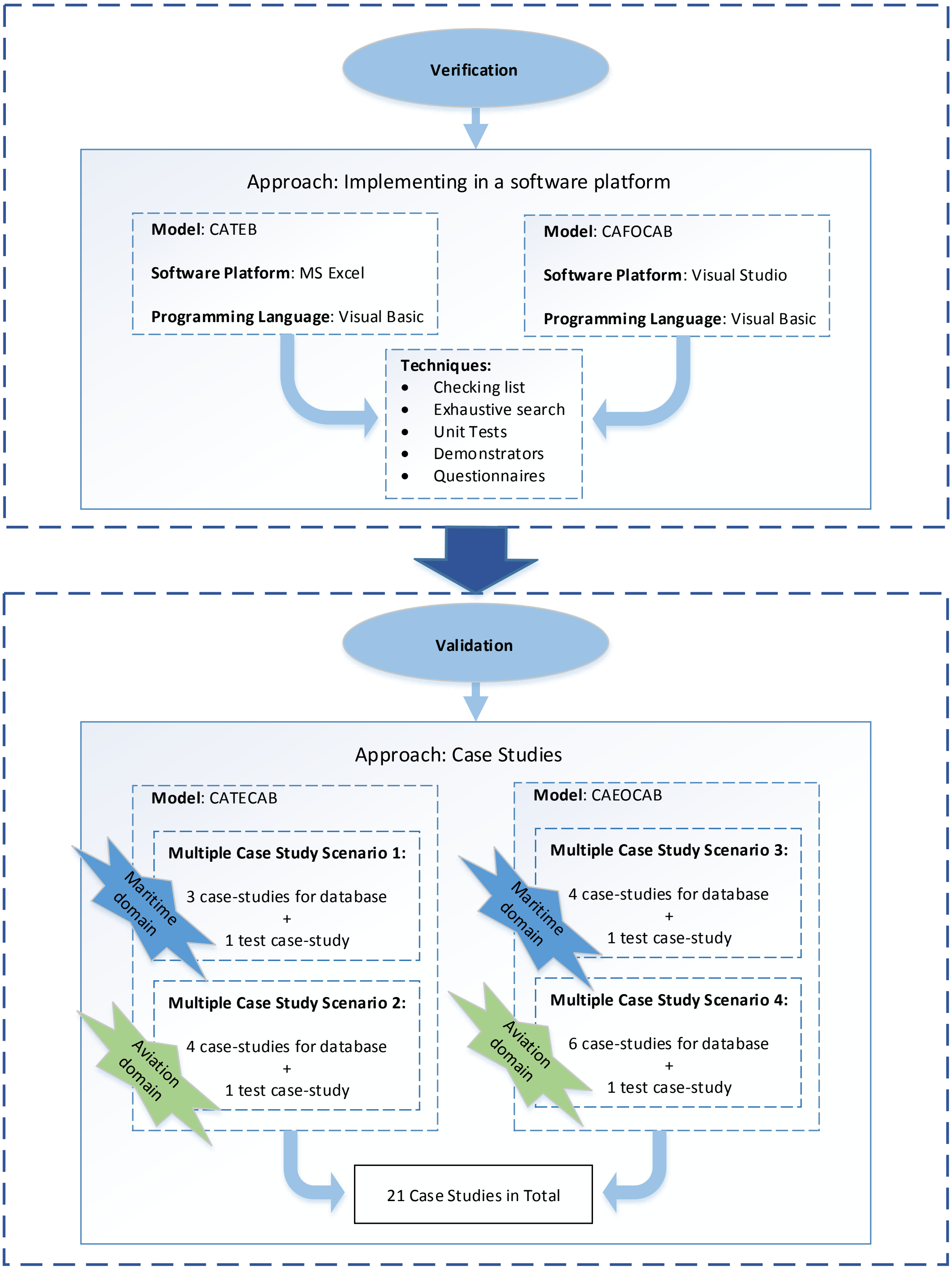


Figure 8-1 Verification and Validation Methodology

8.2 Verification

The first phase of the verification process consisted of ensuring that during this research, the researcher acquired the experience and knowledge necessary to develop the models, and that they have been developed following a methodological process.

These conditions have been reviewed by four experienced academics, where the researcher presented the activities carried out during the research to acquire new knowledge such as: attending training courses, conferences, making individual research, consulting the supervisors and other researchers with more experience in particular areas, etc. Also, the research methodology adopted to carry out the study was reviewed and the outputs of the models were compared against the research objectives to verify coherence.

To complete the further objectives of the verification phase, the models were implemented in software platforms to be developed as simulation models, in order to facilitate the process and obtain higher involvement from the industry stakeholders in the verification. To perform this implementation, the spiral methodology described in Figure 3-12 was adopted. This methodology provided an iterative process to develop the simulation models that considered appropriate actions to verify the model during the development. A key element of the spiral methodology is the use of unit tests. This unit tests enabled to verify specific/smaller parts of the model to see if they were performing as required (e.g. specific equations/functions). The researcher also performed an exhaustive search in the code to spot any error or abnormal output in the different functions of the model, following guidance of the verification procedures presented in Section 3.4.2.

During this process, some issues were noted and some minor changes/corrections were made, primarily to the programming code.

Each simulation model was also inputted with numerical data built based on assumptions and according to the input data requirements of each model, and with the list of attributes elaborated in Chapter 5. The objective was to create a demonstrator of each model and record it in a five to ten minute video, to be shown to the participants at each verification session so that they could have a brief description of the modelling process, inputs/outputs, etc., in a dynamic and structured way. Each demonstrator and video was validated with the academic supervisors to make sure that it covered the key features of each model that should be presented to the participants at each verification session. This approach helped the researcher to better structure the interviews/presentation of the model, keeping track of the time and content, and ensuring that enough time would be allocated for discussion and feedback.

Moreover, a detailed questionnaire was made to collect the feedback from the participants as presented in Appendix A (Questionnaire 1). This questionnaire focused on assessing if the models are aligned with the objectives of the research and have the appropriate level of complexity. The questions were made upon an analysis of the objectives defined for the verification process, and some relevant literature in V&V of modelling and simulation (Cameron *et al.* 2011). A simple 3 point Likert scale (Mellor & Moore 2014) is used to rate the responses (e.g. “yes”, “no” and “need improvements”).

The models were presented to different participants in interviews that lasted between one to two hours, and that were structured in the following way:

1. Reminding/updating the participants about the research objects, purpose of the model(s), and expected outputs;
2. Running the demonstrator of the model or playing the video;
3. Clarifying the participants about any questions related to the research aim/objectives, aspects/features of the model, etc.;
4. Getting feedback from the participants based on Questionnaire 1.

A more detailed analysis of the verification process for each particular model and the feedback received from the participants is presented in the next sub-sections.

8.2.1 CATECAB Verification

The CATECAB was implemented in Microsoft (MS) excel and built as a simulation model. The decision to select MS excel was made based on the agility and flexibility of the software that enabled the implementation and simulation of the algorithms using Visual Basic (VB) programming language. Also, most of the industry organisations and universities have this software, and most of the people in these organisations have a good knowledge and experience using this software, which facilitated the process of sharing the model.

After completing the simulation model, it was first presented to participant SH19, in a face-to-face interview of one hour. Due to time/schedule constraints, there was no opportunity to go through any questionnaire in this particular interview. Nonetheless, the participant agreed that the model was a true and fair reflection of the purpose it was built for, stressing that “nobody is operating at this level of analysis currently”. This comment gave some confidence about the innovation of the research, and the feeling that it was aligned with the initial objectives of the research.

Then, a detailed presentation of the CATECAB was made to participants SH2 and SH3, in a face-to-face interview of two hours, where the participants gave their feedback based on Questionnaire 1. They acknowledged that:

- The model is a true and fair reflection of the purpose it was built for;
- The modelling process is logical and clear;
- The interface is fairly understandable;
- The steps to run the model are clear for any person who has medium/high level of knowledge in MS excel;

- The modelling outputs are understandable and aligned with the initial objectives/expectations;
- The model is overall as expected and can be applied in real-world scenarios, after passing validation tests.

The model was then presented to participant SH25, in a one hour interview, where the participant gave his feedback based on Questionnaire 1 and acknowledged that:

- The model is a true and fair reflection of the purpose it was built for;
- The modelling process is logical and clear;
- The interface is understandable;
- The outputs are clear and aligned with the initial objectives;
- Would apply this model in the business after passing the validation test.

Overall, the results of the CATECAB verification process were indicative that the model is aligned with the initial research objectives, and meet the stakeholders' requirements in terms of complexity and usability. Also, it proved to be a valuable contribution to the current practices after passing the validation tests.

The next subsection presents the verification process of the CAEOCAB model.

8.2.2 CAEOCAB Verification

The CAEOCAB was implemented in Visual Studio (VS) and built as a simulation model. Visual Studio was selected this time to aim at improving the interface of the model and make it more user-friendly compared to the CATECAB model. Participants SH2, SH3 and SH25 considered that the Excel based model (CATECAB) could be optimised regarding to usability parameters, in order to facilitate/enable the use of the model by people that have lower knowledge/experience in software and the model could be of great value (e.g. senior project managers accustomed to "paper and pen" based methods to build their estimates). In conversations with other researchers that developed models in VS (e.g. participant SH24), they suggested that VS is a software platform that facilitates the development of user-friendly models that are easy to share, as they are created as an executable file of small size. Also, it supports the use of VB language, so it was possible to recycle the knowledge and experience acquired during the development of the CATECAB model in the development of the CAEOCAB.

Upon the software implementation, the CAEOCAB model was first presented to participants SH5, SH22 and SH23, in a one hour workshop, and to participant SH20, in a two hours interview. The feedback from the participants in both interviews was given based on Questionnaire 1, and concluded that:

- The model is a true and fair reflection of the purpose it was built for;
- The modelling process is logic and clear;
- The modelling process is robust;
- The list of inputs required is clear;
- The outputs are detailed, understandable and aligned with the initial objectives;
- The model can be applied in real-life CfA bids after passing the validation test.

Moreover, some comments were received from the participants that verify that the model fits the purpose. These comments include: “the approach works well” [participant SH5], “would consider using this model to compare against the current processes estimates” [participant SH22], and “the process is trustable but now it needs to be validated with case studies” [participant SH20].

The results of this verification process gave confidence that the model was aligned with the research objectives, fulfilling the expectations of the stakeholders in terms of complexity and usability, and that can give a valuable contribution to the project managers at the bidding stage of CfA, after passing the validation test. The process carried out to the validation of the models is described in the next section.

8.3 Validation

The validation of the models was done by means of case studies. As both models demand for a minimum of three projects' data to fill in the database, and one more project to be the pilot for the actual estimates, the research considered a multiple case study design (Yin, 2009; Vohra, 2014). In total, four multiple case study scenarios were considered as illustrated in Figure 8-1, where for each multiple case study scenario the researcher had a number of case studies to fill in the database, and a test case study to drive the estimates.

The provenance of data for the case studies and the selection of the appropriate stakeholders to provide/validate the data and validate the results was considered as a key issue in the validation process. The provenance of data in this case means that case studies data is robust, fit for purpose, is up-to-date, and has a suitable audit trail. The selection of the participants targeted those who were involved in the bidding process of the CfA covered in the case studies considered.

This validation section presents the feedback of those experienced participants about the innovation, relevance, usefulness and accuracy of the models, using two multiple case study scenarios for validating each model. Each model was validated in the maritime and aviation domain, and the participants gave their feedback following Questionnaire 2, presented in Appendix B, and Questionnaire 3 presented in Appendix C. Questionnaire 2 focused on the innovation, relevance, and usefulness of the models, and Questionnaire 3 focused on the accuracy of the estimates (e.g. cost, availability and contract duration).

Questionnaire 2 uses three different types of Likert scales: 4 point, 5 point and 6 point, as adapted from (Korn *et al.*, 2003; Marcell and Williams, 2010), whereas in Questionnaire 3 the participants marked the accuracy in a 6 point Likert scale (Chomeya, 2010). In addition, a 10 point rating scale was used to combine with each Likert scale as a support scale, in order to help the respondents to express more accurately their feelings by discriminating within each Likert category (Preston & Colman 2000), defining different levels of granularity for the responses (Reynolds, 1966). Typically, scales with less options can be easily answered and are good to be used when the knowledge about the particular subject is limited (Preston & Colman 2000). On the other hand, scales with more options are more accurate as it gives to the respondent the ability to differentiate between choices (Grote, 2002; Finstad, 2010). Thus, with the diversity of scales used in the questionnaires it was possible to obtain effective feedback from the participants as they could assess according to the level of confidence that they had in the responses.

8.3.1 CATECAB Validation

This section presents the two multiple case study scenarios used to validate the CATECAB model; the first in the maritime domain and the second the aviation domain.

Each multiple case study scenario was assessed as illustrated in Figure 8-2. First, the case studies for the database were loaded into the model. Then, the information related to the test case study was defined. The model was then ran to produce the cost and availability estimates. Trade-off analysis between cost and availability was also considered by changing the investment in an attribute and estimating the cost impact in the other attributes and the new level of availability.

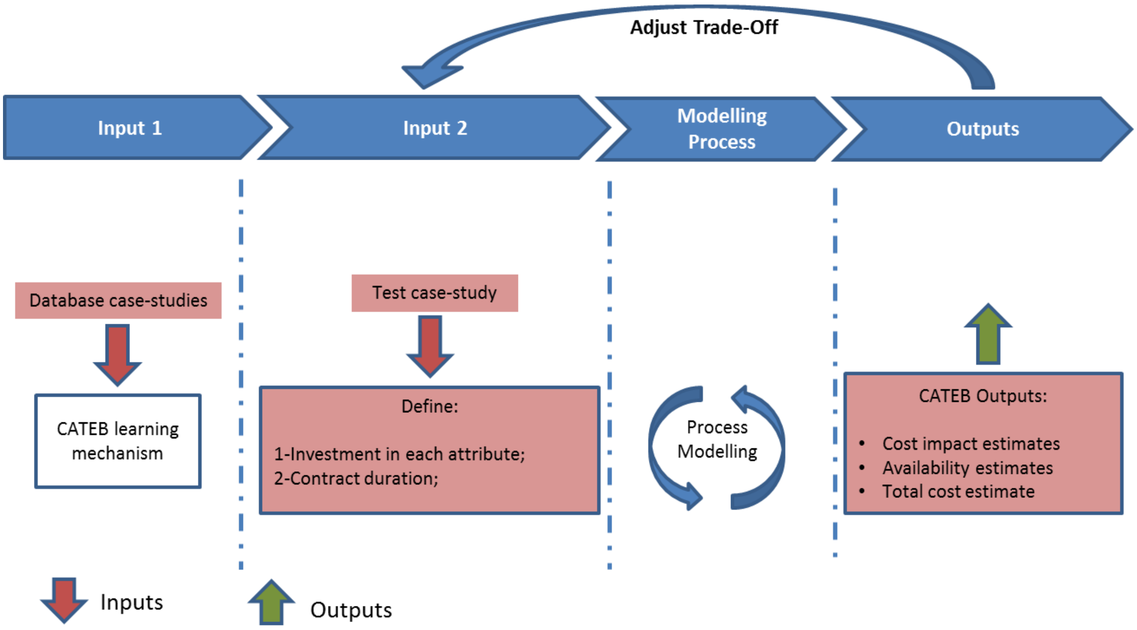


Figure 8-2 CATECAB: Methodology for Model Validation Though Case Studies

8.3.1.1 Multiple Case Study Scenario 1

These multiple case study scenarios covered four comparable CfA solutions conducted by Organisation 1, and the information was given by participants SH2 and SH3. The contracts were in the maritime domain and consisted of:

Case Study 1: A CfA bid that relates to the supply of a small number of complex systems to the UK Royal Navy (RN) and their support over 10 years. These systems are new introductions to the UK and therefore there are no existing infrastructures which could be used to offset costs. They will be supported in a collaborative working environment.

Case Study 2: A CfA bid that relates to the supply of a large number of complex systems to the RN and their support over 10 years. These systems are new introductions to the UK and therefore there are no existing infrastructures which could be used to offset costs. They will be supported in a collaborative working environment.

Case Study 3: A CfA bid that relates to the supply of support services for an increased number of complex systems, already in service, installed in the RN ships. These systems are considered critical to the ships' operational capability. The contract has five years duration and the equipment is no longer manufactured by the original equipment manufacturer (OEM) which lifts the risk of obsolescence. The engineering support is not included in the core contract, supplied only by exceptional tasking.

Case Study 4: A CfA bid that relates to the supply of support services for an increased number of complex systems, already in service, installed in the RN ships. These systems are considered critical to the ships operational capability. The contract has five years duration and the risk of obsolescence is very low as the equipment is still manufactured by the OEM and there are several other manufactures in the market producing similar equipment and compatible spares. The engineering support is confined to the UK waters only.

The complex systems covered in these contracts refer to integrated systems comprising hydraulic, pneumatic, mechanical and electronic sub-systems where the safe operation of the overall system is reliant on intricate control systems and associated feedback loops. For each case study information was provided about: a) list of attributes considered; b) investment made in each attribute; c) contract duration; d) level of availability achieved; e) contract duration. This information is presented in Table 8-1.

Some of the cost values in the table appear as “zero cost” because there was no direct investment in those attributes for the particular project(s). As an example, there was no investment in training analysis, documentation, facilities and development in the case studies 3 and 4 because the systems were already in-service at the time of the contract so that cost has already been set up in their implementation. However, considering “zero cost” in these attributes is an unrealistic assumption as there was actually an investment committed in these attributes before the contracts were agreed. Thus, for these cases, the investment is assumed based in an extrapolation of the investment made in the same attributes in other contracts. For example, the investment in training analysis is assumed to be £15 K for the case studies 3 and 4, e.g. half of the investment made in the same attributes in case studies 1 and 2, as contracts have half of the duration.

Table 8-1 Multiple Case Study Scenario 1

		CASE STUDY 1 (Test case study)	CASE STUDY 2	CASE STUDY 3	CASE STUDY 4
Duration (years)		10	10	5	5
Level of Availability Achieved (%)		95	95	90	90
Main-Attribute	Sub-Attribute	Committed Cost (k£):	Committed Cost (k£):	Committed Cost (k£):	Committed Cost (k£):
Training	Training Needs Analysis	30	30	0	0
	Training Development	100	10	0	0
	Training Aids and Documentation	280	240	0	0
	Training Facilities	13000	13000	0	0
	Training Personnel	800	800	200	200
Equipment	Equipment Purchase	33000	88000	0	750
	Installation and setting to work	1300	3200	225	260
	Inventory Costs	5900	17800	6300	7200
	Technology Refresh	390	390	0	0
	Obsolescence Contingency	0	0	350	0
	Equipment Support Facilities	100	100	0	0
	Post Design Services	300	300	100	120
	Repair and Overhaul	0	0	700	520
	Engineering Support	2300	5100	0	200
	Safety Case, RCM study and similar subcontract	3100	3100	300	300

	Project Management	**2900**	**2900**	**265**	**265**
Personnel	**Number of CPOs required**	**650**	**1300**	**0**	**1850**
	Number of POs required	**1100**	**3300**	**2090**	**0**
	Number of LHs required	**2400**	**6400**	**1900**	**1900**
	Number of ABs required	**1800**	**4800**	**1400**	**1400**
	Project team required	**1400**	**1400**	**400**	**400**
Information	**Supporting IT Infrastructure**	**250**	**250**	**0**	**0**
	Plans and Associated Documentation	**250**	**250**	**80**	**80**

Case studies 2, 3 and 4 were used to input the database, and case study 1 was the test case study.

The process was operated as follows:

- Defining the relevant main-attributes;
- For each main-attribute defined, selecting a number of sub-attributes;
- Defining the investment (£) in each sub-attribute selected, for each main-attribute;
- Defining the contract duration;
- Completing the database with information from case studies 2, 3 and 4, as described in Section 6.4.

After loading all of this information into the model, the outputs were produced in the following order:

Output 1: The availability estimates for the defined investment in each attribute

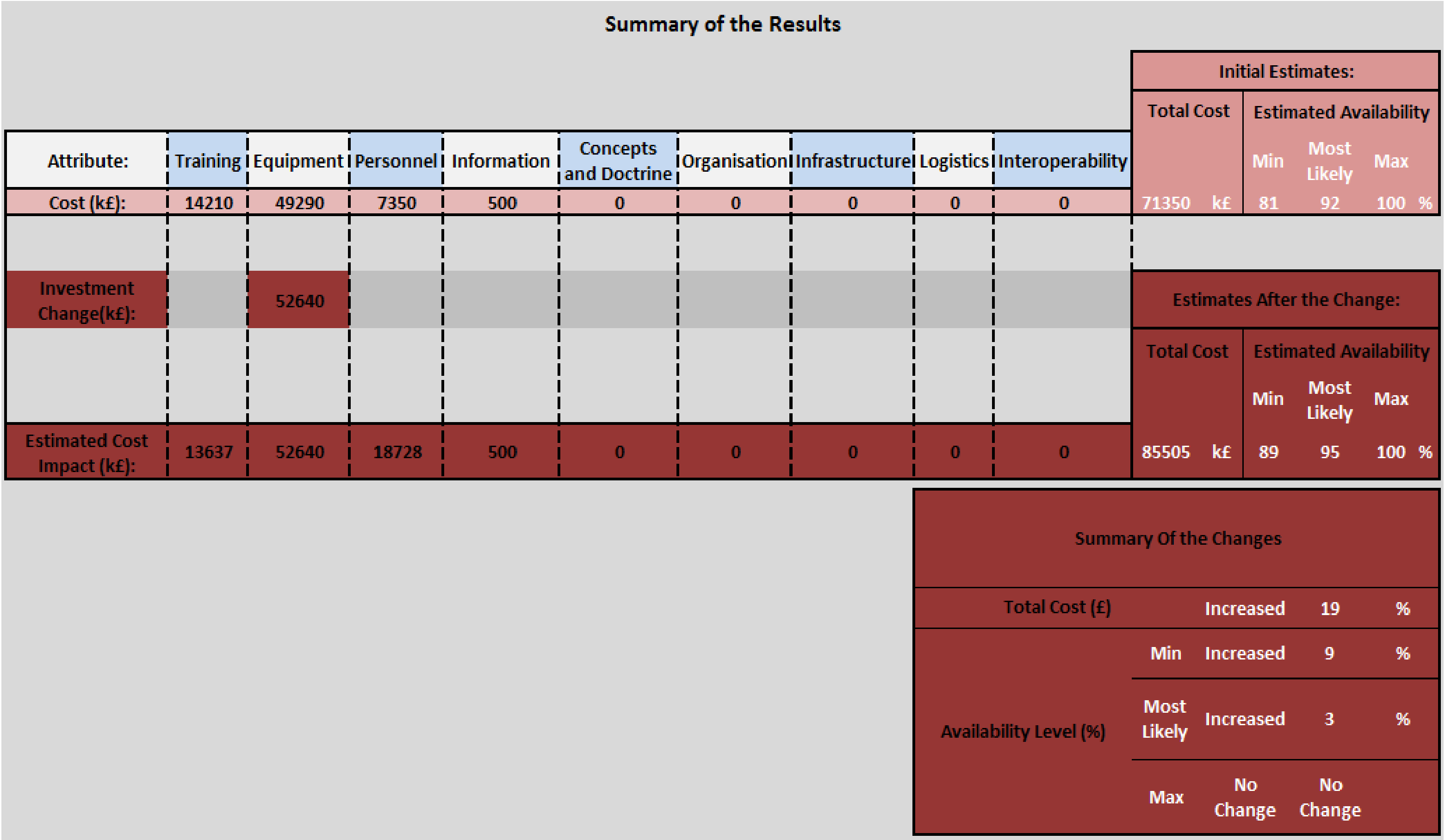
The minimum, most likely and maximum levels of availability were estimated as 81, 92, and 100% respectively, for the system of case study 1 (the test case study). As it can be observed, a three point type estimate was provided.

Actually, the model repeats the simulation a finite number of times in order to predict the worst, best and most likely scenarios for the level of availability of the system. Due to the wide range of factors that can impact the availability during the contracts duration, this is a more realistic way of defining the estimates than just predicting a single value, and it is also aligned with the suggestion made by participant SH6 during the assessment of the first case study presented in Section 4.5.1.

Moreover, the 95% availability achieved in the system of case study 1 is within the range estimated by the model [81,100] %, which suggests accuracy.

Output 2: Cost impact estimates across the different attributes

After estimating the level of availability of the system for the defined investment in each attribute, a different investment was proposed in Equipment from £49,290 to £52,640. This change aimed at performing a trade-off analysis between cost and availability, trying to obtain the same level of availability (or higher) for a lower cost. The model automatically calculated the cost impact of that investment change in the cost of the other main-attributes and respective sub-attributes, and the new system availability estimated as illustrated in Figure 8-3. It shows that for an initial (total) investment of £71,350 the estimated level of system availability during the 10 years period of the contract is (most likely) 92%, whereas this value will (most likely) increase to 95% if the initial investment increases as much as 19%. This trade-off analysis could also be explored more exhaustively by setting different allocations of the budget across the attributes and generating the corresponding availability estimates.



Summary of the Results

Attribute:	Training	Equipment	Personnel	Information	Concepts and Doctrine	Organisation	Infrastructure	Logistics	Interoperability
Cost (k£):	14210	49290	7350	500	0	0	0	0	0
Investment Change(k£):		52640							
Estimated Cost Impact (k£):	13637	52640	18728	500	0	0	0	0	0

Initial Estimates:

Total Cost		Estimated Availability			
		Min	Most Likely	Max	
71350	k£	81	92	100	%

Estimates After the Change:

Total Cost		Estimated Availability			
		Min	Most Likely	Max	
85505	k£	89	95	100	%

Summary Of the Changes

Total Cost (£)		Increased	19	%
Availability Level (%)	Min	Increased	9	%
	Most Likely	Increased	3	%
	Max	No Change	No Change	

Figure 8-3 Model Output: Cost and Availability Trade-off Analysis

These results actually show coherence with the information related to the case study 1, used as the test case study. This opinion was also shared by participants SH2 and SH3, that were the source of the case-studies information, and recognised that the model appears to be operating accurately, although they also suggested to extend these validation to more case studies, before they can feel enough confidence to apply the model in a real-life bids.

8.3.1.2 Multiple Case Study Scenario 2

This multiple case study scenario covered five comparable CfA conducted with Organisation 1, in the aviation context, and the information was disclosed by participant SH30, who was directly involved in bidding process of these contracts.

Each contract was focused on delivering support to a small/medium size platform and other complex systems operating in challenging scenarios (e.g. under extreme climatic conditions).

The support services provided included:

- Technical services;
- Material support services;
- Depth maintenance;
- Training;

The attributes considered are as presented in Table 8-2. The table also presents the investment made in each attribute, contract duration and level of availability achieved, for each contract data that populated the database, and the proposed investment in each attribute and contract duration, for the test case study. All the numerical figures related to cost presented in the table have been "*sanitised*" in order to ensure the confidentiality of the information, but it preserves the original pattern of the data. The contract duration and availability figures are the original ones.

Table 8-2 Multiple Case Study Scenario 2

	CASE STUDY 1 (Test case study)	CASE STUDY 2	CASE STUDY 3	CASE STUDY 4	CASE STUDY 5
Duration (years)	**5**	**5**	**5**	**3**	**5**
Level of Availability Achieved (%)		**95**	**95**	**90**	**90**
Attribute:	**Committed Cost (k£):**	**Committed Cost (k£):**	**Committed Cost (k£):**	**Committed Cost (k£):**	**Committed Cost (k£):**
Training and Training Equipment	37	40	0	10	15
Personnel	20	10	40	60	65
Supply Support	180	190	150	100	200
Technical Information	30	40	60	20	40
Maintenance Planning	55	25	20	10	10
Support and Test Equipment	10	5	10	10	10
Reliability and Maintainability	5	10	0	8	10
Packaging, Handling, Storage and Transportation	10	5	15	10	8
Whole Life Costs	15	9	10	5	9
Obsolescence	5	10	25	5	35
Configuration Management	5	10	5	5	15
Manpower and Human Factors	20	10	5	10	20

Participant SH30 ran the model based on this data but, for reasons of confidentiality, he did not disclose the output of the model. Rather, he provided a detailed validation of the model based on Questionnaires 2 and 3.

Through Questionnaire 2, participant SH30 acknowledged that:

- On a scale of one to ten, the relevance of the outputs of the model at supporting cost and availability estimates at the bidding stage of CfA is eight, meaning that they are highly relevant;
- On a scale of one to ten, the innovation of these outputs is six, meaning that there are no other models/tools providing the same type of estimates at the required level of analysis; the respondent highlighted that "*I am unaware of cost tool which replicate this function*". He said that the closest tools available estimate availability against stock levels and do not always acknowledge "real world" activity. It is therefore "*extremely difficult to estimate what availability a support solution will deliver*", he said.
- On a scale of one to ten, the usefulness the outputs of the model when compared to the outputs provided by the current methods is five, meaning that they are probably useful. The respondent referred that: "*I feel this tool would be useful however without using it in a productionised format and on an actual bid I cannot comment further*".

Through Questionnaire 3, participant SH30 acknowledged that:

- On a scale of one to ten, the accuracy of the cost estimates in seven, corresponding to an accuracy between 70-80%; the participant also highlighted that "*essentially the outputs were as expected however, the relationships between attributes' cost lines and availability are much more complex than can be mapped/replicated by a mathematical algorithm because some of the negotiated costs are less to do with availability than, for example, affordability*";
- On a scale of one to ten the accuracy of the availability estimates is seven, corresponding to an accuracy of 70-80%; Again, the participant highlighted that "*the availability produced was as expected however using post negotiated costs where funding was removed to meet an affordability target can skew the output*";

- On a scale of one to ten, the effectiveness/accuracy of the overall trade-off analysis process is 8, meaning that it is moderate to highly effective/accurate; as a final remark, the participant recognised that "*this feature appears to work well and I would consider using it for future tasking*". However, he suggests to include capability in the trading analysis as a future enhancement: "*the relationship between cost and availability is complex and enhancements could include trading capability as well*".

Several reasons may explain why participant SH30 has recognised an accuracy between 70-80% to the cost and availability estimates, and said that this is a good level of accuracy for the bidding stage.

Firstly, and as mentioned by participant SH30, the process of building these estimates is very subjective and complex due to external factors that also impact on cost and availability such as affordability. These external factors can be subjective, can have a non-linear nature, and can be specific to each contract. Thus, it may not be possible to assess them with a mathematical algorithm and insight from subject matter experts may be needed to complement the analysis.

Secondly, the techniques applied in the modelling approach have their own limitations. The criteria to select the techniques was more focused on their ability to deal with limited data availability scenarios, and therefore it is possible that other techniques can produce more accurate estimates.

Thirdly, it may be hard for any expert to acknowledge that the estimates produced by the model have an accuracy of 100%, as the model suggestions (e.g. attributes' investment) have not been tested in practice and therefore cannot be compared with actual numbers.

Next section presents the validation of the CAEOCAB model.

8.3.2 CAEOCAB Validation

The CAEOCAB validation followed up the format of validation used for the CATECAB model, considering two multiple case study scenarios, one in the maritime domain and other in the aviation domain, where each multiple case study scenario covers *n* case studies, where *n-1* case studies are to populate the database and the *nth* case study is the test case study to ascertain about the accuracy of the estimates.

Each multiple case study scenario was assessed following the methodology presented in Figure 8-4. First, the case-studies for the database were loaded, and the cost bounds were defined for each attribute in the test case study. Then, the targets were defined in terms of total project cost and total system availability, as described in Section 7.2.2, and the contract duration was specified. The model was then running, performing an automatic trade-off analysis between cost and availability and estimating the best values, according to the target defined. An adjustment of the targets was also considered to see the impact on the performance.

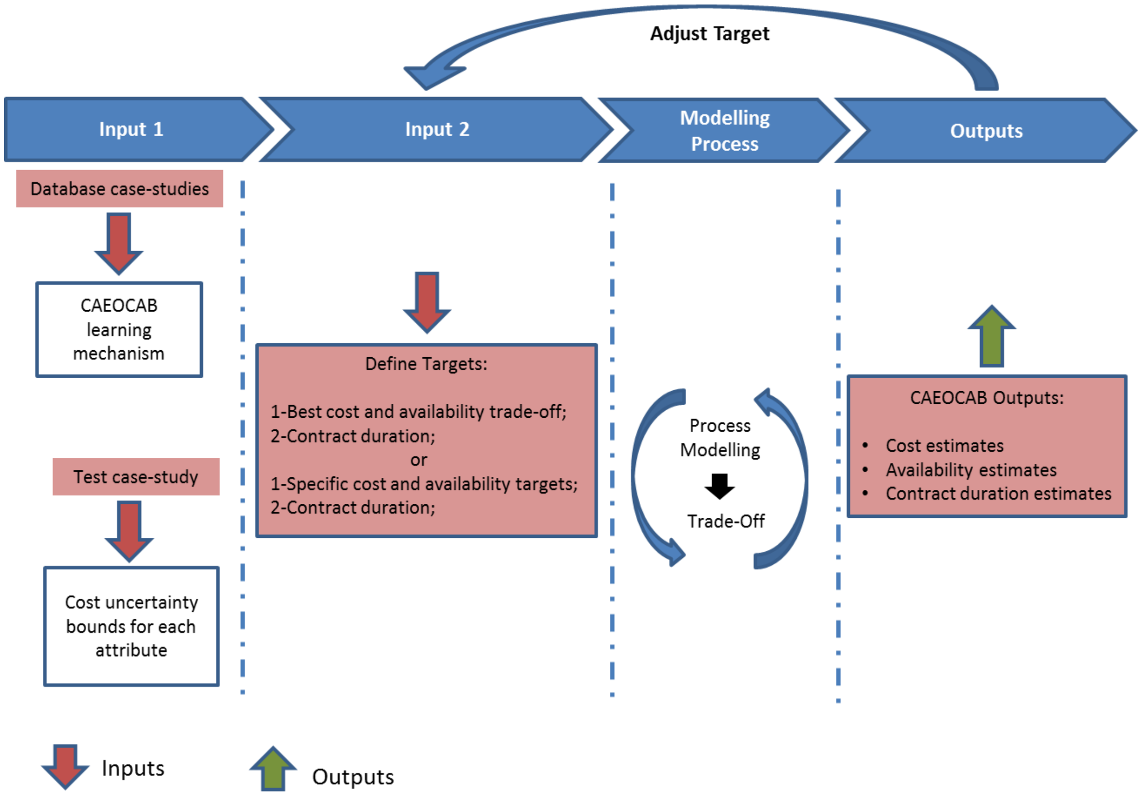


Figure 8-4 CAEOCAB: Methodology for Model Validation Though Case Studies

For each multiple study scenario, the outputs of the CAEOCAB were assessed by project managers that have been involved in the bidding process of those contracts, as they have the best experience and knowledge to perform an assessment of the accuracy of those outputs. Questionnaires 2 and 3 were the basis to collect the feedback from the participants.

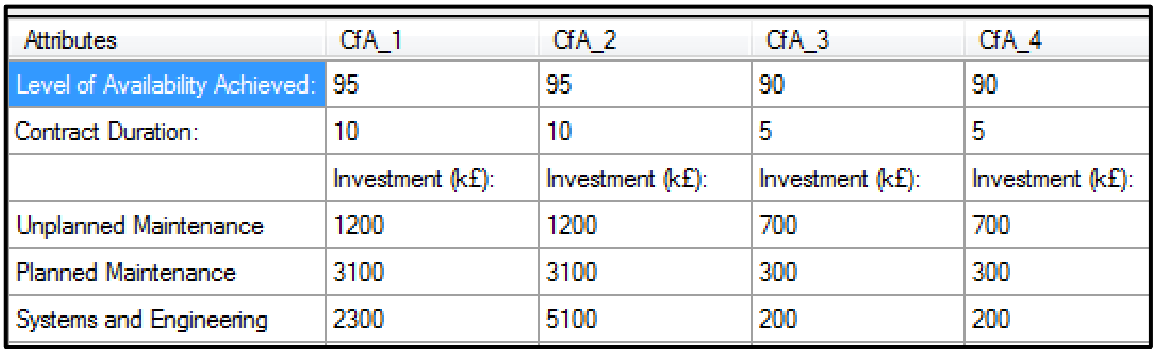
For reasons of confidentiality, the numerical data that will be presented in the next two sub-sections has been "sanitised", and the description of each case study was summarised and generalised, in order to not disclose details that could permit the identification of the actual system(s) and contracts considered.

8.3.2.1 Multiple Case Study Scenario 3

This multiple case study scenario covered four comparable CfA conducted with Organisation 1 and one with Organisation 2, all in the maritime context. The information about the four case studies with Organisation 1 was given by participant SH2, and the information about the case study with Organisation 2 was extracted from literature (Erkoyuncu, 2011). Each contract was focused on delivering support to a small/medium size system of high complexity (e.g. integrated system comprising hydraulic, pneumatic, mechanical and electronic sub-systems where the safe operation of the overall system is reliant on intricate control systems and associated feedback loops). The support provided included: spares, maintenance, provision of design authority and integration.

Three attributes have been considered: “unplanned maintenance”, “planned maintenance” and “systems and engineering”. These attributes have been selected because of their recognised impact on availability in the five CfA considered. The data of the four case-studies conducted with Organisation 1 were inputted to the database as presented in Table 8-3, and the case study with Organisation 2 was the test case study.

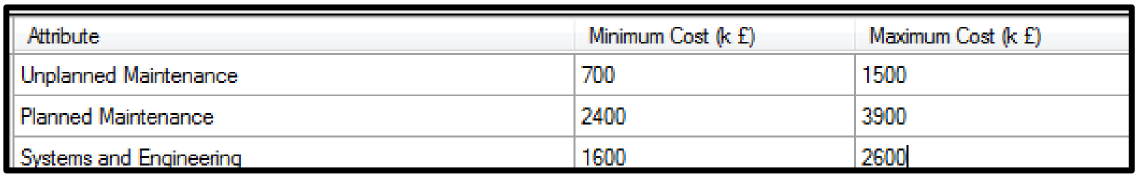
Table 8-3 CAEOCAB Database



Attributes	CfA_1	CfA_2	CfA_3	CfA_4
Level of Availability Achieved:	95	95	90	90
Contract Duration:	10	10	5	5
	Investment (k£):	Investment (k£):	Investment (k£):	Investment (k£):
Unplanned Maintenance	1200	1200	700	700
Planned Maintenance	3100	3100	300	300
Systems and Engineering	2300	5100	200	200

For the test case study, the minimum and maximum cost bounds for each attribute have been defined as in Table 8-4. These values correspond to an uncertainty range measurement that was calculated in (Erkoyuncu, 2011). The values are in thousands of pounds.

Table 8-4 Test Case Study Data



Attribute	Minimum Cost (k £)	Maximum Cost (k £)
Unplanned Maintenance	700	1500
Planned Maintenance	2400	3900
Systems and Engineering	1600	2600

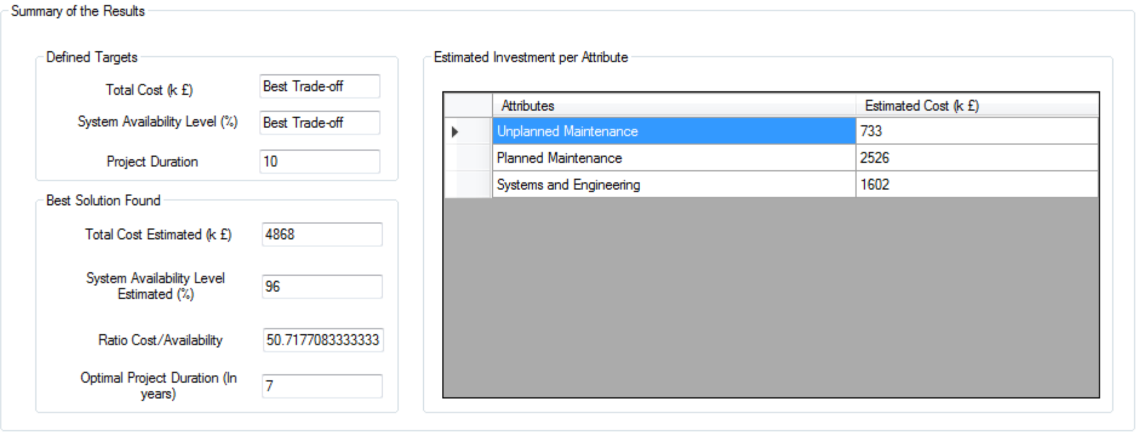
After contacting a person that was involved in the bidding process of the test case study – participant SH27 – it was estimated that, in actual, this contract lasted for 10 years and that the actual cost of each attribute in that contract was as follows: £1000k for “unplanned maintenance”, £3000k for “planned maintenance” and £2000k for “systems and engineering”. These values served as guidance to assess about the accuracy of the model estimates.

The estimates of the model were tested for the two types of targets that it supports and that were defined as:

- Target 1: Calculate the best trade-off between cost and availability for a 10 years contract.
- Target 2: Calculate the closest solution to total contract cost of £6000k and average availability of 96% for a 10 years contract.

The total cost of £6000k that was defined in Target 2 was assumed by adding up the actual cost figures that were estimated for each attribute, as described above.

Figure 8-5 and Figure 8-6 illustrate the estimates built in CAEOCAB for Target 1 (best cost and availability trade-off).



Summary of the Results

Defined Targets

Total Cost (k £): Best Trade-off
System Availability Level (%): Best Trade-off
Project Duration: 10

Best Solution Found

Total Cost Estimated (k £): 4868
System Availability Level Estimated (%): 96
Ratio Cost/Availability: 50.7177083333333
Optimal Project Duration (In years): 7

Estimated Investment per Attribute

Attributes	Estimated Cost (k £)
Unplanned Maintenance	733
Planned Maintenance	2526
Systems and Engineering	1602

Figure 8-5 Cost, Availability and Contract Duration Estimates for Target 1

Figure 8-5 shows that the best trade-off that can be achieved is 96% availability for a total contract cost of £4868k, if the contract duration reduces from 10 years to 7 years. To achieve these results the £4868k must be allocated as: £733k to “unplanned maintenance”, £2526k to “planned maintenance” and £1602k to “systems and engineering”.

Figure 8-6 shows the different combinations of total contract cost and system availability that have been calculated in the optimisation process. The horizontal axis corresponds to the total contract cost (in thousands of £) and the vertical axis corresponds to the system availability level (in %). The different points in the curve correspond to the different solutions found. The values are estimated considering three dimensions: cost, availability and time (contract duration). Note that each total cost value corresponds to a certain allocation of the budget across the attributes considered in Table 8-3. Different allocations of the same budget across the attributes can lead to different levels of availability. Higher availability can also be achieved for less cost; it depends on how well the money is allocated across the attributes and the project duration.

Figure 8-7 and Figure 8-8 illustrate the estimates built in CAEOCAB considering Target 2.

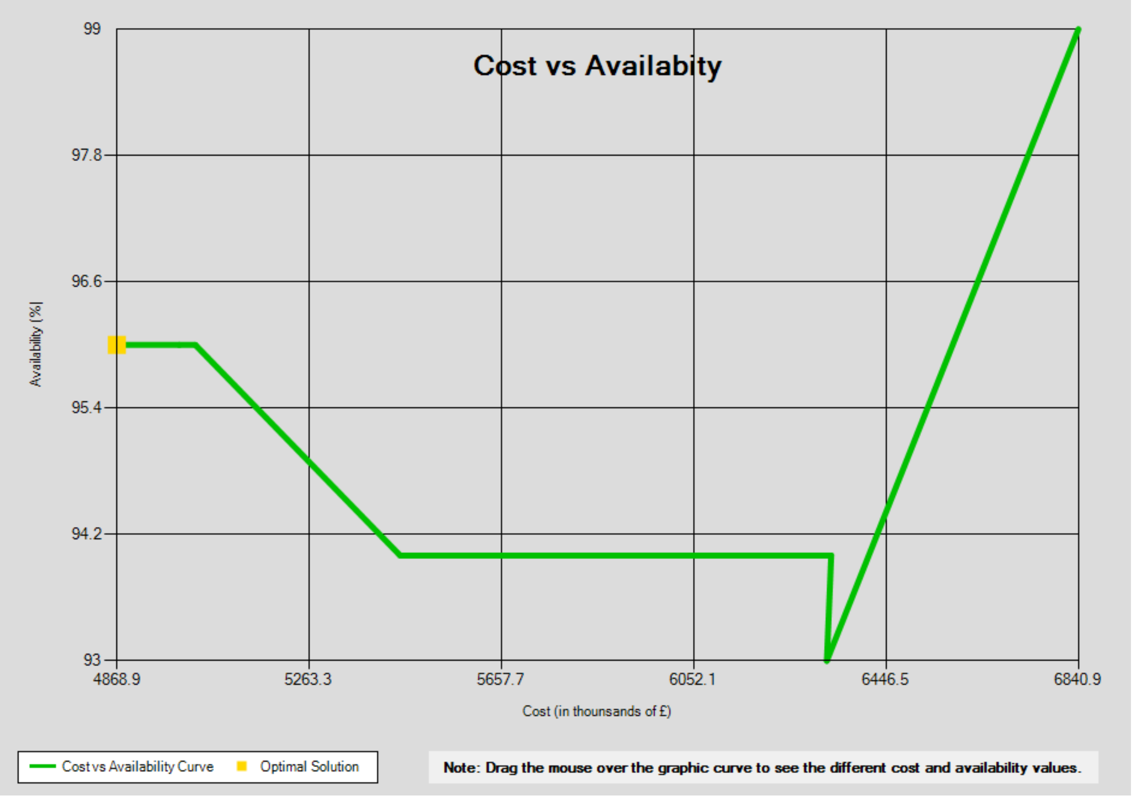
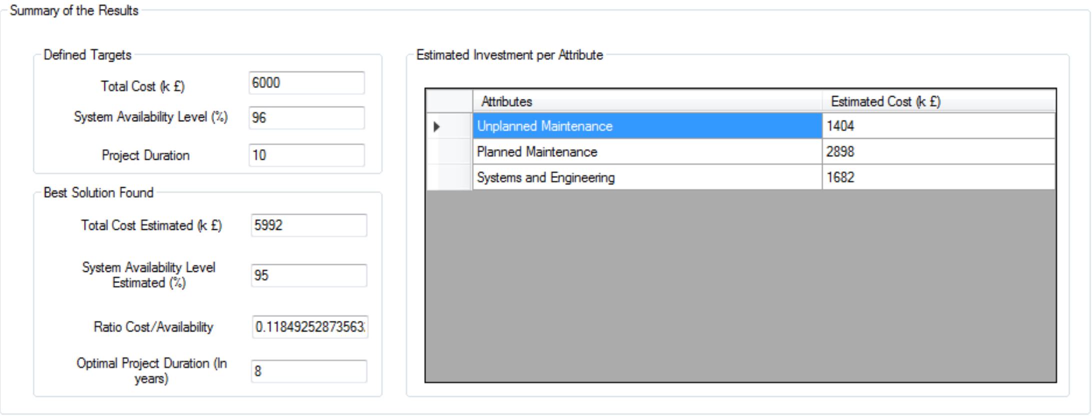


Figure 8-6 Total Contract Cost vs. Availability for Target 1



Summary of the Results

Defined Targets

Total Cost (k £) 6000
System Availability Level (%) 96
Project Duration 10

Best Solution Found

Total Cost Estimated (k £) 5992
System Availability Level Estimated (%) 95
Ratio Cost/Availability 0.11849252873563
Optimal Project Duration (In years) 8

Estimated Investment per Attribute

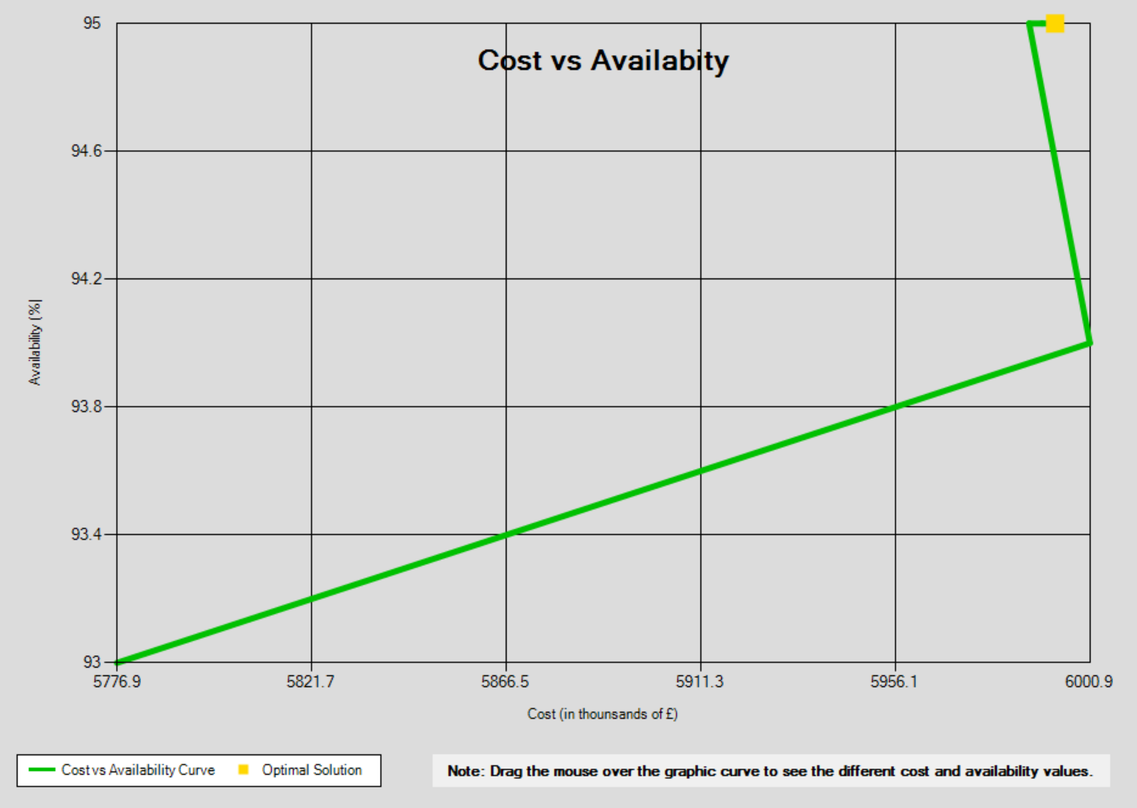
Attributes	Estimated Cost (k £)
Unplanned Maintenance	1404
Planned Maintenance	2898
Systems and Engineering	1682

Figure 8-7 Cost, Availability and Contract Duration Estimates for Target 2

Figure 8-7 shows that for the defined target of £6000k total contract cost and 96% availability over 10 years, the best solution can be achieved if the level of availability decreases slightly to 95% and the contract duration also reduces from 10 years to 8 years. In this case, the estimated total contract cost is £5992k that should be distributed as: £1404k to “unplanned maintenance”, £2898k to “planned maintenance” and £1682k to “systems and engineering”.

Figure 8-8 shows the different combinations of total contract cost and system availability that have been calculated in the optimisation process. The graph specifications are as in Figure 8-6. The different points in the curve correspond to the different solutions found in the optimisation process. The values are estimated considering three dimensions: cost, availability and time (contract duration). Each total cost value corresponds to a certain allocation of the budget across the attributes considered in Table 8-3; as it has been verified with the outputs shown in Figure 8-6, different allocations of the same budget across the attributes can lead to different values of availability.

These results were assessed in detail by participant SH27, who was involved in the bidding process of the test case study, although he had no access to the actual figures. Therefore, he provided an engineering judgement based on his significant experience of reliability, availability and cost modelling.



Note: Drag the mouse over the graphic curve to see the different cost and availability values.

Figure 8-8 Total Contract Cost vs. Availability for Target 2

The feedback received from participant SH27 following the format of Questionnaire 2 concluded that:

- On a scale of one to ten, the relevance of the outputs of the model at supporting cost and availability estimates at the bidding stage of CfA is ten, meaning that they are essential; the respondent also highlighted that: "*Estimates of cost are essential for almost all projects at the bid stage, while estimates of availability are essential for the majority of bids that require delivery of equipment or a service. These estimates are usually required by both supplier and customer, so a tool that enhances them would be of great value to both the suppliers (from various industries) and its customers.*"
- On a scale of one to ten, the innovation of these outputs is eight, meaning that there are no other models/tools providing the same type of

estimates at this level of analysis; the respondent also highlighted that: "*Although there are tools available that provide cost and/or availability estimates, it is harder to identify tools that can provide estimates of both cost and availability to a high level of accuracy without being strongly dependent upon a large amount of data capture on the part of the user. Hence if this tool is able to provide such estimates it will represent a valuable and innovative step forward. I am not aware of other tools that predict the optimal project duration, so this feature would be very useful*".

- On a scale of one to ten, the usefulness of the outputs of the model when compared to the outputs provided by the current methods is eight, meaning that they are moderate to highly useful.

The feedback received from participant SH27 following the format of Questionnaire 3 concluded that:

- On a scale of one to ten, the accuracy of the cost breakdown estimates in seven, corresponding to an accuracy between 70-80%; However, the participant safeguarded that "*as the systems analysed have, for reasons of confidentiality, not been specified, it has not been possible to check model predictions against actual data (which in any case tend to be difficult to obtain with confidence). Therefore the questions can be answered only on the basis of the degree to which the predictions are plausible and believable, rather than the extent to which they are known or strongly believed to be accurate per se*". He also referred that the three attributes described are very high level and, although it reduces the input required, it also might limit accuracy. He also analysed the relationships between attributes that could be extracted from the cost breakdown estimates, saying that: "*a strong relationship between failure rate and unplanned maintenance is to be expected, the other relationships seem weaker, although still present; this, however, is not seen as a fundamental problem with the model as it could be refined*".

- On a scale of one to ten, the accuracy of the total cost estimate is seven, corresponding to an accuracy between 70-80%;
- On a scale one to ten, the accuracy of the availability estimate is seven, corresponding to an accuracy between 70-80%, and this figure was believed regarding to the type of system considered, the respondent said;
- On a scale of one to ten, the accuracy of the suggested “optimal contract duration” is seven, corresponding to an accuracy between 70-80%; the respondent also remarked that “*the number is again plausible. This feature may be more useful to the customer than the supplier in scenarios where the supplier has little control over contract duration. Nevertheless, it could play a part in contract negotiation by providing useful information to support decision making. Scored slightly lower than other questions because I believe it is harder to validate and there are, to my knowledge, few if any other tools around that provide this information (as observed earlier this is good from the innovation viewpoint)”.*

Overall, the feedback from participant SH27 was considered positive, acknowledging an average accuracy of 70-80% to the estimates of the CAEOCAB. Further validation was then performed and is presented in the next section.

8.3.2.2 Multiple Case Study Scenario 4

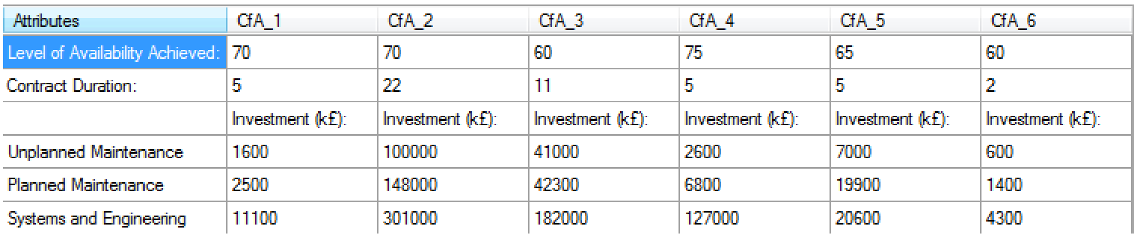
This multiple case study scenario covered seven comparable CfA conducted with Organisation 1, all in the aviation domain. Each contract was focused on delivering support to a small/medium size system of high complexity, covering the same type of support services as in the multiple case study scenario 3.

Three attributes have been considered: “unplanned maintenance”, which corresponds to the failure rate of the systems/sub-systems, “planned maintenance”, covering maintenance policy and periodicity, and “systems and engineering" that includes material support such as repairs and overhauls. These attributes have been selected because of their recognised impact on availability in the seven CfA examples considered.

The data provided was "sanitised" to protect its confidentiality, but it preserves the pattern of the original data.

Six case studies were introduced in the database as illustrated in Table 8-5. It shows the investment that was made in each attribute, contract duration, and level of availability achieved in these six contracts.

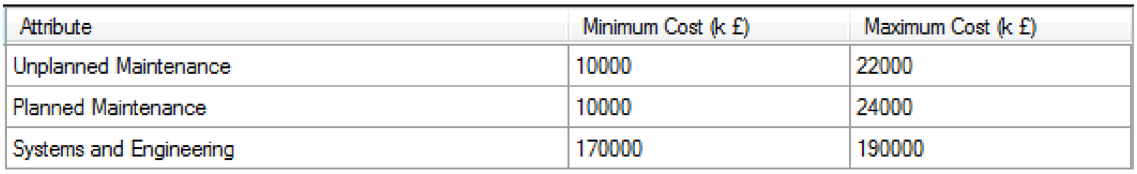
Table 8-5 CAEOCAB Database



Attributes	CfA_1	CfA_2	CfA_3	CfA_4	CfA_5	CfA_6
Level of Availability Achieved:	70	70	60	75	65	60
Contract Duration:	5	22	11	5	5	2
	Investment (k£):	Investment (k£):	Investment (k£):	Investment (k£):	Investment (k£):	Investment (k£):
Unplanned Maintenance	1600	100000	41000	2600	7000	600
Planned Maintenance	2500	148000	42300	6800	19900	1400
Systems and Engineering	11100	301000	182000	127000	20600	4300

For the test case study, the minimum and maximum cost bounds for each attribute have been defined as presented in Table 8-6. These values correspond to the minimum and maximum cost that could be allocated to each attribute in that contract. The values are in thousands of pounds.

Table 8-6 Test Case Study Data

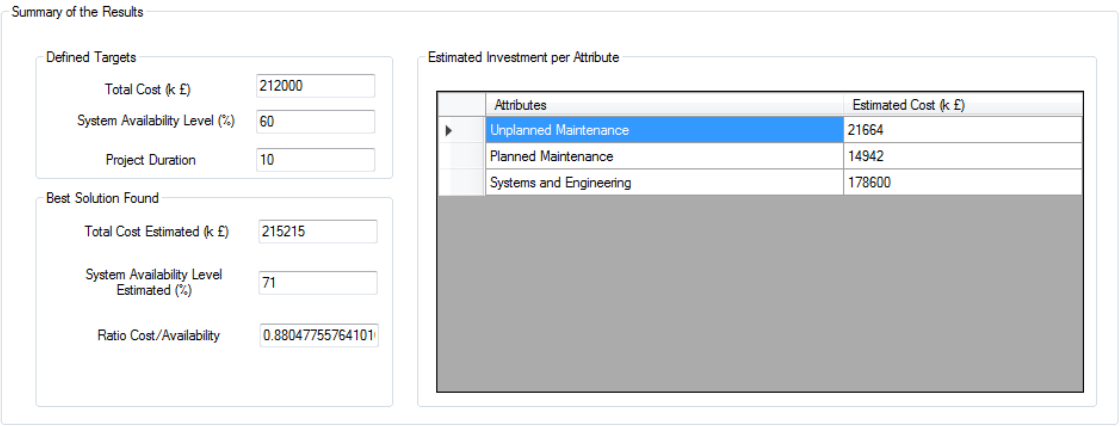


Attribute	Minimum Cost (k £)	Maximum Cost (k £)
Unplanned Maintenance	10000	22000
Planned Maintenance	10000	24000
Systems and Engineering	170000	190000

For the test case study, the following target was defined:

- Total contract cost: £ 212000k;
- Average availability: 60 % ;
- Contract duration: 10 years (This target was considered as not flexible).

Figure 8-9 and Figure 8-10 show the estimates calculated in CAEOCAB considering the above target.



Summary of the Results

Defined Targets

Total Cost (k £): 212000
System Availability Level (%): 60
Project Duration: 10

Best Solution Found

Total Cost Estimated (k £): 215215
System Availability Level Estimated (%): 71
Ratio Cost/Availability: 0.88047755764101

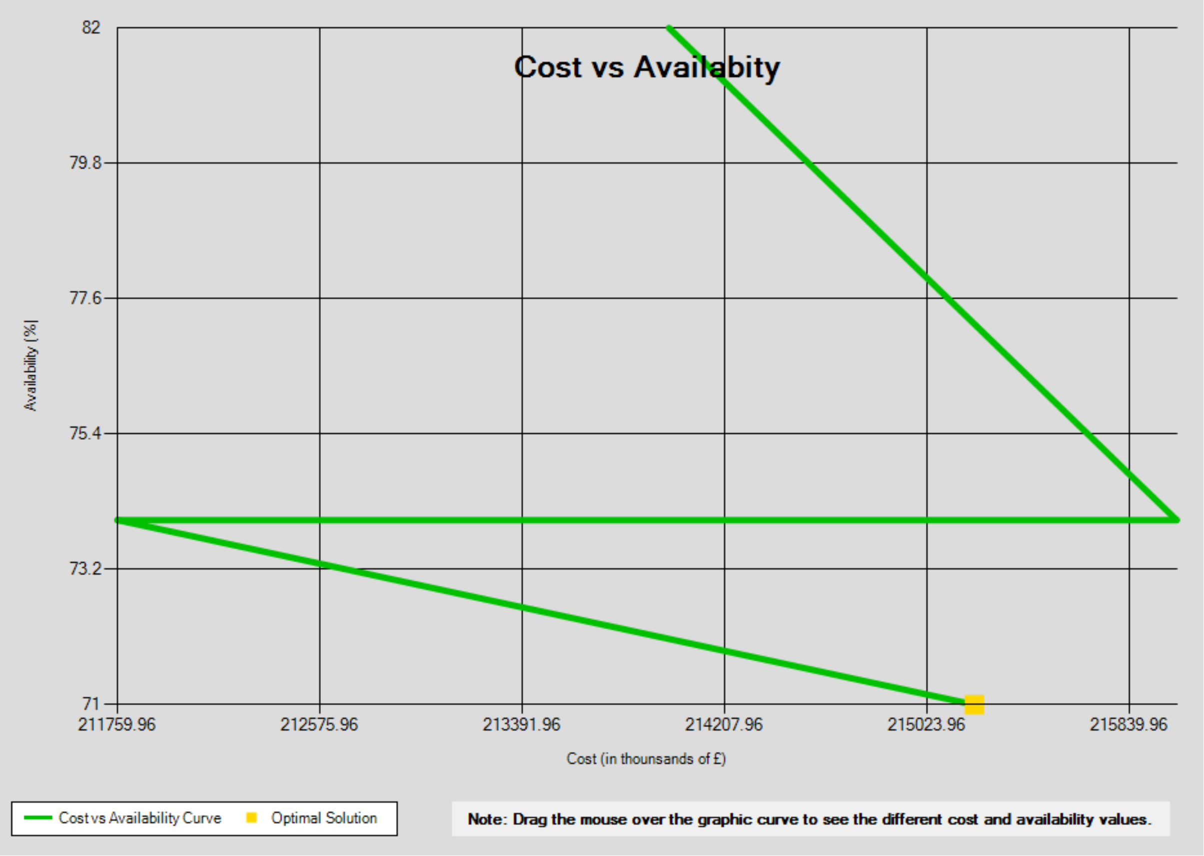
Estimated Investment per Attribute

Attributes	Estimated Cost (k £)
Unplanned Maintenance	21664
Planned Maintenance	14942
Systems and Engineering	178600

Figure 8-9 Cost and Availability Estimates

Figure 8-9 shows that for the defined target of £212000k for total contract cost and 60% for system availability over 10 years, the best solution can be achieved with a higher level of availability, 71 %, if the total contract cost increases to £215215k that should be distributed as: £21664k to unplanned maintenance, £14942k to planned maintenance and £178600k to systems and engineering.

Figure 8-10 shows the different combinations of total contract cost and system availability that have been calculated in the optimisation process. The horizontal axis corresponds to total contract cost (k£) and the vertical axis corresponds to the system availability level (%). The values are estimated for a 10 years contract. The different points in the curve correspond to the different solutions found. Note that each total cost value corresponds to a certain allocation of the budget across the attributes considered in Table 8-4; different allocations of the same budget across the attributes can lead to different values of availability. We can also achieve higher availability for less cost; it depends on how well the money is allocated across the different attributes. Note that these calculations have been performed across three dimensions: cost, availability and time (contract duration); it also explains the non-regular shape of the curve.



Note: Drag the mouse over the graphic curve to see the different cost and availability values.

Figure 8-10 Total Contract Cost vs. Availability Curve

The above results were assessed in detail by participant SH30, who was directly involved in the bidding process of these CfAs. He ran the model multiple times, making adjustments in the target but keeping the same database, to assess the flexibility of the estimates and to be more confident about their accuracy.

The feedback received from participant SH30 following the format of Questionnaire 2 concluded that:

- On a scale of one to ten, the relevance of the outputs of the model at supporting cost and availability estimates at the bidding stage of CfA is seven, meaning that they have moderate relevance;

- On a scale of one to ten, the innovation of outputs of the model is seven, meaning that there are no other models/tools providing the same type of estimates at this level of analysis; the respondent also recognised that "*the complex relationships between availability contract elements means previous attempts to build this type of tool have had limited success. Subject matter expert opinion is more often used in the bid phase as is a 'bottom up' approach to establishing bid costs. However, bid cost seldom gives an overall indication of availability the investment will generate but are more often designed to 'meet the requirement' with a level of risk and opportunity to both customer and supplier*".
- On a scale of one to ten, the usefulness the outputs of the model when compared to the outputs provided by the current methods is five, meaning that they are probably useful. Nonetheless, the respondent safeguarded that "*the usefulness of the tool can only be assessed in its current format and level of development. Were the tool to be fully productionised and populated with domain specific data the score value would be higher*".

The feedback received from participant SH30 following the format of Questionnaire 3 concluded that:

- On a scale of one to ten, the accuracy of the cost breakdown estimates in seven, corresponding to an accuracy between 70-80%; the participant still highlighted that "*during validation the results were broadly as expected*".
- On a scale of one to ten, the accuracy of the total cost estimate is six, corresponding to an accuracy between 60-70%; the participant recognised that "*the overall cost estimate was slightly less accurate than the breakdown figures*";
- On a scale of one to ten, the accuracy of the availability estimate is seven, corresponding to an accuracy between 70-80%; here the

participant recognised that the availability estimate "*was logical in relation to the cost estimates and allocation of investment suggested*";

- On a scale of one to ten, the accuracy of the suggested "optimal contract duration" is seven, corresponding to an accuracy between 70-80%; this estimate received similar comment to the availability estimate by the participant.

The feedback of participant SH30 relating to the accuracy of the CAEOCAB was considered good, as he acknowledged an average accuracy of 70-80% to the model estimates. This feedback is aligned with the feedback received by participant SH27 at the analysis of the multiple case study scenario 3.

8.4 Summary

This section presents the methodology and results from the V&V applied to the CATECAB model presented in Section 6 and the CAEOCAB model presented in Section 7.

The main distinction between verification and validation considered in this study was the level of subjectivity of the assessment, e.g. whilst verification concerned about the more objective tasks such as checking formulas, algorithms, and the alignment of the models' outputs with the research objectives, the validation concerned about the innovation, usefulness and accuracy of the models and estimates.

In order to facilitate the V&V process the models were implemented in software platforms and developed as simulation models. During this implementation an initial verification was performed which focused primarily on the formulas and algorithms of the models. Upon the development of the simulation models, they were presented to different stakeholders that were involved in the initial phase of this study in order to verify that the models were aligned with their expectations and with the objectives of this research.

Furthermore, each model was assessed with two multiple case study scenarios, one in the maritime domain and other in the aviation domain, each of which covered a number of comparable CfA that comprised the support of complex engineering systems for a period between five and twenty-two years. The performance of the models when applied to these case studies was assessed by subject matter experts that were involved in the bidding process of the CfA covered in those case studies. These experts first verified and confirmed that the outputs of the models are innovative and aligned with the initial objectives of this research. Then, they validated the estimates produced by the models and acknowledged that:

- CATECAB produces cost estimates with an accuracy between 70-80%;
- CATECAB produces availability estimates with accuracy between 70-80%;
- CATECAB is moderate to highly effective at trading cost and availability;
- CAEOCAB produces cost breakdown estimates with accuracy between 70-80%;
- CAEOCAB produces total contract cost estimates with accuracy between 60-80%;
- CAEOCAB produces availability estimates with accuracy between 70-80%;
- CAEOCAB suggests optimal contract duration with accuracy between 70-80%.

It is important to refer that the accuracy acknowledged to each model relies on the opinion, experience and knowledge of the subject matter experts that performed the assessment, which might be subjective. However, these experts were selected based on the criteria of identifying the most experienced and knowledgeable people to judge the accuracy of cost and availability estimates for CfA at the bidding stage.

9 DISCUSSION, CONCLUSIONS AND FUTURE WORK

9.1 Introduction

This chapter presents a discussion over the key themes considered throughout this thesis, the conclusions, and the recommendation for future work.

The chapter starts with a discussion over the research findings in Section 9.2, where the key topics are discussed in independent sub-sections. Then in Section 9.3, an analysis is made about the applicability and generalisability of the research. The discussion moves onto an analysis of the quality of the findings in Section 9.4. In Section 9.5 the key research contributions are summarised and in Section 9.6 the research limitations are identified. Finally in Section 9.7 the main conclusions of this research are outlined. The thesis ends with some recommendations for future work as presented in Section 9.8.

9.2 Discussion of Research Findings

The discussion about the research findings is divided according to the following topics: Section 9.2.1 presents the findings of the literature review and the industry interaction, Section 9.2.2 outlines the strengths of the research methodology adopted, Section 9.2.4 discusses about the list of attributes identified that impact on cost and availability in CfA, Sections 9.2.5, 9.2.6 and 9.2.7 discuss about the application, strengths and limitations of the CATECAB, EMOGA and CAEOCAB respectively.

9.2.1 Literature Review and Industry Interaction

In the core literature review performed, as presented in Chapter 3, the focus was on exploring the link between three main research fields including Industrial Product-Service Systems (IPSS), Cost Estimation, and Through-life Engineering.

The focus for research in IPSS centred on Performance-Based Contracts (PBC). There are different types of PBC that vary in terms of a number of parameters such as: performance metrics, support requirements, level of responsibility passed on to the supplier to maintain the overall performance of a system, etc. This research focused on a particular type of PBC called Contracting for Availability (CfA). Under CfA, the supplier is contracted to support and maintain a system(s) availability over a fixed period of time, which can last from 5 to 20 or more years. This support includes complex engineering tasks such as repairs, overhauls, upgrades, training, etc., that are agreed during the contracts' negotiation. The negotiation is part of a bidding process, where one or more organisations (the suppliers) compete for a contract. The bidding process has different phases, starting from the first approach between customer/supplier(s) to initiate the tender process, until the final selection of the supplier(s) and contract agreement. This is one of the most important stages of the contracts' life cycle because it is where most of the contracts' cost is decided and agreed. It is also where the supplier(s) agree in meeting the support requirements to maintain a certain level of availability of the system.

The main stakeholders during the bidding process are the project managers. This includes customer project managers and supplier project managers. From the customer side, the project managers coordinate the bidding process in order to ensure that the supplier(s) meet the bidding timeframes, and assess the bids in order to select the final supplier(s). From the supplier side, the project managers have to coordinate the process of designing and planning the support solution in order to ensure that:

- There is a great understanding of the customer' needs and requirements;
- Possible competitors are identified and the position of the company in the market compared to those competitors is assessed;
- The organisation has the capability to deliver the necessary support in order to satisfy the customer' requirements;

- The bid price is comprehensively built considering: (1) the customer' affordability; (2) other competitors price; (3) the actual (estimated) cost of resources to deliver the required support; (4) the margin of profit;
- There is a good level of communication between the different managers and different departments inside the organisation in order to ensure an effective understanding of the requirements and a collaborative work towards designing the support solution and the estimates.

The most challenging task for the project managers is to build the cost estimate to bid for the contract, which has to be aligned with an estimated level of availability. In this thesis, the cost estimation research focused on the management level analysis.

Throughout the bidding process, the estimates are expected to reduce in uncertainty and increase in accuracy. Typically, the first estimates are built in short time frames and with the minimum of resources, and therefore they tend to have a higher uncertainty associated. As the bidding process evolves, more effort is gradually put in place to develop more accurate estimates and reduce uncertainty. However, an increased effort involves more time and resources, which can be expensive. Also, the bidding is extremely complex because of a number of factors that make estimating challenging such as: the (typically) long time span of contracts, the complexity/unpredictability of the support requirements, the complexity of the systems being supported, challenging scenarios where the systems have to operate, and the lack of experience in delivering availability based solutions.

To build effective cost estimates for the bids the project managers have to ensure that:

1. The designed support solution will maintain the through-life availability of the system(s) at a required level;

2. The cost estimate covers all the support activities and resources included in the support solution designed;
3. The final estimate submitted to the bid is realistic and competitive enough to win the contract.

Firstly, in order to ensure that an effective support solution has been designed for the system for the entire contract duration, project managers have to understand the TES that will make that support. One of the first focuses in this thesis was on identifying what are the TES that impact on the availability of the systems in CfA, as presented in Chapter 5. Moreover, project managers have also to understand what is the cost associated to a through-life support solution, in order to build the cost estimate for the bid.

Systems Engineering (SE) is the field of engineering that supports the management teams with the best-practices to perform the through-life planning and cost estimation. The application of SE to project management decision-making is typically known as Systems Engineering Management (SEM). SEM best practices are typically supported by model-based approaches that enable the analysis, assessment and control of the systems, in order to predict their through-life behaviour and support requirements. These models can have multiple applications such as: prediction of equipment remaining useful life, prediction of mean time between failures, cost estimation, etc. For the purpose of this research, the focus was on developing a model for cost and availability estimation.

Computational based models are perhaps the most popular to build cost and availability estimates, as they have the ability to simulate the behaviour of the system over time and for different scenarios. It is considered as an effective approach to improve the systems' design and maximise its through-life performance at the lowest cost. In the literature review performed, different techniques were identified to develop models for cost and availability estimation, and their appropriateness according to different scenarios of data availability and level of analysis required was assessed.

After investigation of the current practices, it was recognised that project managers have difficulty to find the appropriate models to build their cost and availability estimates. It has been reported that the existent models are very data-intensive and data is typically limited at the bidding stage. The limitations with data at the bidding stage include:

a) Lack of detailed information about the system life-cycle requirements: due to unforeseen scenarios that may affect the system during its life-cycle, it is difficult to define in advance what will be the operational requirements of the system (e.g. number of repairs, number of overhauls, number of updates, lead-times, etc.);
b) Historical data for analysis: data is not properly collected and saved from current projects to be used in future analysis, and in particular at the management level. Moreover, gathering appropriate quality/size data may be expensive. At the early stages of the bidding process, the effort (e.g. cost effort) to produce the estimates is expected to be minimal including with data collection. Moreover, the processes of sharing data between different project management teams within the organisations are inefficient.

In addition, after further investigation in literature, no models or processes have been identified that are able to build cost and availability estimates at the bidding stage of PBC (e.g. CfA), and in particular in limited data scenarios and to support management level decisions. Also, the overall literature dedicated to cost estimation in PBC is limited. In the few documents identified about this topic, challenges are identified but the solutions proposed are typically of high level of abstraction and of conceptual nature. Some literature exists with more concrete solutions but it is focused on reducing uncertainty of the estimates, and not building the actual estimates.

Therefore, different project managers reported that building the estimates based on their experience, trying to establish an analogy with the cost of previous and similar projects. This approach can be however inaccurate, particularly if the estimates are required to be made in a short time frame, or if the systems are new and cannot be compared with other systems from previous projects. Project managers sometimes apply some commercial tools to build the estimates, when possible, but they have to make a lot of assumptions to fulfil all the input requirements of the tools, which can end up with uncertain or unreliable estimates.

This research focused on fulfilling these research gaps by reviewing literature and identifying different modelling techniques that can be applied in the development of models to estimate cost and availability in CfA, under limited data scenarios. It also focused on performing a comprehensive assessment of the bidding process in PBC (and in particular in CfA), identifying the different phases of the bid, the key industrial stakeholders, and important timeframes.

All of this information was used to develop a model-based approach to build the cost and availability estimates at the early stages of the bidding process, and to achieve the aim of this research.

9.2.2 Strengths and Weaknesses of the Research Methodology

There were a number of strengths in the research methodology driven by its focus on the stakeholders that will benefit from the research results.

Firstly, the methodology focused on establishing a rigorous criterion to select the right stakeholders, and allocate enough time with them to gather information and validate the results. In such a way, the researcher interacted with a number of project managers from different organisations (Organisations 1-6), including the larger organisation in the UK that typically acquires support under CfA (Organisation 5) and that is the most important customer for the organisations included in this interaction. This wide collaboration of industry organisations enabled the researcher to develop the study based on the perspective of the two parties involved in a contract (customer and supplier), and understand the current challenges based on a collection of evidence from different sources. The extent of this interaction also enabled to draw a comparison between organisations in the identification of the most critical challenges experienced during the bidding process. Furthermore, the researcher had a strong interaction with the sponsoring organisation of this research. The industrial stakeholders from this organisation (participants SH1, SH2, and SH3) followed the research progress from the beginning, assisting at providing relevant information, identifying other sources of information (e.g. other relevant stakeholders), and validating the results.

Secondly, the application of various methods and techniques to interact with the stakeholders and to collect information, as presented in Chapter 2, ensured that the weaknesses of a particular method/technique were mitigated by the strengths of other method(s), so that it did not influence the quality of the interviews and the gathered data.

Thirdly, the best practices applied during the interaction with the stakeholders. It included taking notes during every interview and workshop, and validating them with the participants after each session. This practice enabled the researcher to perform a sanity check/validation of the contents and prevented the loss of relevant or misunderstandings.

Fourthly, the multidisciplinary approach that was applied to the interaction with other researchers and industry experts. Participants from different backgrounds (e.g. mathematics, through-life engineering, optimisation, etc.) were consulted in order to obtain insights and suggestions to develop solutions about particular issues that were raised during the research.

Fifthly, the active involvement of the project stakeholders during all the stages of the research to ensure the right support and research direction. The stakeholders were invited to perform a continuous validation of all the research findings, and were involved in the process of establishing research directions and objectives. This involvement increased their motivation and supportability throughout the research. It also helped to make sure that the outputs of the research were tailored to their needs and requirements.

Finally, the case-studies used to identify the industry current practices and challenges enabled the researcher to develop the research based on evidences and "tailored for purpose". Also, the case-studies used to validate the CATECAB and CAEOCAB models were based on data from real CfA bids, from multiple domains, to ensure their suitability to be used in the context of different CfA and at the bidding stage. The two domains considered (maritime and air) cover the main focus of application of CfA, according to the insights received by the different industrial stakeholders involved in this project, and by the literature reviewed. Although CfA is also applied in the land domain, the percentage of application is low compared to the other domains and therefore the validation of the models was believed to cover the most important scenarios where CfA are applied. Moreover, the accuracy of the models was assessed by subject matter experts with extensive experience in the preparation of CfA bids. This approach validated that the models can be applied in different domains (at least in the two domains considered in the validation) and produce accurate estimates as presented in Chapter 8.

On the other hand, a number of weakenesses can also be pointed out to the HCD methodology adopted such as:

- It required that a significant amount of time was devoted to the selection of the right stakeholders and to the engagement with them to gather/validate information and to get suggestions for work directions;
- Sometimes it was difficult to interprete the information given by the stakeholders;

- It was hard to validate the results due to the level of subjectivity involved in the human assessment.

9.2.3 Limitations of the Research Methodology

The HCD methodology is based upon an explicit understanding of the needs of the people that will benefit from the research results which requires a good hability to select and interact with the project stakeholders, and to select the appropriate techniques for the purpose.

Moreover, the high effort required to identify and effectively engage with the stakeholders limits the time available for desck-based research to design and develop solutions.

In addiction, the stakeholders not always know what they truly need and considerable amount of time has to be spent in understanding their needs, which also reduces the time available to develop solutions.

Finally, it is possible that too much emphasis is given to the opinion of the stakeholders, which limits the creativity of the researcher in the development of solutions.

9.2.4 List of Attributes Impacting on Cost and Availability

The first objective of this research was to identify the attributes that impact on cost and availability in CfA, in order to develop the study based on a detailed analysis and assessment of those attributes.

Hence, as presented in Chapter 5, a systematic and iterative process was applied to develop the list of attributes. An initial list of nine attributes was developed, as presented in Table 5-1. It was further investigated and validated to ensure that it covers the most important attributes that drive the cost and availability targets in any type of CfA. It was also identified that there are many other attributes that also impact on cost and availability in CfA, but they are closely related to these nine. In parallel, a categorisation approach was suggested considering the nine attributes presented in Table 5-1 as “main-attributes” and all the other attributes as “sub-attributes”. This categorisation approach aimed at defining a standard list of main-attributes that cover any type of CfA requirement, and a number of sub-attributes that are specific to each contract and that can be associated to one or more main-attributes depending on the context and type of contract. A systematic effort was then put in place to extend the list of sub-attributes, by interacting with many subject matter experts from industry and academia. Throughout this process it was understood that it is almost impossible to build a list that covers all possible attributes, as in each of the many interviews performed new suggestions were made to include/exclude attributes from the list, and it was never considered as exhaustive. However, as the interaction with the experts was extensive, covering more than ten people and approximately fifteen interviews, and the experience of the experts was high, the researcher was confident that the set of attributes identified covers the most important in the context of CfA.

One aspect highlighted by all the participants in this study was related to the interrelationships between attributes. One attribute can impact on many others, and this impact is typically not linear and can vary from contract to contract, depending on different aspects such as: contract duration, level of supplier responsibility over the overall system performance, complexity of the system, etc. Also, the understanding of these interrelationships is limited and controversial among different experts.

An on-line survey was then launched to reach different experts with experience in CfA, aimed at understanding some of these interrelationships between attributes. The survey was answered by thirteen participants, with extensive experience in CfA planning and delivery. The number of participants was not very high, but their extensive experience, relevant job position, and level of commitment in responding to the survey (e.g. time spent to assess each question), ensured that quality responses were obtained.

The responses to the survey were very different for some attributes, and consensus was verified in others. Conclusions were then drawn about the association between attributes based on a criteria defined by the level of consensus in the responses as presented in Section 5.3.3. These results were further validated in three interviews with different experts, and a final list of attributes was agreed where the attributes are categorised according to their level of association. This list can help the project managers to easily identify the relevant attributes for a particular project, and build the through-life support plan and estimates following guidance according to the impact between attributes identified. This list is also important to start interpreting and assessing the relationships between attributes, towards building processes and tools to trade-off between cost and availability across the attributes. In fact, in Chapter 5 the author starts from these results to propose a framework that aims at providing guidance for the development of modelling applications to estimate and trade-off cost and availability at the bidding stage of CfA, considering the complexity of the interrelationships between the attributes. This framework guided the development of the CATECAB model presented in Chapter 6, and the CAEOCAB model presented in Chapter 7.

9.2.5 Cost and Availability Trade-Off and Estimation Model (CATECAB)

The CATECAB was developed as a prototype simulation model that allows the use to estimate and trade-off cost and availability for CfA bids. This model is aligned with the fourth objective of this research and reflects the requirements/suggestions of the project stakeholders, and in particular those from Organisation 1 which was the sponsor of this project. It also fulfils a gap in literature related to the limited availability of processes to estimate and trade-off cost and availability in the context of CfA and in limited data availability scenarios. To the best of the author’s knowledge, this model is innovative in the context of CfA bids and in particular at supporting management level decisions.

The main strength of the model is its ability to build cost and availability estimates under limited data scenarios, which is one of the main challenges at the bidding stage. Also, it considers the interrelationships between the attributes that impact cost and availability, which is typically ignored in the current practices because of a lack of knowledge, limited time to build the estimates, and a lack of tools to support in the task. With the CATECAB model the project managers will be able to estimate the impact of an investment change (£) in an attribute in the cost of the other attributes, and also identify those attributes that have more impact on availability in order to have guidance for any investment change. However, in order to achieve the best quality estimates using the model, the user will have to provide appropriate information from previous projects, as described in Section 6.4. This type of information can now be collected more effectively in the current projects, in order to ensure an improved performance of the CATECAB model in future bids.

Moreover, the model contributes to literature as an innovative process to build cost and availability estimates that requires few input data, and combines three well established modelling techniques that were selected based on an assessment of their complexity, accuracy and data requirements as presented in Section 3.4.3. To the best of the author knowledge there is no similar process/model in literature that works at this level of analysis.

The main limitation of the model is not being able to perform optimisation analysis. All the estimates and trade-off analysis are done on a trial and error basis, which can be time consuming and not ensure that the optimal solution will be achieved. Also, the quality of the estimates depend on the quality of the database information, so an effort has to be made to get the right data.

Nonetheless, the strengths of the CATECAB model combined with expert opinion can improve significantly the current processes of building the estimates in both time and quality, giving more confidence to the project managers about the feasibility of the contract and reducing the uncertainty of the estimates.

The selection of MS Excel to implement the CATECAB model was also beneficial, as it is a software package well known by the majority of the people that will use the model, and most of the organisations (if not all) have the software.

9.2.6 Enhanced Multi-Objective Genetic Algorithm (EMOGA)

There are many algorithms for optimisation as identified in the literature review performed in Chapter 3. However, no algorithm was identified to optimise multiple objective functions (independent functions) that assures a normalised comparison between the objectives towards identifying the optimal solution. The EMOGA algorithm is an enhancement of a classic genetic algorithm independent functions and assess the optimal solution based on a normalised comparison between the objectives of each function. In particular, the EMOGA algorithm was developed to find optimal solutions considering functions of cost, availability and time, and assessing “optimal solutions” based in a normalised comparison between these three objectives. To the best of the author knowledge the approach is innovative, and it is flexible as it can be adjusted to give more relevance to one or more objectives in the process of identifying the optimal solution. For example, in non-flexible budget scenarios, it is possible to give more relevance to the total project cost target in comparison to the availability and contract duration targets.

9.2.7 Cost and Availability Estimation and Optimisation Model (CAEOCAB)

The CAEOCAB model was developed as a combination of the CATECAB model and the EMOGA algorithm. This combination aimed at mitigating the limitation of the CATECAB model in performing optimisation analysis. With the CAEOCAB the project managers can build their estimates by fixing cost and availability targets for their bids, and obtain the closest and feasible solution to those targets. The model interprets the interrelationships between the attributes and performs an automated trade-off analysis across those attributes, evaluating different allocations of the budget across those attributes and estimating the impact on availability for a certain contract duration. The model produces quick results and can be applied in limited data scenarios. The CAEOCAB can be seen as an upgrade version of the CATECAB, performing automated trade-off analysis between cost and availability and identifying the best scenario. This model is also more user-friendly in order to facilitate its professional use by project managers across industry.

The main academic contribution of the CAEOCAB is the innovative process to perform optimisation analysis, with few input data required, that automatically estimate the best allocation of the budget across the attributes to achieve the performance targets. The process covers an innovative combination of four well established modelling techniques that were carefully selected based on an assessment of their complexity, data requirements and accuracy, as presented in Section 3.4.3.

For the industry project managers, the innovation of the CAEOCAB covers aspects such as:

- The assessment of the interrelationships between the attributes;
- The assessment of the cost impact of each attribute in the other attributes and on availability;
- The automatic process to trade-off between cost, availability and contract duration;
- The process for building the estimates in limited data scenarios.

To such a degree, the CAEOCAB is believed to bring innovation to the current processes of building cost and availability estimates for CfA, reducing the time required to produce the estimates and increasing the confidence of the cost analysts. Also, it represents a novel contribution to research that can also be adapted to other contexts (e.g. in-service phase) and that will motivate other researchers to develop new processes to compare against the contribution/performance of the CAEOCAB.

9.3 Applicability and Generalisability of the Research Findings

The focus of this section is on discussing the applicability and generalisability of the research findings, focusing in particular on the CATECAB and CAEOCAB models.

Both models are targeted to be applied by project managers during the bidding stage of CfA. The stakeholders that accompanied the development and validation of the models recognised that they are more suitable to be applied during the early stages of the bid, although they can also be applied in the later stages for validation purpose. For example, the models can be used in the later stages of the bid to compare against the estimates built with exhaustive processes (e.g. detailed bottom-up approaches and expert opinion), to increase confidence and/or identify possible mistakes or opportunities for improvement.

One of the main advantages of the models is its ability to produce estimates in limited data scenarios. This feature is particularly important at the bidding stage due to the recognised scarcity of data that is typically verified.

The models produce quick cost and availability estimates, as both setup and processing times are fairly short. As the models already include a pre-defined list of attributes that impact on cost and availability (validated in the context of CfA), the users can identify from this list the most appropriate for a particular project, which facilitates the use of the models and speed up the setup process. The database can also be saved from one project to another which simplifies the setup process. The processing time of the models is only about 5-10 seconds.

Each model has a sequential number of steps to follow, and each step has a detailed explanation of the information that has to be provided in order to produce the results. This makes the models intuitive and easy to use, enabling the use by project manager with limited experience in software.

Based on the validation results of the models, it was acknowledged that they are suitable to be applied in the following scenarios:

- Building initial cost and availability estimates at the early stages of the bidding process;
- Later stages of the bidding process for comparison and validation purpose with estimates built with traditional methods (e.g. expensive and exhaustive methods such as bottom-up costing);
- Cost and availability trade-off analysis to support decision making at the early stages of the bidding process, at the management level;
- Limited data scenarios;
- Maritime and aviation domains;
- Scenarios that require analysis of the interrelationships between attributes.

The restricted suitability of the models to the maritime and aviation domains is due to the extent that was possible to take the validation. It was not possible to identify case studies in other domains such as land or aerospace, and therefore no conclusions can be drawn about their applicability to these domains. However, it does not mean that the models cannot be applied wider, and further validation is encouraged to make that assessment.

9.4 Quality of the Findings

The author was always focused and motivated to achieve the best possible quality research and outputs. To achieve that target, a big effort was committed to identify the best research methodology, and the most appropriate methods and techniques to collect information and produce results, as presented in Chapter 2. The research followed a methodology that focused on the needs and requirements of the people that will benefit from the outputs produced, and a variety of methods and techniques was applied to effectively interact with the key stakeholders and collect/validate information and findings. Triangulation of data and methods was also applied when possible. Furthermore, all the research findings were based on a methodological engagement with more than thirty stakeholders from seven organisations to ensure representability and credibility. Also, the application of four multiple case study scenarios, in two industry domains, to validate the models aimed to achieve a good level of confidence about their applicability and accuracy.

To this extent, and based on the feedback obtained from the stakeholders involved in the project, the researcher believes that the level of quality targeted for this research was achieved. It is also believed that the outputs produced will give an important contribution to improve the current practices in the preparation of CfA bids, and to the enrichment of literature by fulfilling the research gaps identified, as presented in Chapter 3.

9.5 Key Research Contributions

This research provides an increased understanding of the current practices and challenges during the bidding stage of PBC, and in particular at the elaboration of cost and availability estimates for CfA bids, as presented in Chapter 4. It also provides a comprehensive review of IPSS solutions, identifying PBC (e.g. CfA) as a particular type of this innovative business approach, as presented in Chapter 3. This review extends to the exploitation of TES and cost estimation, and identifies SE as the field of engineering that supports in the design and implementation of TES in CfA, typically through the development and use of model-based applications. Different modelling techniques and approaches are identified and assessed in terms of their suitability/appropriateness to be applied in the development of models to build cost and availability estimates in the context of CfA bids.

The focus is then distributed across identifying the attributes that impact the cost and availability targets in CfA, identifying and assessing the interrelationships between attributes, and developing model(s) to estimate and trade-off cost and availability at the bidding stage of CfA. The research concludes with a strong validation of the innovation, usability and accuracy of the models developed.

To summarise, the research has contributed towards formalising the challenges that are associated with cost and availability estimation at the bidding stage of CfA, which is a complex task that commonly involves subjectivity and lacks in-depth and effective analysis. Considering the research gaps presented in Chapter 3, and the challenges recognised by different project managers as presented in Chapter 4, the key contributions of this research are defined as follows:

1. **Identification of the current practices and challenges in building cost and availability estimates at the bidding stage of CfA:** Based on a wide interaction with several project managers from different organisation involved in CfA business, it raised that it is difficult to build the cost and availability estimates at the bidding stage, due to the complexity of the task driven by unpredictable factors that can impact the through-life performance of the systems. Moreover, it was recognised that there are currently no processes or methods that support project managers at building these estimates. Also, the data available for analysis is typically limited at this stage, as well as the time required to produce the estimates, which makes the task more difficult.
2. **Guidance in the selection of modelling techniques to develop models for cost and availability estimation in the context of CfA:** A systematic review of the literature was performed about the topics of interest that were defined at the beginning of the research (e.g. IPSS, CfA, and TES). Each topic was explored in detail in order to build a

comprehensive mind map of the research context and facilitate the identification of new areas for exploitation. Modelling was then identified as the scientific activity that aims to develop solutions to facilitate the understanding of the systems and predict its behaviour, and therefore it was the preferred approach to be adopted to develop a solution for the challenges identified in cost and availability estimation. Thus, different modelling techniques were identified and assessed, as presented in Section 3.4.3, in order to provide guidance in the selection of the appropriate technique according to the context of application considering: data availability, level of analysis required, and complexity of the system and solution. This guidance is provided in two tables where the strengths and limitations of each technique are identified, and in a diagram that guides about the appropriate technique to apply according to the type of decision required. This guidance is innovative as no similar studies were identified in the literature, and in particular in the context of SEM and CfA.

3. **Comprehensive list of attributes impacting the cost and availability targets in CfA:** Based on the research gap associated with understanding all the attributes that impact on cost and availability in CfA, this research presents a list with many of these attributes. Both literature review and industrial interaction facilitated the development of this list. The attributes are categorised in two levels of analysis and according to their degree of association, in order to facilitate their analysis. This list is innovative as no other similar set of attributes was identified in literature, and in particular in the context of CfA, and contributes for a better understanding of the elements that impact on cost and availability in CfA. This list can underpin future research in the field, and guide project managers during the planning of support solutions at the bidding stage.

4. **Conceptual framework to assess the interrelationships between the attributes:** To achieve the research objective associated with assessing the interrelationships between attributes a conceptual framework was developed based on the list of attributes identified. This framework also considers the link between attributes and availability, presenting a process to trade-off between the investment made in each attribute and the availability of the system. The main contribution of this framework is the process suggested to trade-off between cost and availability considering all the interrelationships between the attributes. This type of analysis was limited in practice due to lack of knowledge, and literature provided limited support in this area.
5. **Simulation model to estimate and trade-off cost and availability at the bidding stage of CfA (CATECAB):** The CATECAB model contributes to knowledge driven by the research gap that was identified in lack of processes that support project managers at building cost and availability estimates at the bidding stage of CfA and in limited data scenarios. The model builds availability estimates for a defined investment in each attribute, and cost estimates for each attribute driven by any investment change in an attribute, which facilitates the trade-off analysis between cost and availability towards the identification of improved solutions. The model also contributes to knowledge by building estimates based on an assessment of the interrelationships between attributes, which was missing in the state of art and state of practice.
6. **Enhanced multi-objective algorithm for optimisation (EMOGA):** The EMOGA is an enhanced and innovative genetic algorithm for optimisation that applies to multiple objective problems. In particular, the algorithm is tailored to search for optimal solutions based on a balanced comparison between cost, availability and contract duration targets, which is its main contribution and novelty. Actually, no similar approach was identified in literature that performs the optimisation analysis

considering variables with different currencies, creating a process to convert it in a common currency to allow a comparison between them.

7. **Simulation model to estimate the optimal allocation of a budget across the attributes, according to total contract cost, system availability, and contract duration targets (CAEOCAB):** The CAEOCAB model is perhaps the major contribution of this research. Firstly, the model presents an innovative combination of four well established techniques for modelling and optimisation consisting of: multiple regression analysis, bootstrapping re-sampling, Monte Carlo simulation and genetic algorithms. No other similar approach was identified in literature that aimed at building cost and availability estimates. Secondly, the model is innovative and unique at performing cost and availability estimates for CfA bids, and can be applied in data limited scenarios. The model is able to simulate multiple solutions in order to identify the best allocation of a budget across the attributes to achieve a target level of availability, for a certain contract duration. This approach will outperform the traditional expert opinion based methods that are currently applied to build these estimates, both in time and level of in-depth analysis.

It is believed that each of these contributions has a novel impact to both literature and industry practices, and are aligned with the identified research gaps and with the objectives defined for this research.

9.6 Research Limitations

This sections presents the limitations of the research in terms of the outputs produced. These limitations are discussed in relation to scope, context of application, quality and level of validation.

The research outputs and contributions to novelty are limited to the scope defined, which was according to what was believed to be possible to achieve within the three years of research. Also, the researcher is aware of a number of other factors that may have limited the quality and impact of the research outputs such as:

- Number of (relevant) stakeholders identified and that cooperated in the research;
- Level of engagement with the stakeholders (e.g. number of interviews, duration of each interview, etc.)
- Number of companies involved in the research;
- Extent of the literature review (e.g. number of papers reviewed);
- The techniques adopted to interact with the stakeholders (e.g. interviews, emails, etc.);
- The techniques adopted to gather information from the stakeholders (e.g. meeting summaries);
- The techniques applied to develop solutions (e.g. modelling techniques);
- The researcher’s ability to develop innovative solutions (e.g. academic background, experience, etc.).
- The approach to validate the findings and the extent of the validation.

Being aware of all of these factors, the following actions/strategies were put in place to mitigate their impact:

- Tried to identify and include a wide number of stakeholders during the research development (thirty main stakeholders participated in this research as presented in Table 2-8);
- Tried to establish an effective engagement with the project stakeholders by setting up regular semi-structured interviews of adequate duration to discuss all the relevant ideas;

- Established connection with the maximum number of organisations involved in the CfA business;
- Continuously reviewed the literature throughout the research period to explore in detail important themes/ideas and updated with new relevant articles;
- A variety of techniques were applied to interact with the stakeholders and to collect relevant information, as presented in Section 2.4. These techniques were carefully selected based on a literature review where different techniques were identified and assessed according to their appropriateness to the type of research performed and research methodology adopted;
- The solutions designed and developed (e.g. CATECAB and CAEOCAB models) used techniques that were selected based on a literature review assessment about their suitability and appropriateness to the problem of study;
- The solutions developed have a strong mathematical nature which is aligned with the background and experience of the researcher;
- The validation of the findings followed standard procedures presented in literature, and in particular case studies, that is a widely applied technique for validation in applied research.

9.7 Conclusions

This research was planned to: (1) mitigate challenges experienced by industry project managers in the elaboration of cost and availability estimates at the bidding stage of Contracting for Availability (CfA); (2) fulfil a lack of research in CfA, and in particular in processes that support cost and availability trade-off and estimation at the early stages of contracts (e.g. bidding stage). Under this motivation, a question was raised about the possibility of developing a model that could build these estimates, and that allowed trade-off between cost and availability. The model would be able to assess different allocations of the budget across a number of attributes that impact on the availability of the systems, towards identifying optimised solutions (e.g. achieving certain level of availability for the lowest cost).

Six research objectives were then elaborated to achieve the aim of this research, which focused on presenting a solution to the research question, as outlined in Chapter 1. All the research objectives were successfully achieved.

The first objective focused on identifying a list of attributes that impact the cost and availability targets in CfA. In order to achieve this objective the author conducted the following steps:

- Reviewed literature and interviewed some stakeholders to investigate about typical attributes considered;
- Developed an initial list of attributes based on an initial interaction with few stakeholders;
- Extended the literature review and the stakeholders' interaction to assess the initial list of attributes elaborated and to identify more attributes;
- Established a categorisation approach to analyse the attributes in two levels: main-attributes and sub-attributes; the list of main-attributes was considered fixed and consisted of: training, equipment, personnel, infrastructure, doctrine & concepts, organisation, information, and logistics. The list of sub-attributes was considered to be dynamic, and would be adjusted to each project;
- Extended the literature review and the interaction with the stakeholders to improve/extend and validate the list of attributes (e.g. sub-attributes) as much as possible, within a defined timeframe.

The second objective involved identifying and assessing the interrelationships between attributes. This objective was achieved according to the following sequence of steps:

- Designing and launching an on-line survey to assess the relationships between main-attributes and sub-attributes, e.g. identifying the impact of each sub-attribute in each main-attribute;
- Validating the results of the survey and defining a list of main-attributes and sub-attributes where each main-attribute is associated to a number of closely related sub-attributes;
- Improving the list of categorised attributes through industrial interaction. The list was improved as much as possible within a defined timeframe.

The third objective consisted of building a process to measure the impact of each attribute in the availability of the systems. To accomplish this objective an assessment was made on the list of attributes identified and their impact on availability. It was identified that in each contract there are a number of key performance indicators (KPIs) that make the bridge between the attributes and availability. The KPIs are the variables of a function to measure the level of availability. Thus, the attributes have a direct impact on the KPIs, and the level of each KPI will have a contribution to the availability equation. Under these conditions, a framework was built that presents a process to measure the impact of each attribute on availability in three phases, consisting of: Firstly, the effort in each sub-attribute (considering the appropriate currency, e.g. cost) directly impacts on the performance of each related main-attribute. The interrelationships between sub-attributes are also considered at this level. Secondly, the level of each main-attribute will have an impact on the performance of each KPI. The interrelationships between main-attributes are considered at this level. Thirdly, the level of availability is calculated by evaluating the availability equation with all KPIs. The values of availability and total contract cost (e.g. total cost of effort across the sub-attributes) can then be assessed, and trade-off is possible by changing the effort in the attribute(s) and calculating the impact on availability.

The fourth objective centred on developing the CATECAB model. The development of this model was based on a practical implementation of the framework developed upon completion of objective 3. For reasons of simplification, the model does not consider the KPIs, and the impact of the attributes is measured directly in terms of availability. This simplification was considered due to the difficulty is gathering data related to the performance of each KPI, which would hamper the process of validation, and also because the KPIs are out of the scope of this research. The trade-off target defined for this study considers only the cost of each attribute and availability, and therefore this simplification is believed to do not affect the quality of the results.

The development of the model progressed as follows:

- Identifying modelling technique(s) to develop the model;
- Assessing the technique(s) in terms of complexity, data requirements and possible outputs and validating with the stakeholders;
- Selecting the appropriate technique(s) to develop the model;
- Designing the modelling process in order to ensure that the estimates will reflect: a) the level of responsibility transfer to the supplier in a contract; b) the nature of the attributes that impact the cost and availability targets in a contract; c) the interrelationships between attributes;
- Selecting the software to implement the model and enable simulation;
- Building a demonstrator of the model (simple version with non-representative data) for validation and performing changings according to comments and suggestion received;
- Building the final model and validation.

The fifth objective focused on building the CAEOCAB model. This model automatically estimates the best allocation of the budget across the attributes in order to achieve total contract cost and availability targets. The development of CAEOCAB focused on enhancing the CATECAB model with the capacity of performing optimisation analysis. The fulfilment of this objective proceeded as follows:

- Selecting an optimisation technique and adapting to the context of this research. Genetic algorithms was the optimisation technique selected, and it was adapted/enhanced to be able to perform optimisation analysis in multiple objective functions (e.g. functions of cost, availability and contract duration);
- Selecting the appropriate software to implement the model;
- Implementing the optimisation feature in the CATECAB model.

The sixth and last objective focused on verifying and validating the two models developed through case studies. These case studies covered data from twenty-one CfA scenarios, in the maritime and aviation domains. Evidence from the verification and validation process suggested that the models are innovative at the level of analysis that they were designed to operate, and can be a major contribution to streamline the bidding preparation process in CfA by producing automated estimates with a good level of accuracy for the bidding stage. It was acknowledged by two project managers with extensive experience in CfA that the models can produce estimates with accuracy between 70-80%, based on the results from the case studies. This level of accuracy was considered to be good for the bidding phase, and in particular for the early stages. It has been acknowledged by the experts involved in the validation process that this level of accuracy is perhaps the maximum that can be achieved with a mathematical algorithm, as there are external, uncertain and complex factors that also impact on availability and cannot be predicted/ controlled with the mathematical model such as: reliability, motivation, affordability, etc.

9.8 Recommendations for Future Work

In this section the author suggests potential areas that can be further developed/explored in future research.

The suggestions are based on perceived limitations of this research that were due to restricted time to perform the study, and/or areas that are out of the scope of this study and can be a good complement of the results provided. Each topic suggested for future research is covered in the next sub-sections.

9.8.1 Attributes Impacting the Cost and Availability Targets in CfA

During this research it was acknowledged that different types of CfA have different relevant attributes, and different relationships between these attributes. Although the researcher already committed a considerable effort to identify these attributes and to assess the interrelationships between them, further research can be done. For example, it would be interesting to use the results presented in Chapter 5 to standardise a list of attributes to be accepted and used in the design of any type of CfA, or a reduced number of standard lists of attributes adapted to different types of CfA. In this case, the customer would plan the contract requirements based on this standard list(s) of attributes, rather than being the supplier identifying the attributes based on the customer requirements. This standardisation would also facilitate the assessment of the interrelationships between attributes. Thus, the next step for research would be performing a detailed assessment of the relationships between the attributes for each standard list, and build equations that could describe each relationship.

9.8.2 Sharing Responsibilities in Support Delivery

It has been identified that the level of control and influence over certain attributes that impact on availability is normally shared between customer and supplier(s) (see for instance Table 4-1). However, this shared control/influence mechanism brings two major issues: Firstly, if one party wants to assess the impact on availability through the effort in an attribute, it will always have an uncertainty associated to the level of effort/effectiveness that the other party will have in that attribute. Secondly, this level of control/influence is often not clearly defined during the negotiation of the contracts.

Therefore, it would be important to define at the bidding stage of each contract that each party would be fully responsible for a set of attributes, holding full control and influence over each of those attributes (e.g. training). In this way, each party can perform a better assessment of his impact on availability, and if the level of availability is not achieved during the contract, an assessment can be done to identify the attribute(s) that caused problems on availability and responsibilities can be addressed accordingly.

9.8.3 Enhancing the CATECAB and CAEOCAB Models

With respect to the models developed, there are several aspects that can be further developed such as:

- **The modelling techniques applied to build the estimates:** In the models developed in this thesis four techniques were used: regression analysis, Monte Carlo simulation, bootstrapping re-sampling and genetic algorithms; other techniques can be explored (e.g. following guidance as suggested in Chapter 3) to develop new models, and compare the performance, complexity and usability of the different models.
- **The consideration for dynamic levels of systems' performance requirements throughout the contract life-cycle**: The level of performance that is required to the systems throughout the period of the contract typically changes dynamically, and there are periods where it can be very low and others where it can be very high. It would be interesting to improve the CATECAB and CAEOCAB models to build the estimates based on dynamic performance requirements throughout the contract, rather than a fixed performance target (average performance target).
- **Extending the validation**: Although a big effort was made towards validating all the results produced, and in particular the models, the restricted time available to conduct the study (three years) limited the number of relevant people that was possible to identify and interview,

and the number of case studies. Further validation is encouraged, by identifying more case studies in different industry domains, and different subject matter experts that can contribute with their feedback and give more confidence about the level of accuracy of the estimates produced by the models.

- **Extending the scope of application**: The CATECAB and CAEOCAB models are targeted to be applied in CfA, where the main target for systems' performance in availability. It would be interesting to adapt the model to the context of other type of PBC such as contracting for capability, and assess their accuracy and suitability to this context. Furthermore, this project was focused at the early stages of the bidding process of CfA, where the accuracy of the estimates is not the major concern. However, as the bidding process evolves towards the bid submission, more accuracy is required in the estimates. Therefore, it would be interesting to develop the models in order to adjust to the accuracy requirements of the later stages of the bidding process, and also to the in-service phase (they currently produce estimates with an accuracy between 70-80%, according to the validation results). It can include, for example, the use of different and more accurate techniques for modelling and analysis.

9.8.4 Clarification of Systems Performance Requirements

Through the industry interaction, it raised that the customers' perception about the level of performance that is required for the systems during the period of the contract is typically wrong or not accurate. In particular, in the context of CfA the customer typically overestimate the level of availability that is needed. Therefore, it would be of interest to develop a model/process that helps the customer to understand the actual performance needs (e.g. availability), in order optimise the support requirements and reduce the contracts' cost.

REFERENCES

Abdallah, M. H. (1995) 'A knowledge-based simulation model for job shop scheduling', *International Journal of Operations & Production Management*. Emerald, 15(10), pp. 89–102. doi: 10.1108/01443579510098301.

Abdo, H. and Flaus, J. M. (2016) ‘Uncertainty quantification in dynamic system risk assessment: a new approach with randomness and fuzzy theory’, *International Journal of Production Research*, 54(19), pp. 5862–5885. doi: 10.1080/00207543.2016.1184348.

Abu-Shikhah, N., Elkarmi, F. and Aloquili, O. (2011) ‘Medium-Term Electric Load Forecasting Using Multivariable Linear and Non-Linear Regression’, *Smart Grid and Renewable Energy*, 2(2), pp. 126–135. doi: 10.4236/sgre.2011.22015.

Aguinis, H. and Kraiger, K. (2009) ‘Benefits of training and development for individuals and teams, organizations, and society’, *Annual Review of Psychology*, 60, pp. 451–474. doi: 10.1146/annurev.psych.60.110707.163505.

Aguinis, H. and Pierce, C. A. (2008) ‘Enhancing the relevance of organizational behavior by embracing performance management research’, *Journal of Organizational Behaviour*, 29(1), pp. 139–145. doi: 10.1002/job.493.

Akpan, B. (2017) *Science education: a global perspective*. Springer International Publishing. doi: 10.1007/978-3-319-32351-0.

Al-Zwainy, F., Abdulmajeed, M. and Aljumaily, H. (2013) ‘Using Multivariable Linear Regression Technique for Modeling Productivity Construction in Iraq’, *Open Journal of Civil Engineering*, 3(3), pp. 127–135. doi: 10.4236/ojce.2013.33015.

Alexopoulos, E. C. (2010) ‘Introduction to Multivariate Regression Analysis’, *Hippokratia*, 14(1), pp. 23–28.

Amaran, S., Zhang, T., Sahinidis, N. V., Sharda, B. and Bury, S. J. (2016) ‘Medium-term maintenance turnaround planning under uncertainty for integrated chemical sites’, *Computers & Chemical Engineering*, 84, pp. 422–433. doi: 10.1016/j.compchemeng.2015.09.007.

Anderson, C. (2010) ‘Presenting and Evaluating Qualitative Research’, *American Journal of Pharmaceutical Education*, 74(8), p. 141.

Andrew, D. P. S., Pederson, P. M. and Mcevoy, C. D. (2011) *Research methods and design in sports management*.1st edn. Human Kinetics.

Aragón-Sánchez, A., Barba-Aragáon, I. and Sanz-Valle, R. (2003) ‘Effects of training on business results’, *International Journal of Human Resource Management*, 14(6), pp. 956–980.

Arshad, M., Islam, S. M. and Khaliq, A. (2014) ‘Fuzzy logic approach in power transformers management and decision making’, *IEEE Transactions on Dielectrics and Electrical Insulation*, 21(5), pp. 2343–2354.

Arthur Jr., W., Bennett Jr., W., Edens, P. S. and Bell, S. T. (2003) ‘Effectiveness of training in organizations: A meta-analysis of design and evaluation features’, *Journal of Applied Psychology*, 88(2), pp. 234–245.

Aurich, J. C., Fuchs, C. and Wagenknecht, C. (2006) ‘Life cycle oriented design of technical Product-Service Systems’, *Journal of Cleaner Production*, 14(17), pp. 1480–1494. doi: 10.1016/j.jclepro.2006.01.019.

Australian Department of Defence (2009) ‘*Next Generation Performance-Based Support Contracts – Achieving the Outcomes that Defence Requires’*, pp. 46–49. Available at: http://www.defence.gov.au/casg/Multimedia/Next_GPBSC-9-5978.pdf (Accessed 22 June 2017).

Babariya, N. A. and Rajguru, S. (2017) ‘*Research methodology: Design, method and techniques*’, in Scholarly Communication and the Publish or Perish Pressures of Academia. USA: Global, IGI, pp. 45–73.

Badiru, A. (2005) ‘*Origins of Industrial and Systems Engineering’*, in Handbook of Industrial and Systems Engineering. CRC Press (Industrial Innovation), pp. 1–8.

Baharein, K. and Noor, M. (2008) ‘Case Study: A Strategic Research Methodology’, *American Journal of Applied Sciences*, 5(11), pp. 1602–1604. doi: 10.1177/15222302004003007.

Baines, T. and Lightfoot, H. W. (2013) ‘Servitization of the manufacturing firm: Exploring the operations practices and technologies that deliver advanced services’, *International Journal of Operations & Production Management*, 34(1), pp. 2–35. doi: 10.1108/IJOPM-02-2012-0086.

Baines, T. S., Lightfoot, H. W., Evans, S., Neely, A., Greenough, R., Peppard, J., Roy, R., Shehab, E., Braganza, A., Tiwari, A., Alcock, J. R., Angus, J. P., Basti, M., Cousens, A., Irving, P., Johnson, M., Kingston, J., Lockett, H., Martinez, V., Michele, P., Tranfield, D., Walton, I. M. and Wilson, H. (2007) ‘State-of-the-art in product-service systems’, *Proceedings of the*

Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 221(10), pp. 1543–1552.

Barbour, S. L. and Krahn, J. (2004) '*Numerical modeling-prediction or process?*', Geotechnical News. Available at: http://www.geo-slope.com/res/numerical modelling - prediction or process.pdf (Accessed: 20 June 2016).

Barjis, J. (2011) '*Healthcare Simulation and its Potential Areas and Future Trends'*, Summer Computer Simulation Conference. 1st edn. The Society for Modeling and Simulation International.

Barkdull, W. L. (1976) 'Helicopters fly equipment and casualties in high-rise tests', *Fire Engineering*, 129(1), pp. 100–101.

Barker, R. T. and Camarata, M. R. (1998) 'The role of communication in creating and maintaining a learning organization: Preconditions, indicators, and disciplines', *Journal of Business Communication*, 35(4), pp. 443–467.

Belz, C. and Wuensche, M. (2007) 'Classification of Performance Contracting Solutions: A Managerial Typology', in *Proceedings 2nd International Conference on Business Market Management*. Delft, Niederlande, 25 March 2007.

Bergman, J. J., Noble, J. S., McGarvey, R. G. and Bradley, R. L. (2017) 'A Bayesian approach to demand forecasting for new equipment programs', *Robotics and Computer-Integrated Manufacturing*, 47, pp. 17-21. doi: 10.1016/j.rcim.2016.12.010.

Berkowitz, D., Gupta, J. N., Simpson, J. T. McWilliams, J. B. (2005) 'Defining and Implementing Performance-Based Logistics in Government', *Defense Acquisition Review Journal*, 11(3), pp. 255-268.

Betterton, C. E. and Cox III, J. F. (2012) 'Production rate of synchronous transfer lines using Monte Carlo simulation', *International Journal of Production Research*, 50(24), pp. 7256–7270. doi: 10.1080/00207543.2011.645081.

Biemer, S. M. and Sage, A. P. (2009) '*Systems Engineering: Basic Concepts and Life Cycle'*, in Agent-Directed Simulation and Systems Engineering. Wiley-VCH Verlag GmbH & Co. KGaA, pp. 145–171.

Bierman, M., Marnewick, A. and Pretorius, J. H. C. (2016) 'Productivity management in the South African civil construction industry - factors affecting construction productivity', *Journal of* *the South African Institution of Civil Engineering*, 58(3), pp. 1021–2019. doi: http://dx.doi.org/10.17159/2309-8775/2016/v58n3a5.

Blessing, L. T. M. and Chakrabarti, A. (2009) DRM, a *Design Research Methodology*. 1st edn. Springer-Verlag London.

Boehm, B. W. (1988) ‘A spiral model of software development and enhancement’, *Computer*, 21(5), pp. 61–72. doi: 10.1109/2.59.

Booher, H. R. (2003) *Handbook of Human Systems Integration, Systems Engineering and Management*. Edited by A. Sage. John Wiley & Sons, Inc.

Boord, W. J. and Hoffman, J. B. (2016) ‘*Systems Engineering Fundamentals*’, in Air and Missile Defense Systems Engineering. CRC Press, pp. 3–22.

Bosse, S., Splieth, M. and Turowski, K. (2016) ‘Multi-objective optimization of IT service availability and costs’, *Reliability Engineering & System Safety*, 147, pp. 142–155. doi: 10.1016/j.ress.2015.11.004.

Bowen, G. A. (2009) ‘Document Analysis as a Qualitative Research Method’, *Qualitative Research Journal. Emerald*, 9(2), pp. 27–40. doi: 10.3316/QRJ0902027.

Braamhaar, M. P. F. E. (2016) *How does value-in-use lead to product virality?*. MSc thesis. University of Twente: Faculty of Behavioural, Management and Social Sciences

Bradley, S. P., Hax, A. C. and Magnanti, T. L. (1977) *Applied Mathematical Programming*. Addison Wesley.

Brandes, P., Dharwadkar, R. and Wheatley, K. (2004) ‘Social exchanges within organizations and work outcomes: The importance of local and global relationships’, *Group and Organization Management*, 29(3), pp. 276–301.

Bricki, N. and Green, J. (2009) ‘*A Guide to Using Qualitative Research Methodology’*, pp. 1–29. Available at: http://hdl.handle.net/10144/84230 (Accessed: 22 June 2017).

Briscoe, G., Keränen, K. and Parry, G. (2012) ‘Understanding complex service systems through different lenses: An overview’, *European Management Journal*, 30(5), pp. 418–426. doi: 10.1016/j.emj.2012.06.004.

Brown, K. G. (2001) ‘*Using computers to deliver training: Which employees learn and why?*’, Personnel Psychology, 54(2), pp. 271–296.

Brunetto, Y., Farr-Wharton, R. and Shacklock, K. (2012) ‘Communication, training, well-being, and commitment across nurse generations’, *Nursing Outlook*, 60(1), pp. 7–15.

Bulut, C. and Culha, O. (2010) ‘The effects of organizational training on organizational commitment’, *International Journal of Training and Development*, 14(4), pp. 309–322.

Burdon, S. and Bhalla, A. (2005) ‘Lessons from the Untold Success Story:: Outsourcing Engineering and Facilities Management’, *European Management Journal*, 23(5), pp. 576–582. doi: http://dx.doi.org/10.1016/j.emj.2005.09.012.

Burgess, T. (2001) *A general introduction to the design of questionnaires for survey research*. University of Leeds. Available at: http://iss.leeds.ac.uk/downloads/top2.pdf (Accessed: 22 June 2017).

Caldwell, N. and Howard, M. (2014) ‘Contracting for complex performance in markets of few buyers and sellers’, *International Journal of Operations & Production Management*. Edited by D. Mickey Howard and Dr Nigel Caldwell, 34(2), pp. 270–294. doi: 10.1108/IJOPM-10-2013-0444.

Caldwell, N. and Settle, V. (2011) ‘*Incentives and contracting for availability: procuring complex performance’*, in Complex Engineering Service Systems. London: Springer London (Decision Engineering), pp. 149–162.

Carley, K. M., Svoboda, D. M., Carley, I., Simulated, S. and Process, A. (1996) ‘Modeling Organizational Adaptation as a Simulated Annealing Process’, *Sociological Methods and Research*, 25(1), pp. 138–168.

Casas, P. F. I. (2013) *Formal Languages for Computer Simulation: Transdisciplinary Models and Applications*. 1st edn. Hershey, PA, USA: IGI Global.

Casey, A., Hughes, J., Izard, R. M. and Greeves, J. P. (2014) ‘Supplement use by UK-based British Army soldiers in training’, *British Journal of Nutrition*, 112(7), pp. 1175-1184. doi: https://doi.org/10.1017/S0007114514001597.

Caudill, M. (1987) ‘Neural networks primer’, *AI Expert*, 2(12), pp. 46–52.

Cerqueira, E. O. and Poppi, R. J. (1996) ‘Using dynamic data exchange to exchange information between Visual Basic and Matlab’, *TrAC Trends in Analytical Chemistry*, 15(10), pp. 500–503. doi: 10.1016/S0165-9936(96)00052-0.

Chang, G.-S., Perng, H.L. and Juang, J.N. (2008) ‘A review of systems engineering standards and processes’, *Journal of Biomechatronics Engineering*, 1(1), pp. 71–85.

Chang, G. W., Lu, H. J., Chang, Y. R. and Lee, Y. D. (2017) ‘An improved neural network-based approach for short-term wind speed and power forecast’, *Renewable Energy*, 105, pp. 301–311. doi: 10.1016/j.renene.2016.12.071.

Chattopadhyay, D. (2004) ‘Life-cycle maintenance management of generating units in a competitive environment’, *IEEE Transactions on Power Systems*, 19(2), pp. 1181–1189. doi: 10.1109/TPWRS.2003.821616.

Chen, J. (2014) ‘Study on the application of RFID in the visible military logistics’, in *Proceedings of the 13th International Conference on Man-Machine-Environment System Engineering*; Yantai, China, pp. 167–173.

Chirban, J. T. (1996) *Interviewing in Depth: The Interactive-Relational Approach*. London: SAGE Publications.

Chomeya, R. (2010) ‘Quality of Psychology Test Between Likert Scale 5 and 6 Points’, *Journal of Social Sciences*, 6(3), pp. 399–403. doi: 10.3844/jssp.2010.399.403.

Christensen, J. (2011) ‘Good Analytical Research’, European Accounting Review. *Routledge*, 20(1), pp. 41–51. doi: 10.1080/09638180.2011.559030.

Cogswell, J. (2003) *Developing Visual Studio .Net Macros and Add-Ins*. 1st edn. New York, NY, USA: John Wiley & Sons, Inc.

Cohen, M. A. (2012) ‘Product Performance Based Business Models: A Service Based Perspective’, in *Proceedings of the 45th Hawaii International Conference on System Sciences*, pp. 4814–4819. doi: 10.1109/HICSS.2012.672.

Correll, J. T. (2014) ‘The weinberger doctrine’, *Air Force Magazine*, 97(3), pp. 62–67.

Coticchia, F. and Moro, F. N. (2014) ‘Transforming the Italian Armed Forces, 2001-13’, *International Spectator*, 49(1), pp. 133–148.

Crawford, I. M. (1997) *Marketing research and information systems.* Italy: Food and Agriculture Organization of the United Nations. Issue 4 of Marketing and agribusiness texts.

Dahmann, J. S. and Kelley, M. (2009) *Systems Engineering During the Materiel Solution Analysis and Technology Development Phases*. USA: Department of Defense - Research & Engineering Enterprise.

Damodaran, L. (1996) ‘User Involvement in the Systems Design Process-A Practical Guide for Users’, *Behaviour & Information Technology*, 15, pp. 363–377.

Datta, P. P. and Roy, R. (2009) ‘Cost Modelling Techniques for Availability Type Service Support Contracts: a Literature Review and Empirical Study’, *CIRP Journal of Manufacturing Science and Technology*, 3(2), pp. 142-157. doi: https://doi.org/10.1016/j.cirpj.2010.07.003.

Datta, P. P. and Roy, R. (2010) ‘Cost modelling techniques for availability type service support contracts: A literature review and empirical study’, *CIRP Journal of Manufacturing Science and Technology*, 3(2), pp. 142–157.

Davis, F. D. and Yi, M. Y. (2004) ‘Improving computer skill training: Behaviour modeling, symbolic mental rehearsal, and the role of knowledge structures’, *Journal of Applied Psychology*, 89(3), pp. 509–523.

Ministry of Defence (2013) *JSP 886 Defence Logistics Support Chain Manual - Volume 1 - Part 2*. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/554227/20161002-LEGACY_JSP886-V2P06_FinAcctforInv-FINAL-0.pdf (Accessed: 22 June 2017).

Ministry of Defence (2005) ‘*Defence Industry Strategy: Defence White Paper’*. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/272203/6697.pdf (Accessed: 22 June 2017).

Defence Engineering Group, U. C. L. (2002) ‘*The Defence Systems Engineering Handbook’*. London: University College London.

Defence Equipment and Support Engineering Group (2015) *JSP 912 Human Factors Integration for Defence Systems*. London. Available at: https://goo.gl/KsyeCx (Accessed: 22 October 2016).

Defense Acquisition University Press (2001) *Systems engineering fundamentals*. Fort Belvoir, Virginia: Defence Acquisition University Press.

Degu, G. and Yigzaw, T. (2006) ‘*Research Methodology*’. Ethiopia: University of Gondar. Available at: https://www.cartercenter.org/resources/pdfs/health/ephti/library/lecture_notes/health_science_students/ln_research_method_final.pdf (Accessed: 22 June 2017).

Demeulemeester, E. (1995) ‘Minimizing Resource Availability Costs in Time-Limited Project Networks’, *Management Science*, 41(10), pp. 1590–1598. doi: 10.1287/mnsc.41.10.1590.

Denkena, B., Kršninga, S. and Doreth, K. (2012) ‘Operational Planning of Maintenance Measures by Means of Event-driven Simulation’, in *Proceedings of the 45th CIRP Conference on Manufacturing Systems*. Athens, Greece, 16-18 May 2012, pp. 61–66.

DF, Stroup, JA, Berlin and SC, Morton (2000) ‘Meta-analysis of observational studies in epidemiology: A proposal for reporting’, *JAMA*, 283(15), pp. 2008–2012. doi: 10.1001/jama.283.15.2008.

Dhar, R. L. (2015) ‘Service quality and the training of employees: The mediating role of organizational commitment’, *Tourism Management*, 46(0), pp. 419–430. doi: http://dx.doi.org/10.1016/j.tourman.2014.08.001.

Dial, R. B. (1971) ‘A probabilistic multipath traffic assignment model which obviates path enumeration’, *Transportation Research*, 5(2), pp. 83–111.

Douglas, D. D. (2003) ‘Inductive Theory Generation: A Grounded Approach to Business Inquiry’, *Electronic Journal of Business Research Methods*, 2(1), pp. 47–54.

Draugalis, J. R., Coons, S. J. and Plaza, C. M. (2008) ‘Best Practices for Survey Research Reports: A Synopsis for Authors and Reviewers’, *American Journal of Pharmaceutical Education*, 72(1), p. 11.

Dul, J. and Hak, T. (2008) *Case Study Methodology in Business Research*. New York, USA: Elsevier Ltd.

E. Kreye, M., B. Newnes, L. and Mey Goh, Y. (2013) ‘Information availability at the competitive bidding stage for service contracts’, *Journal of Manufacturing Technology Management*, 24(7), pp. 976–997.

E Shaw, S. and Bailey, J. (2009) ‘Discourse analysis: what is it and why is it relevant to family practice?’, *Family Practice*, 26(5), pp. 413–419. doi: 10.1093/fampra/cmp038.

Edwards, R. and Holland, J. (2013) *What is qualitative interviewing?*. London: Bloomsbury Publishing Plc.

Ehrhardt, K., Miller, J. S., Freeman, S. J. and Hom, P. W. (2011) ‘An examination of the relationship between training comprehensiveness and organizational commitment: Further exploration of training perceptions and employee attitudes’, *Human Resource Development Quarterly*, 22(4), pp. 459–489.

Eisenhardt, K. M. (1989) ‘Building Theories from Case Study Research’, *The Academy of Management Review*, 14(4), pp. 532–550. doi: 10.2307/258557.

Elomda, B. M., Hefny, H. A. and Hassan, H. A. (2015) ‘Fuzzy cognitive map with linguistic values’, in *Proceedings of 2nd International Conference on Engineering and Technology*. Cairo, Egypt, 22 January 2015. IEEE, pp. 1-6.

Elwakil, E., Zayed, T. and Attia, T. (2015) ‘Construction productivity model using fuzzy approach’, in the *Proceedings of the 5th International Construction Specialty Conference*. Vancouver, Canada, 7-10 June 2015. pp 1-10.

Erginel, N. and Gecer, A. (2016) ‘Fuzzy multi-objective decision model for calibration supplier selection problem’, *Computers & Industrial Engineering*, 102, pp. 166–174. doi: 10.1016/j.cie.2016.10.017.

Eriksson, M., Börstler, J. and Borg, K. (2006) ‘7.2.2 Performing Functional Analysis/Allocation and Requirements Flowdown Using Use Case Realizations – An Empirical Evaluation’, *INCOSE International Symposium*, 16(1), pp. 965–979. doi: 10.1002/j.2334-5837.2006.tb02794.x.

Erkoyuncu, J. A. (2011) *Cost Uncertainty Management and Modelling for Industrial Product-Service Systems*. PhD Thesis. Cranfield University.

Erkoyuncu, J. A., Durugbo, C., Shehab, E., Roy, R., Parker, R., Gath, A. and Howell, D. (2013) ‘Uncertainty driven service cost estimation for decision support at the bidding stage’, International *Journal of Production Research*, 51(19), pp. 5771–5788.

Erkoyuncu, J., Khan, S., Hussain, S. and Roy, R. (2016) ‘A framework to estimate the cost of No-Fault Found events’, *International Journal of Production Economics*, 173, pp. 207–222. doi: 10.1016/j.ijpe.2015.12.013.

Erkoyuncu, J., Roy, R., Shehab, E. and Kutsch, E. (2014) ‘An innovative uncertainty management framework to support contracting for product-service availability’, *Journal of Service Management*, 25(5), pp. 603–638.

Errachdi, A., Saad, I. and Benrejeb, M. (2011) ‘Neural Modeling of Multivariable Nonlinear Stochastic System. Variable Learning Rate Case’, *Intelligent Control and Automation*, 2(3), pp. 167–175. doi: 10.4236/ica.2011.23020.

Finstad, K. (2010) ‘Response Interpolation and Scale Sensitivity: Evidence Against 5-point Scales’*, Journal of Usability Studies*, 5(3), pp. 104–110.

Ford, J. K. and Schmidt, A. M. (2000) ‘Emergency response training: Strategies for enhancing real-world performance’, *Journal of Hazardous Materials*, 75(2–3), pp. 195–215.

Forsberg, K. and Mooz, H. (1992) ‘The Relationship of Systems Engineering to the Project Cycle’, *Engineering Management Journal*, 4(3), pp. 36–43. doi: 10.1080/10429247.1992.11414684.

Frezzini, F., Sachan, R. and Azimi, M. (2010) ‘*Review of Systems Engineering Scope and Processes*’, in Systems Engineering Tools and Methods. USA: Taylor and Francis Group, pp. 1–18. Engineering and Management Innovations Series.

Gámiz, M. L. and Martínez Miranda, M. D. (2010) ‘Regression analysis of the structure function for reliability evaluation of continuous-state system’, *Reliability Engineering & System Safety*, 95(2), pp. 134–142. doi: 10.1016/j.ress.2009.09.004.

Gardner, C. P. (2008) *Balancing Government Risks with Contractor Incentives in Performance-Based Logistics Contracts*. MSc thesis. Department of the Air Force, Air University, pp. 1–28.

Garofalo, G. and Parello, C. P. (2007) ‘International Technology Gap and Technology Transmission: The Policy Implications’, *Economia Politica*, 2, pp. 207–232.

Garvin, D. A. (1993) ‘Building a learning organization’, *Harvard Business Review*, 71(4), pp. 78–91.

Giacomin, J. (2014) ‘What is Human Centred Design?’, *The Design Journal*, 17(4), p. 14. doi: 10.2752/175630614X14056185480186.

Gill, J., Lee, H., Barr, T., Baxter, T., Heinzelmann, M., Rak, H. and Mysliwiec, V. (2014) ‘Lower health related quality of life in U.S. military personnel is associated with service-related disorders and inflammation’, *Psychiatry Research*, 216(1), pp. 116–122.

Glaser, B. G. (1978) *Theoretical sensitivity : advances in the methodology of grounded theory*. 1st edn. Mill Valley, California: The Sociology Press.

Grant, A. M., Christianson, M. K. and Price, R. H. (2007) ‘Happiness, health, or relationships? Managerial practices and employee well-being tradeoffs’, *Academy of Management Perspectives*, 21(3), pp. 51–63.

Greasley, A. and Barlow, S. (1998) ‘Using simulation modelling for BPR: resource allocation in a police custody process’, *International Journal of Operations & Production Management*, 18(9/10), pp. 978–988. doi: 10.1108/01443579810225568.

Green, K. T., Beckham, J. C., Youssef, N. and Elbogen, E. B. (2014) ‘Alcohol misuse and psychological resilience among U.S. Iraq and Afghanistan era veterans’, *Addictive Behaviours*, 39(2), pp. 406–413.

Grote, D. (2002) *The Performance appraisal Question and Answer Book: A Survival Guide for Managers*. 1st edn. USA: AMACOM Division of American Management Association.

Gruneberg, S., Hughes, W. and Ancell, D. (2007) ‘Risk under performance-based contracting in the UK construction sector’, *Construction Management and Economics*, 25(7), pp. 691–699. doi: 10.1080/01446190601164097.

Guajardo, J. A., Cohen, M. A., Kim, S.H. and Netessine, S. (2012) ‘Impact of Performance-Based Contracting on Product Reliability: An Empirical Analysis’, *Management Science*, 1, pp. 961–979. doi: http://dx.doi.org/10.1287/mnsc.1110.1465.

Gubata, M. E., Piccirillo, A. L., Packnett, E. R., Niebuhr, D. W., Boivin, M. R. and Cowan, D. N. (2014) ‘Risk factors for back-related disability in the US army and marine corps’, *Spine*, 39(9), pp. 745–753.

Guidat, T., Barquet, A. P., Widera, H., Rozenfeld, H. and Seliger, G. (2014) ‘Guidelines for the Definition of Innovative Industrial Product-service Systems (PSS) Business Models for Remanufacturing’, in *Proceedings of the 6th CIRP Conference on Industrial Product-Service System*. Windsor, Ontario, Canada, 1-2 May 2014. Elsevier. pp. 193–198.

Haida, T. and Muto, S. (1994) ‘Regression based peak load forecasting using a transformation technique’, *IEEE Transactions on Power Systems*, 9(4), pp. 1788–1794. doi: 10.1109/59.331433.

Hall, A. D. (1962) *A Methodology for Systems Engineering*. Princeton, N.J.: Van Nostrand.

Hallberg, L. R.M. (2006) ‘The “core category” of grounded theory: Making constant comparisons’, *International Journal of Qualitative Studies on Health and Well-being*, 1(3), pp. 141–148. doi: 10.1080/17482620600858399.

Ham-Baloyi, W. T. and Jordan, P. (2016) ‘Systematic review as a research method in post-graduate nursing education’, *Health SA Gesondheid*, 21, pp. 120–128. doi: 10.1016/j.hsag.2015.08.002.

Hardon, A., Hodgkin, C. and Fresle, D. (2004) *How to investigate the use of medicines by consumers*. Switzerland: World Health Organization and University of Amsterdam.

Harrison, A. (2006) ‘Design for service - Harmonising product design with a services strategy’, in *Proceedings of the ASME Turbo Expo*. Barcelona, Spain, 8-11 May 2006. pp. 135-143. Volume 2: Aircraft Engine; Ceramics; Coal, Biomass and Alternative Fuels; Controls, Diagnostics and Instrumentation; Environmental and Regulatory Affairs.

Heaton, J. (1998) *Secondary analysis of qualitative data*. UK: University of Surrey. Available at: http://sru.soc.surrey.ac.uk/SRU22.html (Accessed: 22 June 2017).

Heckman, J. J. and Leamer, E. E. (2007) *Handbook of Econometrics*. Elsevier B.V.

Henry, G. (1990) *‘Practical Sampling’*. SAGE Publications.

Hill, N. E., Fallowfield, J. L., Delves, S. K. and Wilson, D. R. (2014) ‘Nutrition research in the military’, *Journal of the Royal Army Medical Corps*, 160(2), pp. 99–101.

Hill, N. S., Kang, J. H. and Seo, M.-G. (2014) ‘The interactive effect of leader-member exchange and electronic communication on employee psychological empowerment and work outcomes’, *Leadership Quarterly*, 25(4), pp. 772–783.

Hippert, H. S., Pedreira, C. E. and Souza, R. C. (2001) ‘Neural networks for short-term load forecasting: a review and evaluation’, *IEEE Transactions on Power Systems*, 16(1), pp. 44–55. doi: 10.1109/59.910780.

Ho, C.F., Tai, Y.M., Tai, Y.M. and Chi, Y.P. (2005) ‘A Structural Approach to Measuring Uncertainty in Supply Chains’, *International Journal of Electronic Commerce*, 9(3), pp. 91–114. doi: 10.1080/10864415.2005.11044334.

Hockley, C. J., Smith, J. C. and Lacey, L. J. (2011) ‘*Contracting for Availability and Capability in the Defence Environment*’, in Irene Ng Peter Wild, Duncan McFarlan, Paul Tasker, G. P. (ed.) Complex Engineering Service Systems. London: Springer London, pp. 237–256.

Hodgetts, T. J. (2014) ‘A roadmap for innovation’, *Journal of the Royal Army Medical Corps*, 160(2), pp. 86–91.

Hoepfl, M. C. (1997) ‘Choosing Qualitative Research: A Primer for Technology Education Researchers’, *Journal of technology Education*, 9(1). doi: https://doi.org/10.21061/jte.v9i1.a.4.

Holmbom, M., Bergquist, B. and Vanhatalo, E. (2014) ‘Performance-based logistics-an illusive panacea or a concept for the future?’, *Journal of Manufacturing Technology Management*, 25(7). doi: 10.1108/JMTM-06-2012-0068.

Hooley, T., Wellens, J. and Marriott, J. (2012) *What is online research?: Using the internet for social science research*. 1st edn. Bloomsbury Publishing Plc.

Humpage, S. (2000) ‘An introduction to regression analysis’, *Sensors* (Peterborough, NH), 17(9), pp. 68–74.

Hypko, P., Tilebein, M. and Gleich, R. (2010) ‘Benefits and uncertainties of performance-based contracting in manufacturing industries: An agency theory perspective’, *Journal of Service Management. Emerald*, 21(4), pp. 460–489. doi: 10.1108/09564231011066114.

Hypko, P., Tilebein, M. and Gleich, R. (2010) ‘Clarifying the concept of performance-based contracting in manufacturing industries: A research synthesis’, *Journal of Service Management*, 21(5). doi: 10.1108/09564231011079075.

Working Group fopr Life Cycle Processing (2011) 1220-2005: IEEE Standard for Application and Management of the Systems Engineering Process. IEEE.

International Standards Organization (1999) *ISO 13407: Human-centred Design Processes for Interactive Systems*. Geneve: International Organization for Standardization.

Islam, M. S. and Nepal, M. (2016) ‘A Fuzzy-bayesian Model for Risk Assessment in Power Plant Projects’, in *Proceedings of the International Conference on Health and Social Care Information Systems*. Porto, Portugal, 5-7 May 2016. Elsevier B.V. pp. 963–970.

Ismail, Z., Yahaya, A. and Shabri, A. (2009) ‘Forecasting Gold Prices Using Multiple Linear Regression Method’, *American Journal of Applied Sciences*, 6(8), pp. 1509–1514. doi: 10.3844/ajassp.2009.1509.1514.

ISO 9241-2010 (2010) *Ergonomics of human-system interaction - Part 210: Human-centred design for interactive systems.* Geneve: International Organization for Standardization.

Jabareen, Y. (2009) ‘Building a Conceptual Framework: Philosophy, Definitions, and Procedure’, *International Journal of Quantitative Methods*, 8(4), pp. 49–62. doi: 10.1177/160940690900800406.

Jackson, B. J. (2004) *Construction Management JumpStart*. 2nd edn. John Wiley & Sons, Inc.

Jimenez, P. and Lopez-Rodriguez, J.M. (2012) ‘The Spanish MoD M&S infrastructure: A new perspective for the development and reusability of simulations assets’, in *Fall Simulation Interoperability Workshop 2012*. pp. 165–171.

Jin, T., Tian, Z. and Xie, M. (2015) ‘A game-theoretical approach for optimizing maintenance, spares and service capacity in performance contracting’, *International Journal of Production Economics*, 161, pp. 31–43. doi: 10.1016/j.ijpe.2014.11.010.

Jin, T. and Wang, P. (2012) ‘Planning performance based contracts considering reliability and uncertain system usage’, *Journal of the Operational Research Society. Nature Publishing Group*, 63(10), pp. 1467–1478.

Jin, T., Xiang, Y. and Cassady, R. (2013) ‘Understanding operational availability in performance-based logistics and maintenance services’, in *Proceedings of the Annual Reliability and Maintainability Symposium, 2013*. Orlando, FL, USA, 28-31 Jan 2013. IEEE. pp 1-6.

Jin, W.-L. (2007) ‘A dynamical system model of the traffic assignment problem’, *Transportation Research Part B: Methodological*, 41(1), pp. 32–48. doi: https://doi.org/10.1016/j.trb.2006.02.010.

Jitwasinkul, B., Hadikusumo, B. H. W. and Memon, A. Q. (2016) ‘A Bayesian Belief Network model of organizational factors for improving safe work behaviors in Thai construction industry’, *Safety Science*, 82, pp. 264–273. doi: 10.1016/j.ssci.2015.09.027.

Johnson, R. B. and Onwuegbuzie, A. J. (2004) ‘Mixed Methods Research: A Research Paradigm Whose Time Has Come’, *American Educational Research Association*, 33(7), pp. 14–26.

Johnstone, S., Dainty, A. and Wilkinson, A. (2009) ‘Integrating products and services through life: an aerospace experience’, *International Journal of Operations & Production Management*, 29(5), pp. 520–538. doi: 10.1108/01443570910953612.

Higgins, JPT and Green, S. (2011) *Cochrane handbook for systematics reviews of interventions*. Sussex, UK: John Wiley & Sons.

Kadam, P. and Bhalerao, S. (2010) ‘Sample size calculation’, *International Journal of Ayurveda Research*, 1(1), pp. 55–57. doi: 10.4103/0974-7788.59946.

Kanarachos, S., Griffin, J. and Fitzpatrick, M. E. (2017) ‘Efficient truss optimization using the contrast-based fruit fly optimization algorithm’, *Computers & Structures*, 182, pp. 137–148. doi: 10.1016/j.compstruc.2016.11.005.

Kang, M.-J. and Wimmer, R. (2008) ‘Product Service Systems as Advanced System Solutions for Sustainability’, in Yoo, S.-D. (ed.) *EKC2008 Proceedings of the EU-Korea Conference on Science and Technology*. Berlin, Germany: Springer Berlin Heidelberg, pp. 191–199.

Karnon, J., Stahl, J., Brennan, A., Caro, J. J., Mar, J. and Möller, J. (2012) ‘Modeling Using Discrete Event Simulation’, *Medical Decision Making*, 32(5), pp. 701–711. doi: 10.1177/0272989X12455462.

Karsten, T. (2013) ‘The Structure of a Fully Integrated Production System for Industrial Services in the Machine Tool Business reference’, in Meier H (ed.) *Product-Service Integration for Sustainable Solutions: Proceedings of the 5th CIRP International Conference on IPSS*. Heidelberg, Germany: Springer Verlag. pp. 17–26.

Keith, N. and Frese, M. (2008) ‘Effectiveness of Error Management Training: A Meta-Analysis’, *Journal of Applied Psychology*, 93(1), pp. 59–69.

Kelley, K., Clark, B., Brown, V. and Sitzia, J. (2003) ‘Good practice in the conduct and reporting of survey research’, *International Journal for Quality in Health Care*, 15(3), pp. 261–266.

Kerr, C., Phaal, R. and Probert, D. (2006) ‘A framework for strategic military capabilies in defence transformation’, in *Proceedings of the 11th International Command and Control Research and Technology Symposium: ‘Coalition Command and Control in the Networked Era’*. Arlington, VA. Alezandria, 20-22 June 2005. American Society of Naval Engineers. pp 1-10.

Khanka, S. S. (2002) *Organisational Behaviour (Text and Cases)*. 1st edn. S. chand & Company Pvt. Ltd.

Khusainova, R. M. (2015) ‘Selection of Appropriate Statistical Methods for Research Results Processing’, *Mathematics Education*, 11(1), pp. 303–315. doi: 10.12973/iser.2016.21030a.

Kim, D. B., Shin, S.-J., Shao, G. and Brodsky, A. (2015) ‘A decision-guidance framework for sustainability performance analysis of manufacturing processes’, *International Journal of Advanced Manufacturing Technology*, 78(9–12), pp. 1455–1471.

Kim, S.-H. (2016) ‘Reliability or Inventory? An Analysis of Performance-Based Contracts for Product Support Services’, in Ha, Albert Y., Tang, Christopher S. (ed.) *Handbook of Information Exchange in Supply Chain Management*. Springer International Publishing. pp. 65–88. Springer Series 5: Supply Chain Management

Klose, A. and Drexl, A. (2005) ‘Facility location models for distribution system design’, *European Journal of Operational Research*, 162(1), pp. 4–29.

Knapik, J. (1989) ‘The Army Physical Fitness Test (APFT): A review of the literature’, *Military Medicine*, 154(6), pp. 326–329.

Knapik, J. J., Burse, R. L. and Vogel, J. A. (1983) ‘Height, weight, percent body fat, and indices of adiposity for young men and women entering the U.S. army’, *Aviation Space and Environmental Medicine*, 54(3), pp. 223–231.

Knapik, J. J., Canham-Chervak, M., Hauret, K., Hoedebecke, E., Laurin, M. J. and Cuthie, J. (2001) ‘Discharges during U.S. Army basic training: Injury rates and risk factors’, *Military Medicine*, 166(7), pp. 641–647.

Knapp, M. S. (2016) ‘The Practice of Designing Qualitative Research on Educational Leadership’, *Journal of Research on Leadership Education*, 12(1), pp. 26–50. doi: 10.1177/1942775116647365.

Koksalan, M., Erkip, N. and Moskowitz, H. (1999) ‘Explaining beer demand: A residual modeling regression approach using statistical process control’, *International Journal of Production Economics*, 58(3), pp. 265–276. doi: 10.1016/S0925-5273(98)00207-2.

Konak, A., Coit, D. W. and Smith, A. E. (2006) ‘Multi-objective optimization using genetic algorithms: A tutorial’, *Reliability Engineering & System Safety*, 91(9), pp. 992–1007. doi: 10.1016/j.ress.2005.11.018.

Kopach-Konrad, R., Lawley, M., Criswell, M., Hasan, I., Chakraborty, S., Pekny, J. and Doebbeling, B. N. (2007) ‘Applying Systems Engineering Principles in Improving Health Care Delivery’, *Journal of General Internal Medicine*. New York: Springer-Verlag, pp. 431–437. doi: 10.1007/s11606-007-0292-3.

Korn, L. M., Reichert, S., Simon, T. and Halm, E. A. (2003) ‘Improving Physicians’ Knowledge of the Costs of Common Medications and Willingness to Consider Costs When Prescribing’, *Journal of General Internal Medicin*e, 18(1), pp. 31–37. doi: 10.1046/j.1525-1497.2003.20115.x.

Kosko, B. (1986) ‘Fuzzy cognitive maps’, *International Journal of Man-Machine Studies*, 24(1), pp. 65–75.

Kossiakoff, A., Sweet, W. N., Seymour, S. J. and Biemer, S. M. (2011) *Systems Engineering Principles and Practice*. 2nd edn. Wiley.

Kothari, C. R. and Garg, G. (2004) ‘Research Methodology: An Introduction’, in *Research Methodology: Methods and Techniques*. New Delhi, India: New Age International Publishers, p. 470.

Kozlowski, S. W. J., Gully, S. M., Brown, K. G., Salas, E., Smith, E. M. and Nason, E. R. (2001) ‘Effects of Training Goals and Goal Orientation Traits on Multidimensional Training Outcomes and Performance Adaptability’, *Organizational Behaviour and Human Decision Processes*, 85(1), pp. 1–31.

Krishnan, N. T. B. (1992) ‘A simulation model for maintenance planning’, in *Proceedings of the Annual Reliability and Maintainability Symposium 1992*. Las Vegas, NV, USA, 21-23 Jan 1992. pp. 109–118.

Laryea, S. and Hughes, W. (2011) ‘Risk and Price in the Bidding Process of Contractos’, *Journal of Construction Engineering and Management*, 137(4), pp. 248–258. doi: http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000293#sthash.vZB2b92w.dpuf.

Lazzarotto, B. O., Borchardt, M., Pereira, G. and Almeida, C. (2014) ‘Analysis of management practices in performance-based outsourcing contracts’, *Business Process Management Journal*, 20(2), pp. 178–194. doi: 10.1108/BPMJ-01-2013-0007.

Lee, E. A., Neuendorffer, S. and Zhou, G. (2014) *Dataflow, System Design, Modeling, and Simulation using Ptolemy II*. California: Plotemy.org

Lee, K. S., Keh, H. T. and Chung, T. S. (1999) ‘Single versus Multiple Source Purchasing Strategy’, *Academy of Management Journal*. Kuala Terengganu, 5(1), pp 27-44.

Levinson, W. A. (2006) ‘Bringing the Fishbone Diagram into the Computer Age’, *Quality Progress*, 39(12), pp. 128.

Li, K. and Wu, M. (2004) *Effective Software Test Automation: Developing an Automated Software Testing Tool*. 1st edn. Alameda, CA, USA: SYBEX Inc.

Liang, F., Bai, H. W. and Liu, G. D. (2014) ‘Application of internet of things in military equipment logistics’*, Applied Mechanics and Materials*, Vols. 556-562, pp. 6723–6726.

Lima, P. and Paulino, R. (2006) *Handbook of Recommended Practices for Questionnaire Development and Testing in the European Statistical System*. Available at: https://goo.gl/xCwFgD (Assessed 22 June 2017).

Lin, S.P., Yang, C.L., Chan, Y. and Sheu, C. (2010) ‘Refining Kano’s “quality attributes–satisfaction” model: A moderated regression approach’, *International Journal of Production Economics*, 126(2), pp. 255–263. doi: 10.1016/j.ijpe.2010.03.015.

Lindstrom, J., Plankina, D., Nilsson, K., Parida, V., Ylinenpaa, H. and Karlsson, L. (2013) ‘Functional Products: Business Models Elements’, in: Meier H. (eds.) *Product-Service Integration for Sustainable Solutions. Lecture Notes in Production Engineering*. Berlin, Germany: Springer, Heidelberg.

Loevinsohn, B. (2008) *Performance-Based Contracting for Health Services in Developing Countries : A Toolkit. Health, Nutrition, and Population Series*. Washington, DC: World Bank.

Maanen, J. Van (1979) ‘Reclaiming Qualitative Methods for Organizational Research: A Preface’, *Administrative Science Quarterly*, 24(4), pp. 520–526. doi: 10.2307/2392358.

Maguire, M. (2001) ‘Methods to support human-centred design’, *International Journal of Human-Computer Studies*, 55(4), pp. 587–634. doi: 10.1006/ijhc.2001.0503.

Maiden, N., Gizikis, A. and Robertson, S. (2004) ‘Provoking creativity: imagine what your requirements could be like’, *IEEE Software*, pp. 68–75. doi: 10.1109/MS.2004.1331305.

Marcell, M. M. and Williams, E. (2010) ‘Relevance ratings and salience categorizations for objects in a set of 80 pictures’, *Behaviour Research Methods*, 42(2), pp. 438–451. doi: 10.3758/BRM.42.2.438.

Mardle, S. and Pascoe, S. (1999) ‘An overview of genetic algorithms for the solution of optimisation problems’, *International Review of Economics Education Journal (IREE)*, 13(1), pp. 16–20.

Maria, A. (1997) ‘Introduction to modeling and simulation’, in *Proceedings of the Winter Simulation Conference. Atlanta, GA, USA, 7 December 1997. Piscataway, NJ, United States: IEEE*, pp. 7–13.

Marin-Garcia, J. A. and Bonavia, T. (2015) ‘Relationship between employee involvement and lean manufacturing and its effect on performance in a rigid continuous process industry’, *International Journal of Production Research*, 53(11), pp. 3260–3275. doi: 10.1080/00207543.2014.975852.

Marini, F. and Walczak, B. (2015) ‘Particle swarm optimization (PSO). A tutorial’, *Chemometrics and Intelligent Laboratory Systems*, 149, pp. 153–165. doi: 10.1016/j.chemolab.2015.08.020.

Martins, E. and Soares, M. (2012) ‘Automation under suspicion - Case flight AF-447 Air France’, *Work*, 41(1), pp. 222–224.

Martins, J. R. R. A. and Lambe, A. B. (2013) ‘Multidisciplinary Design Optimization: A Survey of Architectures’, *Journal of American Institute of Aeronautics and Astronautics*, 51(9), pp. 2049–2075. doi: 10.2514/1.J051895.

Martorell, S., Martón, I., Carlos, S. and Sánchez, A. I. (2015) ‘Evaluation of risk impact of equipment ageing and asset management for LWR GEN II and III NPPs in the horizon 2020’, in *Proceedings of the European Safety and Reliability Conference.* Zurich, Switzerland, 7-10 September 2015, pp. 627–634.

Masood, T., Roy, R., Harrison, A., Xu, Y., Gregson, S. and Reeve, C. (2014) ‘Integrating through-life engineering service knowledge with product design and manufacture’, *International Journal of Computer Integrated Manufacturing*, 28(1), pp. 59–74. doi: 10.1080/0951192X.2014.900858.

Maxwell, D. and D., V. D. V. (2003) ‘Developing sustainable products and services’, *Journal of Clear Production*, 11(8), pp. 883–895.

Mcauley, william J. (1987) *Applied Research in Gerontology*. New York: John Wiley & Sons.

McGaghie, W. C., Bordage, G. and Shea, J. A. (2001) ‘Problem Statement, Conceptual Framework, and Research Question’, *Academic Medicine*, 76(9), pp. 923-924.

Medini, K. and Boucher, X. (2016) ‘Configuration of Product-Service Systems value networks – Evidence from an innovative sector for sludge treatment’, *CIRP Journal of Manufacturing Science and Technology*, 12, pp. 14–24. doi: 10.1016/j.cirpj.2015.10.003.

Meier, H., Roy, R. and Seliger, G. (2010) ‘Industrial Product-Service systems-IPS2’, *CIRP Annals - Manufacturing Technology*, 59(2), pp. 607–627.

Ministry of Defence (2007) *Ministry of Defence annual report and accounts 2005-06*.Available at: https://www.gov.uk/ (Accessed: 22 June 2017).

Ministry of Defence (2014) ‘Integrated Logistic Support Part 1’, in *JSP 886 The Defence Support Chain Manual*, pp. 11–13.

Ministry of Defence (2015) *JSP 912 Human Factors Integration for Defence Systems Part 2*. Available at: https://goo.gl/KsyeCx (Accessed: 22 June 2017).

Minku, L. L., Esterle, L., Nebehay, G. and Chen, R. (2016) ‘Knowledge Representation and Modelling: Structures and Trade-Offs’, in Lewis, P.R., Platzner, M., Rinner, B., Tørresen, J., Yao, X. (Eds.) *Self-aware Computing Systems: An Engineering Approach*, pp. 79–111. doi: 10.1007/978-3-319-39675-0.

Mirjalili, S., Saremi, S., Mirjalili, S. M. and Coelho, L. dos S. (2016) ‘Multi-objective grey wolf optimizer: A novel algorithm for multi-criterion optimization’, *Expert Systems with Applications*, 47, pp. 106–119. doi: 10.1016/j.eswa.2015.10.039.

Mkandawire, B. O., Ijumba, N. M. and Saha, A. K. (2014) ‘Component Risk Trending Based on Systems Thinking Incorporating Markov and Weibull Inferences’*, IEEE Systems Journal*, 9(4), pp. 1185-1196.

Moher, D., Hopewell, S., Schulz, K. F., Montori, V., Gøtzsche, P. C., Devereaux, P. J., Elbourne, D., Egger, M. and Altman, D. G. (2010) ‘CONSORT 2010 Explanation and Elaboration: updated guidelines for reporting parallel group randomised trials’, BMJ, pp. 340. doi: https://doi.org/10.1136/bmj.c869.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G. and Group, T. P. (2009) ‘Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement’, *PLOS Medicine*, 6(7). doi: 10.1371/journal.pmed.1000097.

Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P. and Stewart, L. A. (2015) ‘Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement’, *Systematic Reviews*, 4(1), p. 1. doi: 10.1186/2046-4053-4-1.

Monfared, J. H. and Derakhshan, H. (2015) ‘The comparison qualitative and quantitative research’, *Indian Journal of Fundamental and Applied Life Sciences*, 5(2), pp. 1111–1117.

Morrow, J. E. (2008) *Integrated Logistics Support*. Washington: Department of the Army. Available at: https://goo.gl/ZPSB2v (last access 22-10-2016).

Mouzas, S. (2016) ‘Performance based contracting in long-term supply relationships’, *Industrial Marketing Management*, 59, pp. 50–62. doi: 10.1016/j.indmarman.2016.05.028.

Nassar, N. and Austin, M. (2013) ‘Model-Based Systems Engineering Design and Trade-Off Analysis with RDF Graphs’, in *Proceedings of the Conference on Systems Engineering Research*. Atlanta, Georgia, 19-22 March 2013. Georgia Institute of Technology. 16, pp. 216–225.

National Aeronautics and Space Administration (2008) *NASA/SP-2007-6105: Systems Engineering Handbook*. Washington, USA: National Aeronautics and Space Administration.

Nezzar, R. M., Farah, N., Kdadir, M. T. and Chouired, L. (2016) ‘Mid-Long Term Load Forecasting using Multi-Model Artificial Neural Networks’, *International Journal on Electrical Engineering and Informatics*, 8(2), pp. 389–401. doi: 10.15676/ijeei.2016.8.2.11.

Ng, I. C. L., Maull, R. and Yip, N. (2009) ‘Outcome-based contracts as a driver for systems thinking and service-dominant logic in service science: Evidence from the defence industry’, *European Management Journal*, 27(6), pp. 377–387. doi: http://dx.doi.org/10.1016/j.emj.2009.05.002.

Ng, I. C. L. and Nudurupati, S. S. (2010) ‘Outcome-based service contracts in the defence industry – mitigating the challenges null’, *Journal of Service Management*, 21(5), pp. 656–674. doi: 10.1108/09564231011079084.

Noah, N. (2008) ‘The STROBE Initiative STrengthening the Reporting of OBservational studies in Epidemiology (STROBE)’, *Epidemiology and Infection*, 136(7), p. 865. doi: 10.1017/S0950268808000733.

Nouri, H. and Parker, R. J. (2013) ‘Career growth opportunities and employee turnover intentions in public accounting firms’, *British Accounting Review*, 45(2), pp. 138–148.

Nowicki, D., Kumar, U. D., Steudel, H. J. and Verma, D. (2008) ‘Spares provisioning under performance-based logistics contract: profit-centric approach’, *Journal of the Operational Research Society*, 59(3), pp. 342–352. doi: 10.1057/palgrave.jors.2602327.

Nowicki, D., Randall, W. S. and Gorod, A. (2010) ‘A framework for performance based logistics: A system of systems approach’, in *Proceedings of the International Congress on Ultra Modern Telecommunications and Control Systems and Workshops*. Moscow, Russia, 18-20 October 2010. IEEE, pp. 681–692. doi: 10.1109/ICUMT.2010.5676562.

American Association of State Highway and Transportation Officials (2011): *Transportation Asset Management Guide. Washington, USA*. Available at: http://onlinepubs.trb.org/onlinepubs/nchrp/docs/AASHTO_TAMGFI-1.pdf (Accessed: 22 June 2017).

Oke, S. A. (2005) ‘An Overview of Industrial and Systems Engineering’, in *Handbook of Industrial and Systems Engineering. CRC Press (Industrial Innovation)*, pp. 8–11. doi: doi:10.1201/9781420038347.pt3.

Oliver, D. W. (1996) ‘Trade-off Analysis in Model Based Systems Engineering’, *INCOSE International Symposium*, 6(1), pp. 307–315. doi: 10.1002/j.2334-5837.1996.tb02019.x.

Olshausen, B. (2004) *Information processing models in neuroscience and psychology*. Wellman, USA. Available at: http://redwood.berkeley.edu/bruno/npb163/ (Accessed 22 June 2017).

Ortega, P. A. (no date) ‘Subjectivity, Bayesianism, and causality’, *Pattern Recognition Letters,* 64(15), pp. 63-70. doi: http://dx.doi.org/10.1016/j.patrec.2015.04.018.

Paradies, Y. and Stevens, M. (2005) ‘Conceptual diagrams in public health research’, *Journal of Epidemiology and Community Health*, 59(12), p. 1012 LP-1013. doi: http://dx.doi.org/10.1136/jech.2005.036913.

Parekh, S., Roy, R. and Baguley, P. (2014) ‘Design and manufacturing uncertainties in cost estimating within the bid process: Results from an industry survey’, in *Proceedings of the 19th CIRP Design Conference-Competitive Design*. Cranfield, UK, 30-31 March 2009. pp. 178.

Paris, R. (2014) ‘The “Responsibility to Protect” and the Structural Problems of Preventive Humanitarian Intervention’, *International Peacekeeping*, 21(5), pp. 569-603. doi: 0.1080/13533312.2014.963322.

Parry, J. L. (1985) ‘Mathematical modelling and computer simulation of heat and mass transfer in agricultural grain drying: a review’, *Journal of Agricultural Engineering Research*, 32(1), pp. 1–29. doi: http://dx.doi.org/10.1016/0021-8634(85)90116-7.

Patalano, A. (2014) ‘Japan as a Seapower: Strategy, Doctrine, and Capabilities under Three Defence Reviews, 1995-2010’, *Journal of Strategic Studies*, 37(3), pp. 403–441.

Pedhazur, E. J. (1997) *Multiple regression in behavioural research: explanation and prediction*. 2nd edn. Harcourt Brace College Publishers.

Petrovic, D., Irwin, C. and Zdanowicz, P. (2013) ‘Modelling and Analysis of Defense Lines of Developments Using Fuzzy Causal Maps with a Practical Example’, in *Proceedings of the International Symposium on Military Operational Research*. London, UK, 31-02 August 2013.

Pieth, M. and Thelesklaf, D. (2009) *Countering terrorist financing: the practitioner’s point of view*. Verlag Peter Lang.

Pires, M. C. and Frazzon, E. M. (2016) ‘On the research of linear programming solving methods for non-hierarchical spare parts supply chain planning’, *IFAC-PapersOnLine*, 49(30), pp. 198–203. doi: 10.1016/j.ifacol.2016.11.167.

Polishuk, P. and Yin, C. (2013) ‘Components for Unmanned Vehicle Systems Aircraft/Ground/Sea/Space: Systems, Subsystems, Components, Materials, and Other Infrastructure Equipment and Services’, *Fiber and Integrated Optics*, 32(5-6), pp. 288–323. doi: 10.1080/01468030.2013.845512.

Pope, R. P., Herbert, R., Kirwan, J. D. and Graham, B. J. (1999) ‘Predicting attrition in basic military training’, *Military Medicine*, 164(10), pp. 710–714.

Pryor, G. A. (2008) ‘Methodology for estimation of Operational Availability as Applied to Military Systems’, *ITEA Journal*, 29, pp. 420–428.

Punnathanam, V. and Kotecha, P. (2017) ‘Multi-objective optimization of Stirling engine systems using Front-based Yin-Yang-Pair Optimization’, *Energy Conversion and Management*, 133, pp. 332–348. doi: 10.1016/j.enconman.2016.10.035.

Rajasekar, S., Philominathan, P. and Chinnathambi, V. (2006) *Research Methodology*. Available at: https://arxiv.org/pdf/physics/0601009.pdf (Accessed: 22 June 2017).

Roy, R., Erkoyuncu, J. and Shaw, A. (2013) ‘The Future of Maintenance for Industrial Product-Service Systems’, in H. Meier (Ed.) *Product-Service Integration for Sustainable Solutions*. Springer-Verlag Berlin Heidelberg, pp. 1-15.

Ramanathan, R., Engle, R., Granger, C. W. J., Vahid-Araghi, F. and Brace, C. (2001) *Essays in Econometrics*. New York, NY, USA: Cambridge University Press, pp. 497–516.

Redding, L. (2012) ‘Challenges and Opportunities in Through-life Engineering Services - A Survey of Manufacturing Organisations’, in *Proceedings of the 10th International Conference on Manufacturing Research*. Aston, UK, 11-13 September 2012. Aston University, pp. 1–5.

Redding, L. (2015) *Through-Life Engineering Services: Definition and Scope: A Perspective from the Literature*, in Louis Redding, R. R. (ed.) Through-life Engineering Services. 1st edn. Springer, pp. 13–29.

Reddy, N. and Acharyulu, G. V. R. K. (2008) *Marketing Research*. 1st edn. Anurag Jain.

Reynolds, W. H. (1966) ‘Some Empirical Observations on a Ten-Point Poor-to-Excellent Scale’, *Journal of Marketing Research*, 3(4), pp. 388–390. doi: 10.2307/3149856.

Ritchie, J., Ormston, R., Lewis, J. and Nicholls, C. M. (2013) *Qualitative research practice: a guide for social science students and researchers*. 2nd edn. Sage Publications Ltd.

Robinson, S. (2004) *Simulation: the practice of model development and use*. West Sussex, UK: John Wiley & Sons.

Rodrigues, D., Erkoyuncu, J., Starr, A., Wilding, S., Dibble, A. and Laity, M. (2015) 'Review of the Modelling Approaches for Availability Contracts in the Military Context', in *Proceedings of the 7th CIRP Conference on Industrial Product-Service Systems*. St. Etienne, France, 21-22 May 2016. pp. 451–456.

Rodrigues, D., Erkoyuncu, J., Starr, A., Wilding, S., Dibble, A., Laity, M. and Owen, R. (2015) 'A Conceptual Framework to Assess the Impact of Training on Equipment Cost and Availability in the Military Context', in *Proceedings of the 4th CIRP International Conference on Through-life Engineering Services*. Cranfield, UK, 4-5 November 2015. pp. 112–117.

Rogerson, W. P. (2003) 'Simple menus of contracts in cost-based procurement and regulation', *American Economic Review*, 93(3), pp. 919–926.

Rouse, W. B. (2001) 'Human Centred Product Planning and Design', in Salvendy, G. (ed.) *Handbook of Industrial Engineering: Technology and Operations Management*. 3rd edn, pp. 1296–1311.

Royce, W. W. (1987) 'Managing the Development of Large Software Systems: Concepts and Techniques', in *Proceedings of the 9th International Conference on Software Engineering*. Los Alamitos, CA, USA: IEEE Computer Society Press (ICSE '87), pp. 328–338.

Russell R, Chung M, Balk EM, Atkinson S, Giovannucci EL, Ip S, Lichtenstein AH, Taylor Mayne S, Raman G, Ross AC, Trikalinos T, West KP Jr, Lau J. (2009) 'Systematic Review Methods', in *Issues and Challenges in Conducting Systematic Reviews to Support Development of Nutrient Reference Values: Workshop Summary*. Nutrition Research Series.

Saenz, O. A. (2005) *Framework for Enterprises Systems Engineering*. Florida International University.

Sambunjak, D. and Franić, M. (2012) 'Steps in the undertaking of a systematic review in orthopaedic surgery', *International Orthopaedics*, 36(3), pp. 477–484. doi: 10.1007/s00264-011-1460-y.

Saunders, M. N. K., Lewis, P. and Thomhill, A. (2012) *Research Methods for Business Students*. 6th edn. Pearson Education Limited.

Schmidt, G. and Wilhelm, W. E. (2000) ‘Strategic, tactical and operational decisions in multi-national logistics networks: A review and discussion of modelling issues’, *International Journal of Production Research*, 38(7), pp. 1501–1523. doi: 10.1080/002075400188690.

Schoenmaker, R. and de Bruijn, H. (2015) ‘Embracing complexity in performance-based contracts for road maintenance’, *International Journal of Productivity and Performance Management*, 65(1), pp. 4–24. doi: 10.1108/IJPPM-02-2014-0034.

Schutt, R. K. (2012) *Investigating the social world*. 7th edn. SAGE Publications.

Schweitzer, E. and Aurich, J. C. (2010) ‘Continuous improvement of industrial product-service systems’, *CIRP Journal of Manufacturing Science and Technology*, 3(2), pp. 158–164. doi: 10.1016/j.cirpj.2010.04.002.

Seepersad, C. C., Pedersen, K., Emblemsvåg, J., Bailey, R., Allen, J. K. and Mistree, F. (2006) ‘The Validation Square: How Does One Verify and Validate a Design Method?’, in Lewis, K. E., Chen, W., and Schmidt, L. C. (eds) *Decision Making in Engineering Design*. New York, NY: ASME.

Selviaridis, K. and Norrman, A. (2015) ‘Performance-based contracting for advanced logistics services: Challenges in its adoption, design and management’, *International Journal of Physical Distribution & Logistics Management*, 45(6), pp. 592–617. doi: 10.1108/IJPDLM-11-2014-0267.

Shafiei, E., Stefansson, H., Asgeirsson, E. I., Davidsdottir, B. and Rabaerto, M. (2013) ‘Integrated Agent-based and System Dynamics Modelling for Simulation of Sustainable Mobility’, *Transport Reviews*, 33(1), pp. 44–70. doi: 10.1080/01441647.2012.745632.

Sheard, S. A. and Lake, J. (Jerry) G. (1998) ‘2.5.1 Systems Engineering Standards and Models Compared’, *INCOSE International Symposium*, 8(1), pp. 591–598. doi: 10.1002/j.2334-5837.1998.tb00086.x.

Shinjuku, K. and Hino, S. (2013) ‘A Method for Exploring PSS Technologies Based on Customer Needs’, in Meier H. (eds) *Product-Service Integration for Sustainable Solutions. Lecture Notes in Production Engineering*. Springer, Berlin, Heidelberg, pp. 215-225.

Singh, S. K. and Yadav, S. P. (2015) ‘Modeling and optimization of multi objective non-linear programming problem in intuitionistic fuzzy environment’, *Applied Mathematical Modelling*, 39(16), pp. 4617–4629. doi: 10.1016/j.apm.2015.03.064.

Smith, D. J. (2013) ‘Power-by-the-hour: the role of technology in reshaping business strategy at Rolls-Royce’, *Technology Analysis & Strategic Management*, 25(8), pp. 987–1007. doi: 10.1080/09537325.2013.823147.

Songer, T. J. and LaPorte, R. E. (2000) ‘Disabilities due to injury in the military’, *American Journal of Preventive Medicine*, 18(3), pp. 33–40.

De Sordi, J. O., Nelson, R. E., Meireles, M. and da Silveira, M. A. (2016) ‘Development of digital products and services: Proposal of a framework to analyse versioning actions’, *European Management Journal*, 34(5), pp. 564–578. doi: 10.1016/j.emj.2016.01.009.

Squires, R. R. and Hoffman, K. L. (2014) ‘A military maintenance planning and scheduling problem’*, Optimization Letters*, 9(8), pp. 1675-1688. doi: 10.1007/s11590-014-0814-y.

Stergiou, C. and Siganos, D. (1997) *Neural Networks*. London: Imperial College. Available at: http://www.doc.ic.ac.uk/ (Accessed: 22 June 2017).

Stevens, J. (2009) 'Applied Multivariate Statistics for the Social Sciences', in Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.) *Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press. pp. 119-158.

Sultana, M., Rahman, A. and Chowdhury, S. (2012) ‘Performance Based Maintenance of Road Infrastructure by Contracting - A Challenge for Developing Countries’, *Journal of Service Science and Management*, 5, pp. 118–123. doi: http://dx.doi.org/10.4236/jssm.2012.52015.

Sultana, M., Rahman, A. and Chowdhury, S. (2013) ‘A review of performance based maintenance of road infrastructure by contracting’, *International Journal of Productivity and Performance Management*. Emerald, 62(3), pp. 276–292. doi: 10.1108/17410401311309186.

Sumo, R., Valk, W. Van der, Weele, A. Van and Bode, C. (2016) ‘Fostering incremental and radical innovation through performance-based contracting in buyer-supplier relationships’, *International Journal of Operations & Production Management*. Emerald, 36(11), pp. 1482–1503. doi: 10.1108/IJOPM-05-2015-0305.

Sumo, R., Van der Valk, W., Van Weele, A. and Duysters, G. (2016) ‘How Incomplete Contracts Foster Innovation in Inter-Organizational Relationships’, *European Management Review*, 13(3), pp. 179–192. doi: 10.1111/emre.12075.

Sun, P.C., Hsu, W.J. and Wang, K.C. (2012) ‘Enhancing the commitment to service quality through developmental and rewarding systems: CSQ consistency as a moderator’, *International Journal of Human Resource Management*, 23(7), pp. 1462–1480.

Sykes, A. O. (1988) ‘An Introduction to Regression Analysis’, in Eric A. Poster (ed.) *Chicago Lectures in Law and Economics*. New York: Foundation Press.

Szolnoki, G. and Hoffmann, D. (2013) ‘Online, face-to-face and telephone surveys—Comparing different sampling methods in wine consumer research’, *Wine Economics and Policy*, 2(2), pp. 57–66. doi: 10.1016/j.wep.2013.10.001.

Tasker, P., Shaw, A. and Kelly, S. (2014) ‘Through-life Engineering Services – Innovation and the Role of Standards’, in *Proceedings of the 3rd CIRP International Conference in Through-life Engineering Services*. Cranfield, UK, 4-5 November 2014, pp. 197–203.

Tehrani, A. S., Cao, H., Afsardoost, S., Eriksson, T., Isaksson, M. and Fager, C. (2010) ‘A Comparative Analysis of the Complexity/Accuracy Tradeoff in Power Amplifier Behavioural Models’, *IEEE Transactions on Microwave Theory and Techniques*, pp. 1510–1520. doi: 10.1109/TMTT.2010.2047920.

The National Archives (2008) *Acquisition Operating Framework. UK Ministry of Defence*. Available at: https://www.gov.uk/guidance/acquisition-operating-framework (Accessed: 22 June 2017).

Thiagarajan, R., Kwok, H.W., Calbert, G., Gossink, D., Shekh, S. and Allard, T. (2011) ‘A simulation-based risk analysis technique to determine critical assets in a logistics plan’, in *Proceedings of the 19th International Congress on Modelling and Simulation - Sustaining Our Future: Understanding and Living with Uncertainty*. Western Australia, 12-16 December 2011, pp. 503–509.

Thompson, A. W., Larsson, T. C. and Broman, G. (2011) ‘Towards Sustainability-Driven Innovation through Product-Service Systems’, in Hesselbach, J. and Herrmann, C. (eds) Functional Thinking for Value Creation: *Proceedings of the 3rd CIRP International Conference on Industrial Product Service Systems*. Berlin, Germany: Springer Berlin Heidelberg, pp. 117–122.

Toffel, M. W. (2008) 08-063: *Contracting for Servicizing - Harvard Business School Working Paper*. Available at: http://www.hbs.edu/faculty/Pages/item.aspx?num=31939 (Accessed: 22 June 2017).

Tolk, A., Adams, K. M. and Keating, C. B. (2011) ‘Towards Intelligence-Based Systems Engineering and System of Systems Engineering’, in Tolk, A. and Jain, L. C. (eds) *Intelligence-Based Systems Engineering*. Berlin, Germany: Springer Berlin Heidelberg, pp. 1–22.

Treasure, E. (2004) ‘The TREND Statement’, *Evidence-Based Dentistry*, 5(4), pp. 88–91. doi: 10.1038/sj.ebd.6400290.

Tripp, D. (2005) ‘Action research: a methodological introduction’, *Educação e Pesquisa*, 31(3), pp. 443–466. doi: http://dx.doi.org/10.1590/S1517-97022005000300009.

USA Department of Defence (2013) *Defence Acquisition Guidebook*. Available at: https://acc.dau.mil/docs/dag_pdf/dag_complete.pdf (Accessed: 10 October 2015).

Vieira, S. M., Silva, A., Sousa, J. M. C., de Brito, J. and Gaspar, P. L. (2015) ‘Modelling the service life of rendered facades using fuzzy systems’, *Automation in Construction*, 51, pp. 1–7. doi: 10.1016/j.autcon.2014.12.011.

Vohra, V. (2014) ‘Using the Multiple Case Study Design to Decipher Contextual Leadership Behaviors in Indian Organizations’, *Electronic Journal of Business Research Methods*, 12(1), pp. 54–65.

Wacker, J. G., Yang, C. and Sheu, C. (2016) ‘A transaction cost economics model for estimating performance effectiveness of relational and contractual governance: Theory and statistical results’, *International Journal of Operations & Production Management*, 36(11), pp. 1551–1575. doi: 10.1108/IJOPM-10-2013-0470.

Walker, K. (2010) ‘A Systematic Review of the Corporate Reputation Literature Definition, Measurement, and Theory’, *Corporate Reputation Review*, 12(4), pp. 357–387.

Walsh, I., Holton, J. A., Bailyn, L., Fernandez, W., Levina, N. and Glaser, B. (2015) ‘What Grounded Theory Is…A Critically Reflective Conversation Among Scholars’, *Organizational Research Methods*, 18(4), pp. 581–599. doi: 10.1177/1094428114565028.

Wang, G., Xu, T., Tang, T., Yuan, T. and Wang, H. (2017) ‘A Bayesian network model for prediction of weather-related failures in railway turnout systems’, *Expert Systems with Applications*, 69, pp. 247–256. doi: 10.1016/j.eswa.2016.10.011.

Wasson, C. S. (2005) *System Analysis, Design, and Development: Concepts, Principles, and Practices*. Wiley-Interscience. Wiley Series in Systems Engineering and Management.

Wasson, C. S. (2012) ‘System Engineering Competency: The Missing Course in Engineering Education’, in *Proceedings of the Systems Engineering Education Annual Conference & Exposition*. San Antonio, Texas, 10-13 June 2012, pp. 1–29.

West, M. (2011) *Developing High Quality Data Models*. USA: Morgan Kaufmann Publishers - Elsevier.

White, G. (2009) ‘Strategic, Tactical, & Operational Management Security Model’, *Journal of Computer Information Systems*, 49(3), pp. 71–75. doi: 10.1080/08874417.2009.11645326.

Widen, J. J. (2009) ‘Julian Corbett and the Current British Maritime Doctrine’, *Comparative Strategy*, 28(2), pp. 170–185.

Williams, M., Grajales, C. A. G. and Kurkiewicz, D. (2013) ‘Assumptions of multiple regression: Correcting two misconceptions’, *Practical Assessment, Research & Evaluation*, 18(11), pp. 1–14.

Wong, L. P. (2007) ‘Summarizing Research Findings: Systematic Review and Meta-Analysis’, *Malaysian Family Physician : the Official Journal of the Academy of Family Physicians of Malaysia*, 2(1), pp. 8–12.

Xiang, Y., Zhou, Y. and Liu, H. (2015) ‘An elitism based multi-objective artificial bee colony algorithm’, *European Journal of Operational Research*, 245(1), pp. 168–193. doi: 10.1016/j.ejor.2015.03.005.

Yang, G., Wang, Z. M., Cao, Y., Wang, H. J., Wei, J. G., Zhang, J., Li, X. Y. and Ren, Z. X. (2013) ‘Prediction of Coal Permeability Using Dimension Analysis and Multiple Regression’, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 35(16), pp. 1516–1523. doi: 10.1080/15567036.2011.629280.

Yang, X.R., Gong, Y.C. and Li, C. (2010) ‘Analysis model of bottleneck sections in military logistics network’, in *Proceedings of the International Conference on Logistics Systems and Intelligent Management*. Harbin, China, 9-10 January 2010, pp. 1957–1960.

Yin, R. K. (2009) *Case Study Research: Design and Methods, Essential guide to qualitative methods in organizational research*. Sage Publications. Applied Social Research Methods Series.

Yoe, C. (2002) *Trade-off analysis planning and procedures guidebook*. US Army Corps of Engineers, pp. 310.

Zaknich, A. (2005) *Principles of Adaptive Filters and Self-learning Systems*. Springer London.

Zbigniew, M. (1996) *Genetic Algorithms + Data Structures = Evolution Programs*. 3rd edn. Berlin, Germany: Springer-Verlag Heidelberg.

Zemella, G. and Faraguna, A. (2014) *Evolutionary Optimisation of Façade Design*. 1st edn. London: Springer-Verlag London.

Zhao, F., Tian, Z. and Zeng, Y. (2013) ‘Uncertainty quantification in gear remaining useful life prediction through an integrated prognostics method’, *IEEE Transactions on Reliability*, 62(1), pp. 146–159. doi: 10.1109/TR.2013.2241216.

Zietlow, G. (2015) *Road Asset Management and Performance Based Contracts*. Available at: http://performance-based-road-contracts.com/pres/ADB.PBC.pdf (Accessed: 22 June 2017).

Zikmund, W. G. (2010) Business Research Methods. 7th edn. Thomson.

Zou, S. (2013) ‘Based on agent of logistics information system research and design’, *Journal of Theoretical and Applied Information Technology*, 48(2), pp. 1184–1189.

APPENDICES

Appendix A Questionnaire 1: Models Verification

The following list of questions aims to verify that the model is being developed according to the objectives defined for this research, and the requirements and needs of the project stakeholders.

Date: / /

Personal Information	
Name and Surname	
Company Name	
Industry Sector	
Job Role	
Years of Experience	
Email (optional)	

Question	Response			Observations/ Suggestions
	Yes	No	Need improvements	
Is the model a true and fair reflection of the purpose it was built?				
Is the modelling process logical and clear?				
Is the modelling process trustable?				
Is the interface easy to understand?				
When you run the model is the process intuitive?				

When you run the model, is it clear what are the required inputs?				
Is there any definition of variables that are not clear in the model?				
Is the list of pre-defined values (e.g. attributes) valid?				
Are the model outputs understandable?				
Are the outputs as expected for the input data provided?				
Do you suggest any changes to the model? (Please specify)				
Would you rely on this tool to plan your next bid? If your answer is no, please specify the reasons (e.g. needs more validation, modelling process not reliable, etc.)				

Appendix B Questionnaire 2: Models Verification

Personal Information	
Company Name	
Industry Sector	
Job Role	
Years of Experience	
Email (optional)	

Q1 - How relevant are the outputs of this tool at supporting cost and availability estimates at the bidding stage of CfA? Please indicate the number according to scale 1.

R:____

Scale 1									
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Definitely not relevant	**Probably not relevant**		**Probably relevant**		**Moderate relevance**		**Highly relevant**		**Essential**

Please address any comments that you consider relevant:

Q2 - What is the level of innovation of these outputs? Please indicate the number according to scale 2.

R:____

Scale 2									
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
No innovation	**There are many tools providing the same type of outputs**		**There are some tolls providing the same type of output**		**There are no tools providing the same output but similar outputs can be easily**		**It is very hard to build this type of analysis but it is possible**		**Totally innovative**

			achieved with expert-opinion		

Please address any comments that you consider relevant:

Q3 - How useful are the outputs of this tool when compared to the outputs provided by the current methods? Please indicate the number according to scale 3.

R:____

Scale 3									
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Definitely not useful	**Probably useful**				**Moderate to high usefulness**				**Extremely useful**

Please address any comments that you consider relevant:

____

Appendix C Questionnaire 3: Models Validation

Personal Information	
Company Name	
Industry Sector	
Job Role	
Years of Experience	
Email (optional)	

Q1 - How accurate are the <u>cost breakdown</u> estimates (cost of each attribute)? Please indicate the number according to scale 4.

R:____

Scale 4									
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
≤10 % accurate	**Between]10, 40] % accurate**		**Between]40, 60] % accurate**		**Between]60, 80] % accurate**		**Between]80, 95] % accurate**		**>95% accurate**

Please address any comments that you consider relevant:

____

Q2 - How accurate is the <u>total cost</u> estimate? Please indicate the number according to scale 5.

R:____

Scale 5									
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
≤10 % accurate	**Between]10, 40] % accurate**		**Between]40, 60] % accurate**		**Between]60, 80] % accurate**		**Between]80, 95] % accurate**		**>95% accurate**

Please address any comments that you consider relevant:

Q3 - How accurate is the availability estimate? Please indicate the number according to scale 6.

R:____

Scale 6									
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
≤10 % accurate	**Between]10, 40] % accurate**		**Between]40, 60] % accurate**		**Between]60, 80] % accurate**		**Between]80, 95] % accurate**		**> 95% accurate**

Please address any comments that you consider relevant:

____

Q4 - In your opinion, how accurate is the suggested (optimal) contract duration? Please indicate the number according to scale 7.

R:____

Scale 7									
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
≤10 % accurate	**Between]10, 40] % accurate**		**Between]40, 60] % accurate**		**Between]60, 80] % accurate**		**Between]80, 95] % accurate**		**>95% accurate**

Please address any comments that you consider relevant:

____