CRANFIELD UNIVERSITY

MARK BENJAMIN JONES

A COST-BENEFIT FORECASTING FRAMEWORK FOR ASSESSMENT OF ADVANCED MANUFACTURING TECHNOLOGY DEVELOPMENT

SCHOOL OF ENGINEERING

PhD THESIS
Academic Year: 2009 - 2013

Supervisors: Prof. Phil Webb and Dr. Paul Baguley
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This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

ABSTRACT

Development of new Advanced Manufacturing Technology (AMT) for the aerospace industry is critical to enhance the manufacture and assembly of aerospace products. These novel AMTs require high development cost, specialist resource capabilities, have long development periods, high technological risks and lengthy payback durations. This forms an industry reluctance to fund the initial AMT development stages, impacting on their success within an ever increasingly competitive environment.

Selection of suitable AMTs for development is typically performed by managers who make little reference to estimating the non-recurring development effort in resources and hardware cost. In addition, the performance at the conceptual stage is predicted using expert opinion, consisting of subjective and inaccurate outputs. AMTs selected are then submerged into development research and heavily invested in, with incorrect selections having a detrimental impact on the business.

A detailed study of the UK aerospace manufacturing industry corroborated these findings and revealed a requirement for a new process map to resolve the problem of managing AMT developments at the conceptual stages. This process map defined the final research protocol, forming the requirement for a Cost-Benefit Forecasting Framework. The framework improves the decision making process to select the most suitable AMTs for development, from concept to full scale demonstration. Cost is the first element and is capable of estimating the AMT development effort in person-hours and cost of hardware using two parametric cost models. Benefit is the second element and forecasts the AMT tangible and intangible performance. The framework plots these quantified cost-benefit parameters and is capable of presenting development value advice for a diverse range of AMTs with varied applications. A detailed case study is presented evaluating a total of 23 novel aerospace AMTs verifying the capability and high accuracy of the framework within a large aerospace manufacturing organisation. Further validation is provided by quantifying the responses from 10 AMT development experts, after utilising the methodology within an industrial setting. The results show that quantifying the cost-benefit parameters provides manufacturing research and technology with the ability to select AMTs that provide the best value to a business.

Keywords: aerospace manufacturing, cost estimation, technology forecasting, technology development, technology readiness level, research and technology

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DEDICATION

In loving memory of 'Dorothy Olwyn Jones.'

The most intelligent and caring Grandma; a true inspiration who is missed dearly.

LIST OF PUBLICATIONS

Journal Papers

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LIST OF ACRONYMS

AACE - Association for the Advancement of Cost Engineering

ACostE - Association of Cost Engineers

AMT - Advanced Manufacturing Technology

AMTech - Advanced Manufacturing Technology Consortia

ANSI - American National Standards Institute

AP - Application Point

BSI - British Standards Institute

CapEx - Capital Expenditure

CER - Cost Estimating Relationship

CMR - Cost Multiplier Ratio

COCOMO - Constructive Cost Model

COTECHMO - Constructive Technology Development Cost Model

COSYSMO - Constructive Systems Engineering Cost Model

DEVAL - Development Value Advice

EMR - Effort Multiplier Ratio

EPSRC - Engineering and Physical Sciences Research Council

FMEA - Failure Mode and Effect Analysis

FP - Function Point

GAO - Government Accountability Office

IMechE – Institution of Mechanical Engineers

IP - Intellectual Property

I-RaCM - Integrated Risk and Cost Model

KPF - Key Performance Factor

LOCOMACHS - Low Cost Manufacturing and Assembly of Composite and Hybrid Structures

MCRL - Manufacturing Capability Readiness Level

MRL - Manufacturing Readiness Level

MS - Microsoft

NAFCOM - NASA Air Force Cost Model

NASA - National Aeronautics and Space Administration

NATO - North Atlantic Treaty Organisation

NPV - Net Present Value

OLS - Ordinary Least Squares

P-Beat - Process Based Economic Analysis Tool

PERFORMO - Performance Forecasting Model

PERT - Project Evaluation and Review Technique

PRED - Prediction Level

QFD - Quality Function Deployment

R & D - Research and Development

R & T - Research and Technology

SCAF - Society of Cost Analysis and Forecasting

SEER - The Systems Evaluation and Estimation of Resources

SEER-H - The Systems Evaluation and Estimation of Resources Hardware

SLOC - Software Lines of Code

SWBVA - System Wide Benefit Value Analysis

TD - Technology Development

TeVa - Technology Value Analysis

TIES - Technology Identification Evaluation and Selection

TM - Technology Management

TRL - Technology Readiness Level

UK - United Kingdom

UP-3P - Unified Portfolio, Project and Programme

US - United States

WBS - Work Breakdown Structure

CHAPTER 1

INTRODUCTION

1.1 Background

The aerospace manufacturing industry forms a vital part of global manufacturing. In the UK alone, the aerospace industry generates billions of pounds to the economy and is regarded as the largest in Europe (KPMG, 2013; Platzer, 2009). The global growth of this sector requires advancement in legislation, cost reduction, energy efficiency and reduction of the labour market (Cranfield Aerospace Manufacturing, 2013; BIS, 2010; KPMG, 2013; EPSRC, 2011; Rolls Royce, 2013).

To meet the ever increasing global demands and remain competitive, millions are invested in the development of state-of-the-art Advanced Manufacturing Technology (AMT) (Cranfield Aerospace Manufacturing, 2013; EPSRC, 2011 and 2013; Rolls Royce, 2013; Catapult High Value Manufacturing, 2013). These technologies form a fundamental platform for the aerospace manufacturer's economic success and competitive capability (Evans, 2013; Chen and Small, 1996; Ordoobadi, 2009; Ordoobadi and Mulvaney, 2001).

Development of novel AMTs within the aerospace manufacturing industry is either performed internally or within state-of-the-art research centres, institutions or universities. These require high development costs, specialist resource capabilities, long development periods, high technological risks and lengthy payback durations (BIS, 2010; Rolls Royce, 2013; EPSRC, 2011 and 2013). This is accompanied by continual AMT development cost, schedule and resource overruns (Neal, 2009). Additionally, from a lack of performance forecasting assessment techniques, AMT developments continually fail to meet the required manufacturing performance enhancements (Evans, 2013). This explains the reluctance of industry to fund the initial AMT development stages, impacting on their success within an ever increasing competitive environment (BIS, 2010; EPSRC, 2013; KPMG, 2013). Selection of suitable AMTs for development is regarded as a high risk operation and industrial managers typically make selections based on their experience alone, generating inconsistent, inaccurate and subjective outputs (Evans, 2013; Evans et al., 2012; Evans et al., 2013).

Existing subjectivity in the selection of aerospace AMTs at the conceptual development stages has formed a requirement to develop a novel Cost-Benefit Forecasting Framework. The framework needs to improve the decision making process to select the most suitable AMTs for development from concept to full scale demonstration. Cost is the first element and must be capable of forecasting the AMT development effort in person-hours and the cost of hardware. Benefit is the second element and needs to forecast the AMT tangible and intangible performance. The framework must plot the quantified cost-benefit parameters to present development value advice for a diverse range of AMTs with varied applications. Quantifying the cost-benefit provides manufacturing Research and Technology (R&T) with the ability to select AMTs that provide the best value for a business. This is essential when research budgets are regularly scrutinised and value for money is determined crucial (Kirby, 2001; Evans, 2013). A detailed case study evaluating a total of 23 novel aerospace AMTs, verifies the capability and high accuracy of the framework within a large aerospace manufacturing organisation. Further validation is provided by quantifying the responses from 10 AMT development experts, after utilising the methodology within an industrial setting.

The following Section of this Chapter provides further detail of how industry aligns and allocates the required AMT development investment, within the manufacturing Technology Management (TM) lifecycle stages, defining and clarifying the research motivation.

1.2 Research Motivation

The management of aerospace AMT development is a complex and highly subjective task. AMTs are developed within the aerospace manufacturing industry using TM techniques, with a typical overview represented in Table 1-1 (Gregory, 1995; Probert et al., 2000; Foden and Berends, 2010).

1. Identification:	**2. Selection and Approval:**	**3. Development Research:**	**4. Acquisition:**	**5. Exploitation:**
- Technology Networking - Technology Watch - Benchmarking - Make the Future	- R&T Investment Decision - Technology Strategy - Technology Roadmapping	- Technology Investment - Technology Readiness Levels - Technology Proving and Validation	- Adoption to Shop Floor - Production Ready State	- Deployed and Implemented onto Shop Floor

Table 1-1 Manufacturing Technology Management Lifecycle Stages (Adapted from Gregory, 1995; Probert et al., 2000; Foden and Berends, 2010)

In Stage 1 of the TM lifecycle the AMT is initially identified using techniques such as: technology networking, technology watch and benchmarking. Stage 2 evaluates potential technologies and where suitable, aligns with technology roadmaps and strategies. At this stage, AMTs are selected for development based on the industrial managers' prediction of the future, consisting of profoundly complex and subjective information. This creates inconsistent and inaccurate AMT selection outputs, with the AMTs submersed into the Technology Readiness Level (TRL) development platform. The TRL is a development maturity metric consisting of 9 levels of classification, ranging from ‘Basic Principles Observed and Reported’ (TRL1) to ‘Actual System through successful Mission Operations’ (TRL9) (Fernandez, 2010; Mankins, 2009). To develop an AMT using the TRL, there are high levels of investment required in technical expert capability (resources) and hardware costs. Currently there is a lack of capable models and techniques for estimating the AMT development resources in person-hours and hardware cost, prior to the AMT entering Stage 3 of the TM lifecycle, presented in Figure 1-1. Cost research so far has focused on costing the manufacturing process, not the development effort and cost (Shehab and Abdalla, 2001; Curran and Price, 2004; Ordoobadi, 2009; Ordoobadi and Mulvaney, 2001). Subsequently, estimation of development resources and hardware cost to develop a novel AMT is formed using the expert opinion of management, consisting of remarkably low accuracies with minimal repeatability. Furthermore, management do not currently allocate resources and hardware costs to the TRL incremental development stages, losing the potential to increase existing accuracy. This highly subjective approach leads to development cost, resource and schedule overruns, creating substantial losses to the organisation (BIS, 2010; Neal, 2009). Consequently, with budgets typically allocated on an annual basis, the poor accuracies can demand further investment mid-way through the development. This can stop AMT development, with potential benefits to the business missed, creating large investment losses.

To acknowledge the lack of AMT development resources and cost estimation models, the cost estimation domain was explored within the literature. This analysis clarified availability of cost estimation techniques and state-of-the-art models for varied applications (Boehm, 2005; Valerdi, 2005; Trivailo et al., 2012; PRICE Systems, 2011; SEER, 2011; Schankman, and Reynolds, 2010; DePasquale, and Charania, 2008). However, each had never been applied for estimation of AMT development resources and hardware cost, at the early stages of development, forming the requirement for the development of two cost models. The first must be capable of estimating the AMT development resources in person-hours and the second, AMT hardware cost.

In addition, prior to AMTs entering Stage 3 of the TM lifecycle represented in Figure 1-1, there is a lack of technique and models to forecast the AMT performance at the initial stages of development. At this stage, the prediction of performance is challenging and sometimes impossible to forecast, from a lack of knowledge and data to form a development trend (Kirby, 2001; Kirby and Mavris, 2002; Evans, 2013; Evans, 2012). From these challenging factors, performance is predicted at the early stages of development using expert opinion, creating subjective and inconsistent outputs. These inaccuracies can suggest development of incorrect AMTs, with an organisation investing in the high R&T development resources and hardware costs. This leads to significant investment losses, with AMTs not successfully developed and implemented within their target manufacturing application. From the lack of AMT performance forecasting toolsets and models available for evaluation at the preliminary development stages, the technology forecasting domain was explored within the literature. Detailed evaluation of existing technology forecasting techniques revealed the lack of available models capable of forecasting AMT performance at the conceptual stages. At this stage, there are high levels of uncertainty with diverse and incomparable AMTs with varied applications (Evan, 2013; Catapult High Value Manufacturing, 2013; Evans, 2013; Rolls Royce, 2009; EPSRC Centres for Innovative Manufacturing, 2013). In response, there is a need for two AMT performance forecasting models. These models should be capable of capturing both tangible and intangible performance, for evaluation of diverse AMTs with varied applications.

To summarise, there is a specific need to develop two cost models capable of estimating AMT development resources in person-hours and hardware cost. In addition, there is a requirement to develop two AMT performance forecasting models, to quantify both tangible and intangible AMT performance, at the initial development stages. Quantifying each of these parameters will enhance the existing R&T investment decision formed within Stage 2 of the TM lifecycle, presented in Figure 1-1.

Plotting the AMT development resources and hardware cost with each performance forecast output would further enhance the R&T investment decision, by presenting the organisation with development value advice. Existing literature has identified there is currently no toolset, technique or model, capable of providing such an output for comparison of a diverse range of AMTs, at the early development stages. Therefore, to enhance existing management of AMT development and justify the required R&T investment, there is a need to systematically control the novel AMT development resources, cost and performance forecasting models. This forms the requirement for a novel Cost-Benefit Forecasting Framework. To meet the requirements within the existing TM lifecycle, the framework must be capable of operating within an aerospace industrial R&T function and utilised by AMT development experts, research and project managers. This will enhance the R&T

investment decision, prior to entering development research within Stage 3 of the TM lifecycle, illustrated in Figure 1-1.

1.3 Research Domain and Collaboration

Figure 1-1 presented an overview of a typical TM lifecycle used within the aerospace manufacturing industry. The existing body of literature has identified a lack of understating how industry and state-of-the-art AMT research centres estimate AMT development resources in person-hours and hardware cost. Moreover, there is a specific lack of knowledge of how they engage with the TRL for each estimate.

Furthermore, there is a lack of knowledge in existing literature of how the aerospace manufacturing industry forecasts and justifies performance at the conceptual stages. To address, a detailed understanding of how AMT performance is currently estimated within the aerospace manufacturing industry is required. To recognise these detailed industrial practices, this research is supported by a large aerospace manufacturing organisation within the UK. This direct collaboration has allowed for access into the company, allowing full assessment of their existing practices and techniques. The organisation develops novel AMTs internally and in collaboration with external state-of-the-art manufacturing research institutions and universities. Technologies readily available from fully external AMT vendors will not be assessed within the scope of the framework.

To remain at the panicle of state-of-the-art and resolve the problem in the most effective manor, the cost estimation and performance forecasting models have been developed using knowledge and collaborations from international universities, institutions and companies. This ensures the research is not biased towards the large aerospace manufacturing organisation supporting the research, with the problem resolved using the most suitable approach. For the final solution to be proven effective, it must be demonstrated within an R&T function of the large aerospace manufacturing organisation supporting this research.

The first framework requirement is for two AMT development cost models. These must be verified using statistical techniques and meet the specification detailed from the collaborating aerospace manufacturing organisation.

The development of two AMT performance forecasting models is the second framework requirement. Following the cost model verification, each must be verified using actual data from industry.

To validate the overall Cost-Benefit Forecasting Framework within its industrial setting, including the operation and final outputs, the framework must be validated within the aerospace organisation using expert feedback in a structured format. Included within this analysis is the desired development value advice output, providing data to advance the AMT development selection process. This presents the R&T function with development value to progress into Stage 3 of the TM lifecycle, presented in Figure 1-1.

1.4 Research Aim

The detailed discussion presented within this Chapter has defined the need for development and implementation of a Cost-Benefit Forecasting Framework. Therefore, the research aim is:

"*To develop, implement, verify and validate a cost-benefit forecasting framework capable of quantifying the AMT development effort, cost and perceived performance at the conceptual stages; providing development value advice.*"

1.5 Thesis Structure and Summary

This Section categorises the thesis structure, outlined in Figure 1-2, providing a breakdown of the activities followed to achieve the research aim. The following is an overview of the Thesis Chapters:

Chapter 2

This Chapter presents a review of the relevant literature evaluated as part of this research. It includes the management of aerospace AMT development, the theory of cost estimation and technology forecasting. The objective is to provide an enhanced understanding of each domain and identify any knowledge gaps in existing research.

Chapter 3

The focus of this Chapter is to form the key objectives of the research, explain the research methodology development and describe the final research methodology adopted to address the objectives.

Chapter 4

This Chapter presents a detailed study into existing techniques used within the aerospace manufacturing industry. Each study was performed within large aerospace manufacturing organisations and state-of-the-art research centres, using a series of interviews and a review of internal documentation. The study uses detailed industry analysis to design a new management of aerospace AMT development process map using the identified requirements. This formed the final research protocol that was validated by industry.

Chapter 5

Chapter 5 presents the development of two parametric 'Constructive Technology Development Cost Models' (COTECHMO). The 'COTECHMO Resources' is the first model and is capable of forecasting aerospace AMT development effort in person-hours. The second, the 'COTECHMO Direct Cost' model, is capable of forecasting the AMT development hardware cost. Each model is capable of forecasting the R&T non-recurring development effort.

Chapter 6

Chapter 6 presents the development of two 'Performance Forecasting Models' (PERFORMO). The first is the 'PERFORMO Tangible' model and is capable of forecasting the performance enhancement or degradation, from a tangible perspective. The second is the 'PERFORMO Intangible' model and is capable of forecasting AMT performance enhancement, or degradation, using intangible metrics.

Chapter 7

Chapter 7 presents a novel 'Cost-Benefit Forecasting Framework,' capable of systematically operating the developed cost and performance models within an industrial setting, discussed in Chapter 5 and 6. The framework plots outputs from each model within a Development Value Advice (DEVAL) toolset.

Chapter 8

Chapter 8 performs a detailed industrial verification and validation of each COTECHMO cost model presented in Chapter 5, PERFORMO detailed in Chapter 6 and the Cost-Benefit Framework described in Chapter 7.

This involves a case study using the framework for evaluation of 15 AMTs within the collaborating aerospace manufacturing organisation. Data from this case study was used for the verification of each COTECHMO model. PERFORMO was verified using data from a further 8 AMTs with known conclusions, from inside the collaborating organisation. Both COTECHMO and PERFORMO models were validated, using the detailed responses from 10 AMT development experts. Finally, the Cost-Benefit Forecasting Framework was validated for the operational effectiveness within its industrial setting, including the final development value advice outputs for the 15 AMTs used within the empirical study. This was also validated using the responses from 10 AMT development experts.

Chapter 9

The final Chapter of this thesis provides the overall research discussion and conclusions. This includes evaluation of the research findings, key research contributions, limitations and recommendations for future research.

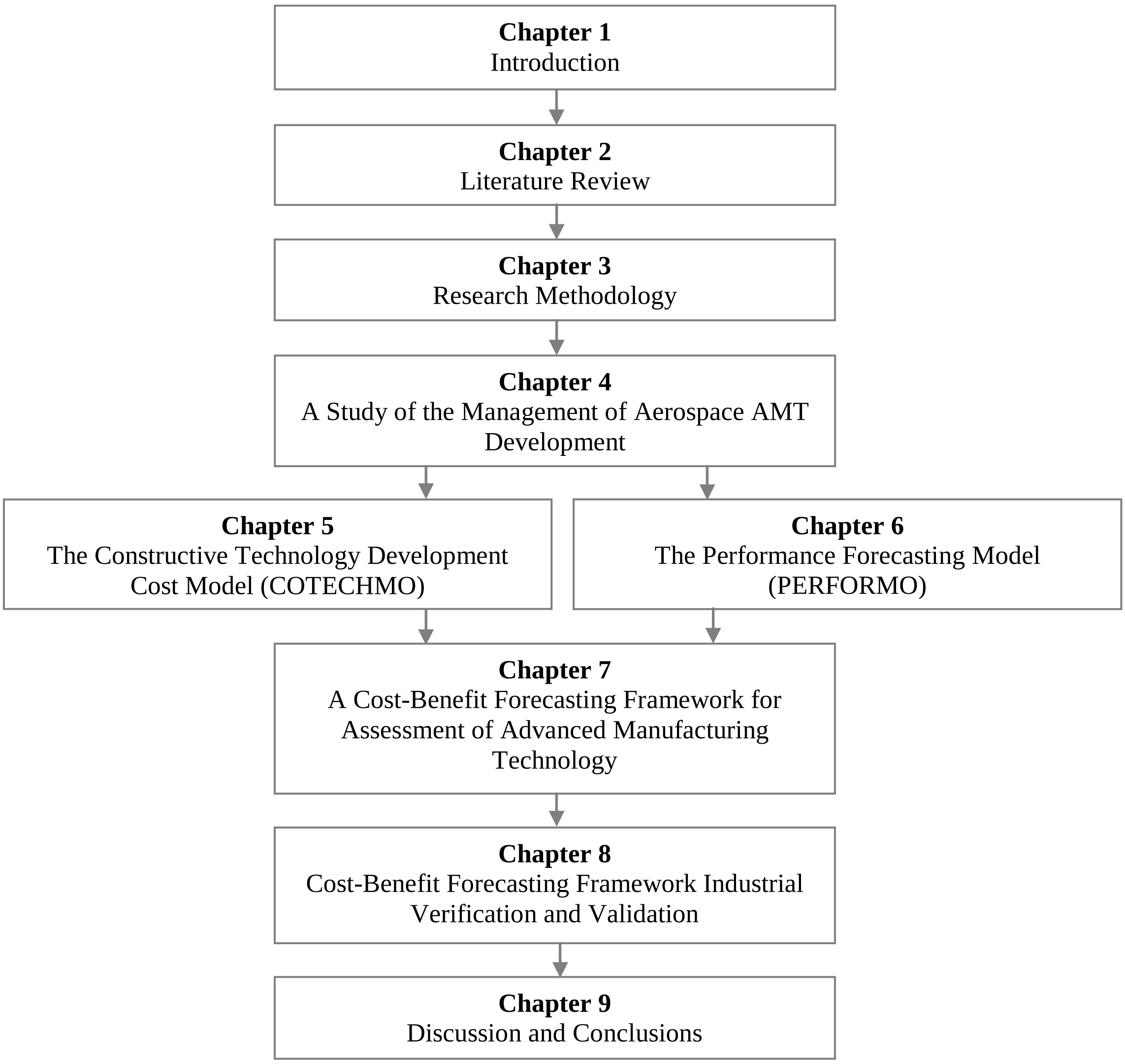

Figure 1-1 Thesis Structure

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This Chapter presents a review of the relevant literature evaluated as part of this research. The primary objective is to provide an enhanced understanding of how aerospace Advanced Manufacturing Technology (AMT) developments are managed at the early stages of the technology lifecycle. At these early stages, AMT developments require high investment in cost of hardware and specialist resource capabilities. This involves a decision whether to invest in a new AMT, when benefits are hard to justify and the cost of development is vague and imprecise.

To refine the review and understand how the AMT development resources and hardware costs are estimated, the cost estimation domain is explored. Advancing existing understanding of how AMT benefits and performances are justified and forecast at the conceptual stages is also regarded as crucial. In response, the technology forecasting domain is explored. A state-of-the-art review of standards and methodologies for the management of AMT development, cost estimation and technology forecasting is also provided. To conclude, gaps in the existing body of knowledge are defined and detailed.

2.2 Management of Advanced Manufacturing Technology Development

Development of new AMTs for the aerospace industry is critical to enhance the manufacture and assembly of aerospace products. Industrialised companies are constantly striving to improve their competitive capability and lower production costs by investing in new or proven AMTs (Ordoobadi, 2009). Small (2006) best defines an AMT:

> "...AMT represents a wide variety of modern technologies devoted to improving operational efficiency and, as a consequence, the competitiveness of manufacturing firms."

AMTs are developed within the aerospace manufacturing industry using Technology Management (TM) techniques, a discussion point for the proceeding Sub Section.

2.2.1 Technology Management

TM is the management of new or potential technologies through the technology lifecycle. Foden and Berends (2010) built on earlier technology management work of Gregory (1995) and Farrukh et al. (2004) to produce and integrate a TM framework and align it to the manufacturing domain. This proposed framework consisted of six stages, with alignment to the technology lifecycle and included:

i) Identification and monitoring. A technology is in the form of a concept or idea that could have potential to enhance the organisation operations.

ii) Selection and approval. Selection of technologies predicted to meet the business requirements with potential to deliver successful investment opportunities. These technologies are typically presented to Research and Technology (R&T) for funding approval. If this funding is accepted, the proceeding development research stage is activated and technologies are matured to identify capability.

iii) Development research. This stage involves the development of technologies within an R&T context for their target production application. Technologies that are successfully developed and proven for their target production application are then advanced to the proceeding stage.

iv) Acquisition and adaptation. On attainment of technology maturity for the target application, technologies are ready for implementation into production in a ready state.

v) Exploitation and review. Within this stage, mature technologies are fully deployed onto the shop floor.

vi) Protection. The technology must be continually protected throughout the technology lifecycle. This protects against distribution of Intellectual Property (IP) beyond the organisation. The technology risks, knowledge and re-use are also managed within this stage.

Each of the stages is illustrated in Figure 2-1 and builds on other TM available literature (Gregory, 1995; Farukh et al., 2004; Probert et al., 2000). Foden and Berends (2010) also summarised the typical TM tools used within the stages, each listed in Table 2-1. When evaluating this overall TM lifecycle framework, AMT development feeds into Stage iii, development research, a discussion point for the proceeding Sub Section.

Table 2-1 Typical Technology Management Tools used within the Framework Stages (Adopted from Foden and Berends, 2010)

Framework Stage	Tool	Description
Identification and Monitoring	Technology Networking	Exploratory tool for increasing external environment awareness through participant networking.
	Technology Watch	Identification of organisation's critical established, competing and disruptive technologies.
	Make-the-Future	Inward-facing technology opportunity identification aligned with product development programmes.
	Technology Maturity Assessment	The assessment of the position of a technology's maturity along its S-curve/life cycle.
	Technology Benchmarking	Internal benchmarking of technology alternatives with the organisation and benchmarking against competitors.
Selection and Approval	Make-the-Future Selection	Inward-facing technology opportunity down-selection aligned to new product drivers.
	Technology Roadmapping	Convergence of inward and outward technology opportunities aligned to market and product drivers to enable selection of R&D programmes.
	R&T Funding Approval	Technology investment decision making for technology opportunities presented by Technology Roadmapping.
Capability Development: Development Research. Acquisition & Adaptation, and Exploitation & Review stages	Technology Make-Buy	Make or buy decision-making for development of down selected technology programme capabilities.
	Capability Acquisition	Definition, launch and management of technology programmes aimed at developing technology maturity through R&D.
	Technology Readiness Scale	A gated process against which current technology maturity can be gauged and managed.
Protection	Technology Risk Management	Management of risks arising from R&D technology programmes.
	Knowledge Base Protection	Capture of valuable knowledge such that it can be re-used.
	Intellectual Property (IP) Protection	Protection against unauthorised transfer of IP outside of the organisation.

2.2.2 Technology Development

The previous Sub Section described the general TM process within aerospace manufacturing. When referring to the overall TM framework illustrated in Figure 2-1, Technology Development (TD) feeds directly into Stage iii, development research. Cooper (2006) describes the term TD as:

"...A special class of development projects where the deliverable is new knowledge, new technology, a technology capability, or a technological platform."

Cooper (2006) defines that TD projects are vital for a company's future growth, prosperity and long term survival. Additionally, this author discusses how these projects are typically ill managed, equating to minimal benefits for the organisation. This author also identifies how TD projects can lead to nothing after investing heavily, or in contrary, development is cancelled prematurely, losing millions in potential profits.

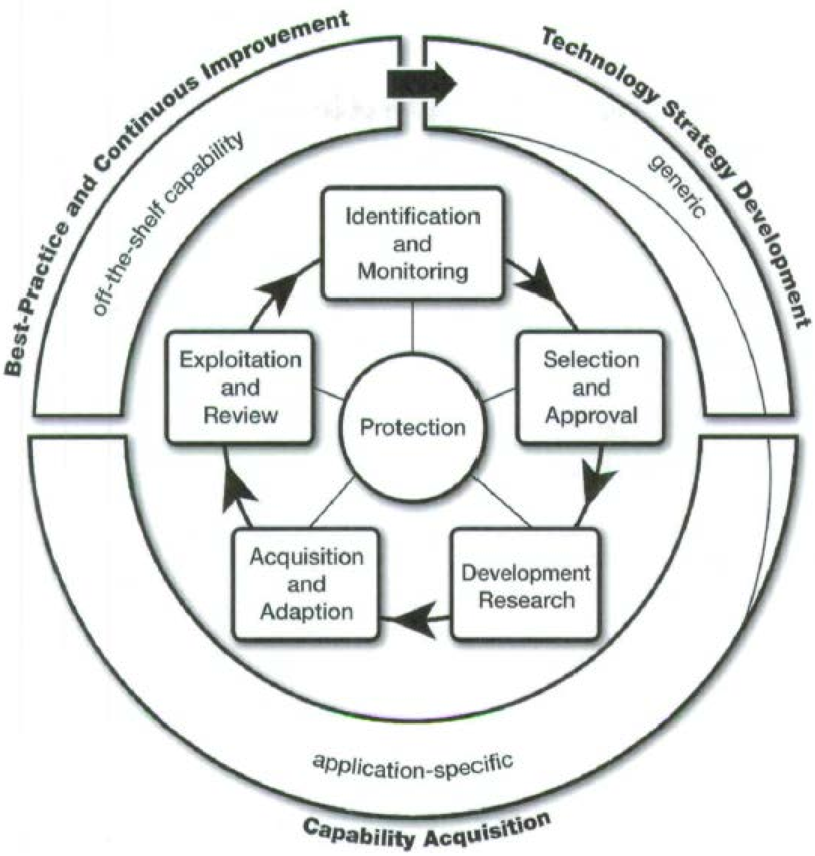

Figure 2-1 Integrated Technology Management Framework Developed for an Aerospace Manufacturing Company (Adopted from Foden and Berends, 2010)

When referring to AMT developments, a specialist refinement of TD, these are typically high risk projects with significant levels of uncertainty. At the initial development stages, prediction of AMT success can be low (Evans, 2013). The solution can appear years of development effort away, generating low confidence in a final solution (Evans, 2013; Chen and Small, 1996). To allow an AMT development to progress from Stage ii (selection and approval) to Stage iii (development research), AMTs require a decision of R&T investment, illustrated in Figure 2-1 and detailed in Table 2-1. At this stage, the development effort and cost to mature an AMT through the maturity platforms should be a primary focus. Additionally, the perceived impact of the AMT should be forecast and quantified at this stage. At this initial development stage, each is not available within the existing body of literature. To provide an evaluation of how AMTs are matured within the available literature, readiness level techniques are discussed in the following Sub Section.

2.2.3 Readiness Level Techniques

TD was discussed previously and requires a structured management platform to evaluate technology maturity. To assist, aerospace manufacturing organisations use Technology Readiness techniques (Chan et al., 2000; Evans, 2013; Rolls Royce, 2009; Ward et al., 2012). The term ‘Technology Readiness’ was originally defined within the National Aeronautics and Space Administration (NASA) in the 1960s. In the 1970s the term developed to ‘Technology Readiness Levels’ (TRL). This maturity platform was initially created to assess the readiness and risk of space technology (Fernandez, 2010). TRLs are best defined by Mankins (1995) as:

> “...TRLs are a systematic metric/measurement system that supports assessment of the maturity of a particular technology and the consistent comparison of maturity between different types of technology.”

The original TRL scale consisted of 9 levels of classification, ranging from ‘Basic Principles Observed and Reported’ (TRL1) to ‘Actual System through successful Mission Operations’ (TRL9). Each TRL definition and descriptions is listed in Table 2-2. Mankins (2009) summarised that the TRL has been very successful in communication of the maturity of new technologies, sometimes in collaboration with a diverse range of organisations and institutions.

This TRL scale has now been developed and adapted to suit the aerospace manufacturing industry and is used to harmonise all AMTs under development (Chan et al., 2000; Evans, 2013; Rolls Royce, 2009; Ward et al., 2012). Many aerospace manufacturing companies and organisations have tailored the TRL to directly suit AMT development, including Manufacturing Capability Readiness Levels (MCRLs) (Ward et al., 2012) and Manufacturing Readiness Levels (MRLs) (Wiggs, 2010; Department of Defence, 2011; Morgan, 2008). Ward et al. (2012) discusses the adaption of the TRL into a Manufacturing Capability Readiness Level (MCRL) scale.

This 9 point scale was derived directly from the original TRL listed in Table 2-2. The MCRL does have a 10th level and is for the purpose of continuous improvement. Table 2-3 lists the MCRL definitions and description.

Table 2-2 Technology Readiness Level Definitions (Adopted from Mankins, 2009)

TRL	Definition	Description
1	Basic principles observed and reported.	Basic scientific research has evolved into an observation and reporting of basic principles suited to transfer into applied research and development.
2	Technology concept and/or application formulated.	Practical applications are applied of invented for the basic principles defined previously.
3	Analytical and experimental critical function and/or characteristic proof-of-concept.	Activation of research and development within the appropriate environment to physically validate the proof of concept for the application.
4	Component and/or breadboard validation in a laboratory environment.	Basic technological parameters of the development must be integrated to evaluate whether they function and attain the concept performance requirements at the level of component and/or breadboard.
5	Component and/or breadboard validation in relevant environment.	Basic technological elements must be integrated with other supporting developments and tested in a realistic environment.
6	System/sub-system model or prototype demonstration in a relevant environment.	A full scale prototype system or system must be tested in a relevant environment, typically space. This demonstration will typically have many technologies integrated.
7	System prototype demonstration in the expected operational environment.	An actual system prototype is required and demonstrated in the aligned operational environment. The prototype should be near or at full scale.
8	Actual system completed and 'qualified' through test and demonstration.	This is the end of the development for most technologies applied to the system. This can also involve addition of a new technology to an already developed system.
9	Actual system 'flight proven' through successful mission operations.	All technologies being developed and applied to the system progress through TRL9. However, the refinement and bug fixing of the system are not defined until the final launch of the system. This forms the definition of TRL9.

Further to the development of the MCRL, the Department of Defence (2011) describes the adaption of the TRL into a MRL. Following the MCRL, this maturity platform follows the TRL with a 9 point scale, although it has a 10th level that is used for lean manufacture. Table 2-4 lists each MRL definition and description.

The discussed TRL, MCRL and MRL are development maturity platforms and structure the 'development research,' Stage iii, presented earlier in Figure 2-1. The literature defines that the TRL, MCRL and MRL all cross reference to a coherent scale (Ward et al., 2012; Fernandez, 2010; Wiggs, 2010; Department of Defence, 2011; Morgan, 2008). In summary, Readiness Levels for the development of AMTs are well documented within the literature. The proceeding Sub Section evaluates the available literature in estimating the development cost and effort, when maturing through Readiness Levels.

Table 2-3 Manufacturing Capability Readiness Level Definitions (Adopted from Ward et al., 2012)

MCRL	Definition	Description
1	Process concept proposed with scientific foundation.	The invention has been proposed but test work is not required.
2	Applicability and validity of concept described and vetted, or demonstrated.	Potential target applications are defined along with the basic requirements of each using an internal customer or process specification.
3	Experimental proof of concept completed.	Demonstrate the process is suitable by applying to a something similar to the defined application.
4	Process validated in laboratory using representative development equipment.	Understanding of the process fundamental capabilities is required and a detailed progression plan to MCRL9.
5	Basic capability demonstration using production equipment.	This requires the demonstration of the process using standardised production equipment.
6	Process optimised for capability and rate using production equipment.	Trials must verify the process and allow for no operational change. Operations staff and final production must operate the process within the trails.
7	Capability and rate confirmed via economic run lengths on production parts.	Process must be demonstrated at the early stages of production with no major process change.
8	Fully production capable process qualified on all parts over significant run lengths.	Process must be demonstrated with statistically significant volume production with no major process changes.
9	Fully production capable process qualified on all parts over extended period (all business case metrics achieved).	Process should be demonstrated with volume production over an extended period with no major process changes.

2.2.4 AMT Development Cost Estimation

Existing literature, aligning with development cost estimation, feeds into Stage iii 'development research' of the TM framework presented in Figure 2-1. Current manufacturing cost research has focused on the costing of the manufacturing process (Shehab and Abdalla, 2001; Curran and Price, 2004; Ordoobadi, 2009; Ordoobadi and Mulvaney, 2001). There is currently a lack of existing AMT development cost estimation research available within the literature. To respond, general cost estimation and existing techniques from varied domains are discussed in detail within Section 2.3. This helps to define existing research from similar domains and provide a platform to systematically cross reference.

Table 2-4 Manufacturing Readiness Level Definitions (Adopted from Department of Defence, 2011)

MRL	Definition	Description
1	Basic manufacturing implications identified.	Basic definitions of manufacturing principles are observed.
2	Manufacturing concepts identified.	Development of a new manufacturing approach or capability with low levels of data.
3	Manufacturing proof of concept developed.	Identification of the current manufacturing concepts within a laboratory, although can possess limited functionality.
4	Capability to produce the technology in a laboratory environment.	Manufacture of the design concepts must be complete and ready for investment with the assigned risks.
5	Capability to produce prototype components in a production relevant environment.	All technologies must be at TRL5. There must be a detailed manufacturing strategy with an integrated risk management plan.
6	Capability to produce a prototype system or subsystem in a production relevant environment.	All technologies matured to TRL6 with the majority of manufacturing processes defined and characterised.
7	Capability to produce systems, subsystems or components in a production representative environment.	Technologies must be matured to TRL7. Manufacturing process must be demonstrated in a production representative environment.
8	Pilot line capability demonstrated; ready to begin low rate initial production.	Technologies should be matured to TRL7. Manufacturing and quality processes must be proven in a pilot line environment with risks defined for low rate production.
9	Low rate production demonstration; capability in place to begin full rate production.	System must be in place within production and successful achieve low rate initial production with manufacturing processes controlled to three-sigma or equivalent.
10	Full rate production demonstrated and lean production practices in place.	Technologies are all matured to TRL 9. Lean practices are well established and continuous process improvements are ongoing.

2.2.5 AMT Performance Evaluation Techniques

AMT performance evaluation at the initial development stages feeds into Stage iii ‘development research’ of the TM framework, presented in Figure 2-1.

Existing literature for benefit or performance evaluation of aerospace AMTs at the initial stages of development is limited, with the majority of research evaluating from purely a cost perspective (Curran and Price, 2004; Ordoobadi, 2009; Ordoobadi, et al., 2001). Evaluation of AMT tangible and intangible performance at the initial stages of development is currently incomplete within the existing body of literature. To respond, focus has been placed on general evaluation of AMTs outside the initial development stages. Ordoobadi (2009) addresses this issue and evaluates AMT alternatives with similar financial results using Taguchi’s loss function. This is achieved by the decision maker evaluating the importance of the benefit; the required goals of the new AMT and how it meets these benefit goals. This information is then used in Taguchi’s loss functions to assign quantitative ranks to AMT alternatives. A further AMT justification toolset has been developed using System Wide Benefit Analysis (SWBVA) and moves away from the traditional economic financial analysis (Ordoobadi et al., 2001). This toolset is utilised if the AMT is not economically justified. Users follow a structured procedure to determine if the value of the system wide benefits is sufficient to justify the calculated gap. An additional study developed a decision making toolset for the selection of manufacturing automated technologies (Almannai et al., 2008). This used Quality Function Deployment (QFD) in conjunction with Failure Mode and Effects Analysis (FMEA). The toolset aimed to identify the most suitable manufacturing automation alternative and the associated risk. Evans et al. (2012) developed a justification method for evaluation of manufacturing technologies for use within manufacturing systems. This technique applied fuzzy decision trees to establish patterns using a case repository. Elaboration of this research captured expert knowledge and experience of a decision maker when making future selection decisions (Evans et al., 2013).

In summary, there is a limitation of existing models or toolsets capable of capturing AMT performance from a tangible and intangible perspective at the initial stages of development. At this development stage there are high levels of uncertainty from lack of knowledge of the AMT process, the predicted development pattern and level of success.

2.2.6 Management of AMT Development Summary and Analysis

This Section has summarised the existing literature and techniques for the management of AMT development. Focus was initially placed on TM within manufacturing organisations and presented a suitable aerospace manufacturing TM framework, illustrated in Figure 2-1. Refinement was then placed on TD and its alignment within the TM framework in Figure 2-1, within Sub Section 2.2.2. This identified the lack of literature in transitioning an AMT from selection and approval (Stage ii), to development research (Stage iii). Transition between these stages requires R&T investment to mature an AMT. Also identified is the lack of available techniques to quantify the development effort to mature an AMT and estimate the perceived performance impact. Sub Section 2.2.3 that followed evaluated maturity readiness techniques available within the aerospace manufacturing industry, an area well documented within the literature. From the lack of techniques available to quantify R&T investment to mature an AMT, focus was then placed on AMT development cost estimation in Sub Section 2.2.4. This aspect of the research categorised that there are limited techniques or models available to estimate the cost and effort required to develop a novel AMT. From the lack of literature available to quantify AMT performance at the initial stages of development, focus was then placed on general AMT evaluation techniques in Sub Section 2.2.5. This identified there are limited available models or techniques capable of quantifying AMT performance, from a tangible and intangible perspective at the early stages of development.

Figure 2-2 summarises this overall Section, with the lack of available literature and techniques highlighted in red. The red aspects of this illustration form focus for the following Sections of this Chapter, with the proceeding Section focussing on cost estimation. Section 2.4 follows by evaluating Technology Forecasting techniques, with inclusion of uncertainty and its relevance to technology development.

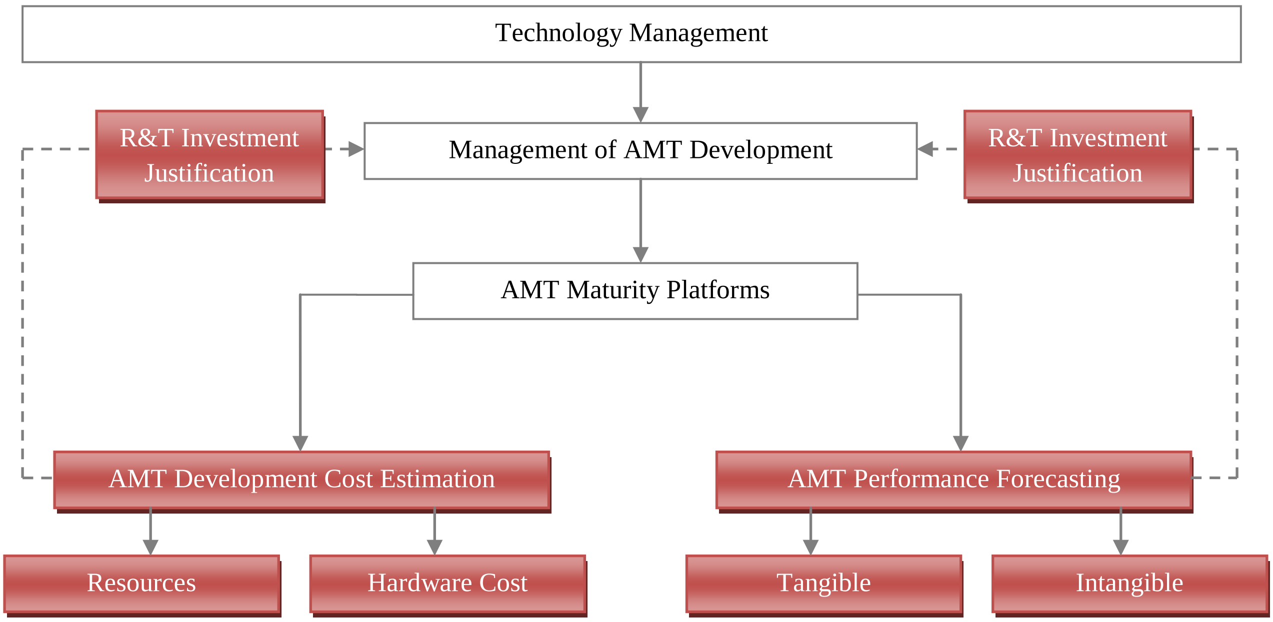

Figure 2-2 Management of Advanced Manufacturing Technology Development Existing Literature Summary

2.3 Cost Estimating

Sub Section 2.2.4 identified the lack of available techniques within the literature, capable of estimating AMT development effort and cost at the initial stages of development. Quantifying each parameter would enhance the estimation of the required R&T investment to develop the selected AMT for its assigned application. To respond, the cost estimation domain is explored within this Section. This defines the main cost estimation techniques and their suitability for application at the early stages of development. Cost estimation is best defined by the Association for the Advancement of Cost Engineering (AACE, 1990):

> "...The determination of quantity and the predicting or forecasting, within a defined scope, of the costs required to construct and equip a facility, to manufacture goods, or to finish a service."

Romero Rojo (2011) discusses that generally speaking, cost estimation aims to forecast the future costs of resources, methods and management, using historical data and experience. Leonard (2009) defines that in order to generate credible cost estimates, a best practice cost estimating process should be followed. Figure 2-3 identifies their process and its 12 steps.

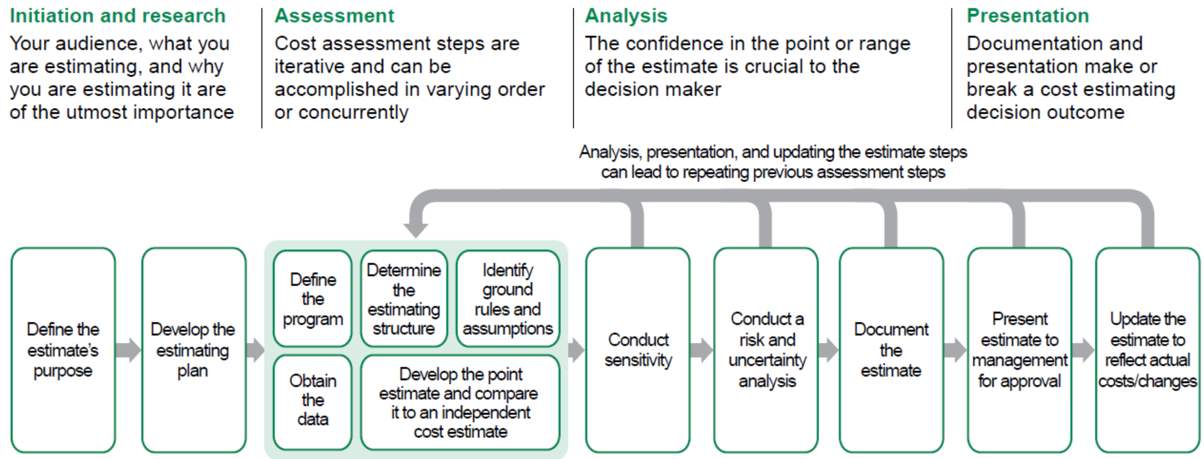

Figure 2-3 GAO Cost Estimating Process (Adopted from Leonard, 2009)

Romero Rojo (2011) lists several challenges in creating successful cost estimates including:

- Data specific problems. Lack of data, unreliable data and data not normalised. Each is typical when evaluating a new product, process or a state of the art technology.
- The analyst performing the estimate has a lack of experience.
- Not defining the uncertainty and risks, leading to overoptimistic and unrealistic estimates.
- Assumptions made with ambiguity.
- Programme stability.
- Limited time to generate estimates.

2.3.1 Cost Estimating Techniques

Niazi et al. (2006) and Romero Rojo (2011) categorise cost estimating techniques into qualitative and quantitative, represented in Figure 2-4. For the purpose of this research, the main cost estimation techniques are now discussed in detail.

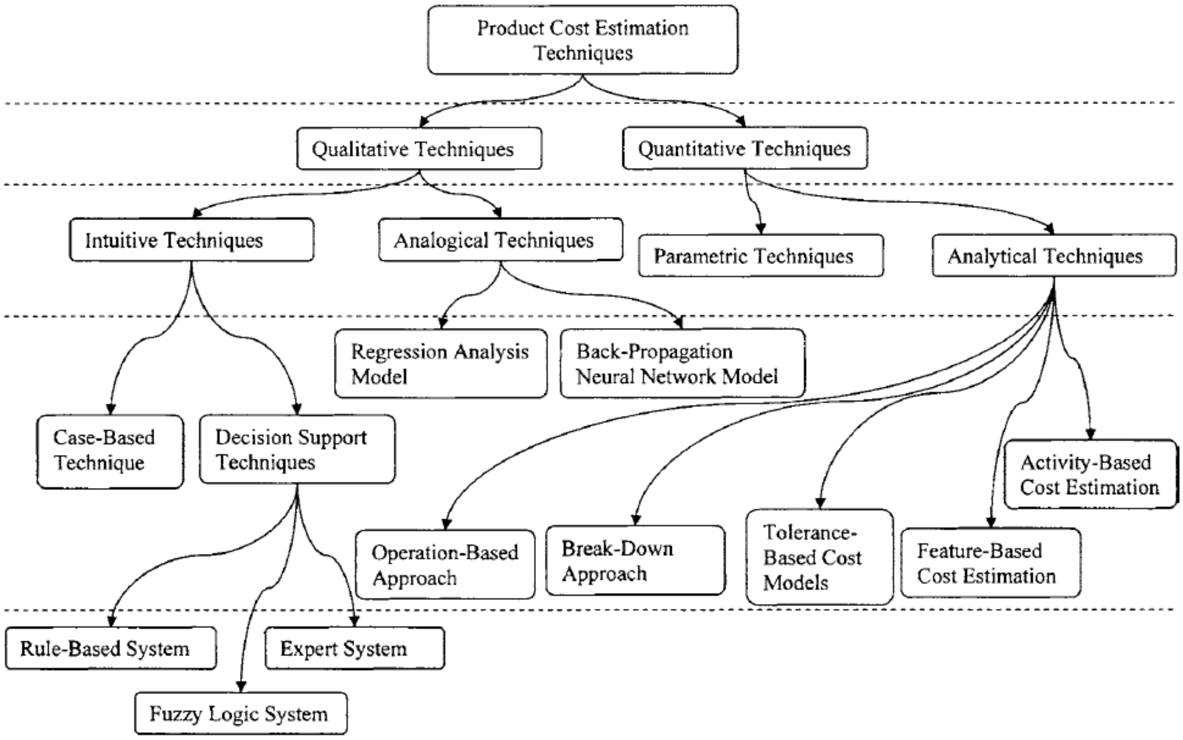

Figure 2-4 Classification of the Cost Estimation Techniques (Adopted from Niazi et al., 2006)

2.3.1.1 Parametric Estimation

Stewart et al. (1995) and Romero Rojo (2011) best define the parametric cost estimating technique as:

> "...The process of estimating cost by using mathematical equations that relate cost to one or more physical or performance variable associated with the item being estimated."

The technique uses historical data to form mathematical correlations and create Cost Estimating Relationships (CERs). The CERs aim to categorise performance, technical or complexity parameters that impact the cost (Trivailo et al., 2012). Forming these CERs is a complex task and requires significant historical data to verify (Valerdi, 2005; Shermon, 2009; NASA, 2008; Niazi et al., 2006). Trivailo et al. (2012) identifies that a parametric cost model can only become as reliable as the database supporting the CERs and can require high levels of adjustment to become consistent. These authors clarify that the parametric cost estimating technique is typically utilised at the early stages of the TM lifecycle and assumes a top down approach, making it suitable for the initial development stages of a system, software or technology (Valerdi, 2005; Shermon, 2009; NASA, 2008; Niazi et al., 2006; Roy, 2003). This technique assumes that factors affecting historical cost will continue to impact the future cost (NASA, 2008).

2.3.1.2 Bottom-up Costing

This technique involves defining the Work Breakdown Structure (WBS) and estimating the cost of each activity. These estimates are typically performed by the engineer or expert carrying out the work (Trivailo et al., 2012). The activity costs are then compiled to provide a total project cost estimate (Leonard, 2009; Romero Rojo, 2011). This technique is a very slow method requiring high levels of resource and data input (Romero Rojo, 2011). However, this technique is used for many industrial applications from its high accuracy, although is only suitable when the WBS is well defined, making it not suited for the early TM stages with high levels of uncertainty (Romero Rojo, 2011; Trivailo et al., 2012; Cavalieri et al., 2004; Roy, 2003; Niazi et al., 2006).

2.3.1.3 Analogy Estimation

This technique is based on the platform that similar projects have similar costs (Romero Rojo, 2011; Roy, 2003). The technique assumes that each new development project keeps similarity to an existing project and has evolved by changing or adding new parameters (Leonard, 2009; Romero Rojo, 2011). The project cost bearing the most similarity is then adjusted using the new project parameters. To operate successfully, this technique requires historical project data and identification of the characteristics and is most suited for the initial stages of TM lifecycle (NASA, 2008; Romero Rojo, 2011).

2.3.1.4 Expert Judgement

Expert judgement uses the experience and knowledge of an estimator to form a cost estimate and is regarded as a subjective approach (Trivailo et al., 2012). This technique is typically applied when time, information or other resources are inadequate to utilise another cost estimation technique (Romero Rojo, 2011). Despite being misunderstood by those outside the cost estimation domain, this technique is widely used for cost estimation and is suitable for application to any area of the TM lifecycle (Roy, 2003; Trivailo et al., 2012; Romero Rojo, 2011). Expert opinion has been applied for development of state of the art cost models, using the Wideband Delphi Technique (Valerdi, 2005 and 2011; Boehm et al., 2005). The Wideband Delphi Technique involves the capture of expert opinion in a controlled data collection form. The purpose of this technique is for the experts to reach consensus on the final estimate (Valerdi, 2011; Romero Rojo, 2011).

2.3.2 Comparative Analysis of Cost Estimating Techniques

The cost estimation techniques are evaluated for their strengths, weaknesses and typical applications, listed in Table 2-5 (Romero Rojo, 2011). Additionally, their alignment to the stages of the TM framework, presented earlier in Section 2.2.1, is also listed. To provide further evaluation, each cost estimation technique's suitability is compared to a programme life cycle and is illustrated in Figure 2-5 (NATO, 2009). This diagram clearly defines parametric and analogy as the most suitable approaches for the initial stages of development within the programme life cycle.

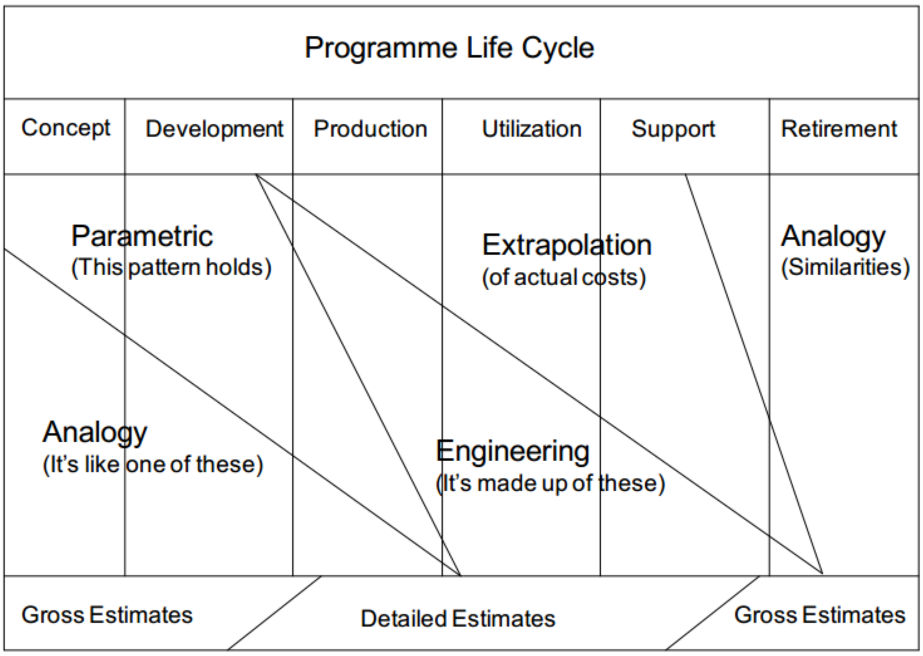

Figure 2-5 Suitability of Cost Estimating Techniques when aligned to the Programme Life Cycle (Adopted from NATO, 2009)

2.3.3 Cost Models and Toolsets

The cost estimation techniques discussed previously, define the platform of techniques suitable to Technology Development (TD). Figure 2-5 illustrates how parametric and analogy are the techniques suited to development cost estimation of AMTs at the conceptual stages of development. For the purpose of this research, the main cost models and toolsets available from varied domains are now discussed.

Table 2-5 Comparison of Main Cost Estimating Techniques (Adapted from Romero Rojo, 2011)

Technique	**Strengths**	**Weaknesses**	**Application**	**TM Framework Alignment**
Parametric	- Fast - Constructive - Good audit trail - Repeatable - Cost driver visibility	- Lacks detail - Model building investment - Black box syndrome - Cultural barriers - Non cost experts don’t understand operation	- Budgetary estimates - Design to cost - Baseline estimate - Cost goal allocations - Cross check	i) Identification and monitoring ii) Selection and approval iii) Development research
Bottom-up	- Easily audited - Sensitive to labour rates - Tracks vendor quotes - Time honoured	- Requires detailed data - Time consuming - Costly to implement and operate	- Production Estimating - Software development - Negotiations	iv) Acquisition and adaptation v) Exploitation and review
Analogy	- Requires few data - Based on actual data - Reasonably fast - Good audit trail - Self leaning	- Subjective adjustments - Accuracy dependant on similarity of projects - Difficult to assess effect of design changes - Blind to cost drivers - Similar past case requirements	- When few data sets are available - Rough order of magnitude estimate - Cross check	i) Identification and monitoring ii) Selection and approval iii) Development research iv) Acquisition and adaptation
Expert Judgement	- No historical data required - Easy and fast - Improves understanding of program - Few resources in terms of time and cost - Flexible	- Lack of objectivity - Expert bias - Low accuracy - Low transparency for audit trails - Inconsistent and unstructured - Non deterministic	- Cross check - Baseline estimate - Cost goal allocations - Cost model development (Delphi)	i) Identification and monitoring ii) Selection and approval iii) Development research iv) Acquisition and adaptation v) Exploitation and review

2.3.3.1 COCOMO®

The Constructive Cost Model (COCOMO) is a parametric cost model capable of estimating the cost, effort in person months and the schedule of a new software development. COCOMO II is the latest version and has three sub models broken down into: applications composition, early design and post architecture models (Boehm, 2005). Each model calculates the size and uses Function Points (FPs) to count Software Lines of Code (SLOC) and adjusts using cost drivers. Although this model has been applied to a number of applications, COCOMO has never been aligned with estimating AMT development effort.

2.3.3.2 COSYSMO®

The Constructive Systems Engineering Cost Model (COSYSMO) was based on COCOMO methodology and tailored for estimation of System Engineering. This model was developed by Valerdi (2005) and calculates the functional size of the system using FPs and adjusts using multiplicative cost drivers. These are then used to adjust a normalised baseline and estimate the person-months required to develop a novel system. COSYSMO has never been used to estimate AMT development effort.

2.3.3.3 Trueplanner by PRICE® Systems

Trueplanner by PRICE® Systems has a suite of parametric cost models, including True-H for estimation of hardware and True-S for estimation of software. Both models utilise CERs formed from detailed analysis of historical data. The models have the flexibility for local calibration by adjusting the CERs to suit the aligned organisation (Trivailo et al., 2012; Koury, 2010; PRICE Systems, 2011). Despite there being a vague development cost estimation evaluation within this toolset, this is not aligned with the development cost of AMTs.

2.3.3.4 SEER® by Galorath Incorporated

The Systems Evaluation and Estimation of Resources (SEER) and for Hardware (SEER-H) are cost models developed by Galorath Incorporated. Each model is suited to estimating at the initial stages of development. The models follow a two stage evaluation, the first applying an analogy and the second using parametric CERs to compare results of the analogy. The models can also be tailored and calibrated to industrial applications, although in each form, have not been applied to estimating the development cost of AMTs (Trivailo et al., 2012; SEER, 2011).

2.3.3.5 P-Beat

The Process-Based Economic Analysis Tool (P-Beat) was developed by Boeing R&T and NASA Glenn Research Centre to evaluate technology development projects. This tool combines parametric and analogy estimation, to allow technologies at different levels of maturity to be estimated. Within the model, specific CERs are used to estimate technology development costs with key drivers' focussing on: the TRL, design maturity, design team capability and software and hardware complexity. In the most recent publication, this model was applied to Boeing Air Traffic Management technology projects (Schankman, and Reynolds, 2010).

Despite having a manufacturing complexity and TRL assessment capability, this model has not been specifically used for estimating the development cost of AMTs.

2.3.3.6 SpaceWorks I-RaCM

SpaceWorks Engineering developed an Integrated Risk and Cost Model (I-RaCM) for simultaneous cost and risk assessment development of a new system (DePasquale, and Charania, 2008). This model integrates existing software tools such as SEER-H, NASA Air Force Cost Model (NAFCOM) and their own versions. Included within the model is a technology development cost estimation tool able to estimate technology development costs to TRL6. However, this is only based on historical development time and cost and does not define the cost drivers (DePasquale and Charania, 2008).

2.4 Technology Forecasting

Sub Section 2.2.5 defined the lack of available techniques within the literature capable of evaluating an AMT performance at the initial stages of development. Quantifying the predicted performance at these development stages would help justify R&T investment to mature the technology, detailed earlier in Sub Section 2.2.1. To respond, the technology forecasting domain is explored within this Section, defining the key technology forecasting techniques and their suitability for application at the conceptual development stages. Technology forecasting is best defined by Kirby and Mavris (2002) as:

> "...Technology forecasting is a prediction of future characteristics of useful machines, procedures or techniques."

Forecasting provides an enhanced quantitative vision of the future and the evolutionary path to follow. This creates a more informed decision and estimates the associated risk and uncertainty (Kirby, 2001; Kirby and Mavris, 2002; Twiss, 1992). Kirby (2001) defines that there are two broad categories of forecasting, exploratory and normative. The exploratory technique evaluates historical trends and extrapolates to predict what can happen in the future (Kirby, 2001; Kirby and Mavris, 2002). This process relies on the presumption that the past progress follows an evolutionary pattern (Kirby, 2001; Twiss, 1992). In contrast, the normative process starts with the future goals and works backwards, defining the performance requirements to achieve and if they are obtainable with the accessible resources (Kirby, 2001; Kirby and Mavris, 2002). Either one of these broad categories uses one, or an amalgamation of the main techniques including: trend analysis, expert opinion, modelling or scenario development (Porter et al., 2011). Each of these main forecasting techniques is discussed in the proceeding Sub Section.

2.4.1 Forecasting Techniques

2.1.1.1 Trend Analysis

Trend analysis uses quantitative historical data to predict the future, assuming a continuation of the historical trend. Generally speaking, trend analysis covers a wide spectrum of economic forecasting techniques (Firat et al., 2008). These can diversify from straightforward regression to enhanced methods with an example being the Box-Jenkins technique (Firat et al., 2008; Porter et al., 2011). The complexity of the technique applied depends on the complexity and availability of the data. There is no need to apply an advanced technique when simple regression would adequately fit the purpose and meet the accuracy requirements. When required and with availability of data, techniques including Fisher-Pry and Gompertz can form S-curve projections, to analyse the growth curve of technologies (Porter et al., 2011; Kirby, 2001; Firat et al., 2008).

2.4.1.2 Expert Opinion

The expert opinion technique involves capturing the opinion of experts in a controlled format and analysing the data provided (Porter et al., 2011). These authors define that this technique presumes that experts in the subject domain are more capable of forecasting technology developments than those outside. Experts forecasting alone can generate unacceptable estimates. The most applied technique used to capture expert opinion is the Delphi method (Firat et al., 2008). The Delphi technique follows the structure of that used by the Cost Estimation Techniques, presented in Sub Section 2.3.1. This includes experts reaching consensus on a single forecast, after several rounds of expert data collection (Porter et al., 2011; Kirby, 2001; Firat et al., 2008). Many authors within the technology forecasting domain challenge the methods accuracy and subjectivity (Woundenberg, 1991; Campbell, 1966; Parente et al., 1984).

2.4.1.3 Modelling

A model is best defined by Porter et al. (2011) as:

> "...A simplified representation of the structure and dynamics of part of the real world."

Models are typically either computer based or judgement based, with either type requiring modelling assumptions (Porter et al., 2011; Firat et al., 2008). The assumptions within computer based models are typically quantitative. Judgement based models can be determinant on the forecaster's capability to form judgements of parameters and their impact on the forecast (Porter et al., 2011).

2.4.1.4 Scenario Development

Scenario development form snapshots of characteristics of the future and/or the route to follow to get there. Application of this technique is suitable even when time series data, experts or effective models are unavailable. These can form outstanding platforms to connect outputs from other forecasting techniques and can also enhance and contribute. A further benefit of this technique is its capability to combine quantitative and qualitative data and provide descriptions for a range of forecasters with diverse or limited skill sets (Porter et al., 2011).

2.4.2 Comparative Analysis of Technology Forecasting Techniques

The forecasting techniques are evaluated for their strengths, weaknesses and typical applications, with each listed in Table 2-6 (Porter et al., 2011).

2.4.3 Technology Development and Uncertainty

Section 2.2 described the management of AMT development. Within this Section, the general Technology Management (TM) process was described and presented a TM framework, illustrated in Figure 2-1. Additionally, Technology Development (TD) was discussed in detail within Sub Section 2.2.2. This identified the high level of uncertainty when developing novel AMTs. This significant uncertainty level creates an R&T investment dilemma at the initial stage of AMT development, involving whether to invest and mature a technology through Readiness Levels, discussed in Sub Section 2.2.3. Considering all AMTs within the aerospace industry are developed through Readiness Levels, understanding uncertainty within this development maturity metric is determined crucial. When a technology is at the initial stages of development, a low TRL, the shape of the development curve is challenging and sometimes impossible to forecast. This is from lack of knowledge and data to form a defined development trend. Subsequently, when a technology is at the lower stages of development, the expert opinion technique is deployed, creating subjective outputs (Kirby, 2001; Kirby and Mavris, 2002). Therefore, a forecast should be performed by contemplating the possible benefits, or drawbacks, if the development was successful (Kirby, 2001; Twiss, 1992). To bound uncertainty, Kirby (2001) suggests using the method of analogy to define what is predicted to occur, if the technology developed at a successful rate. This author suggests a successful technology development programme could potentially develop with a linear trend, illustrated in Figure 2-6.

Table 2-6 Comparison of Main Technology Forecasting Techniques (Adopted from Porter et al., 2011)

Technique	**Strengths**	**Weaknesses**	**Application**
Trend Analysis	- Substantial data based forecasts using quantifiable parameters - Accurate over short time frames	- Required large data sets - Can only be performed with quantifiable parameters - Vulnerable to cataclysms and discontinuities - Projections misleading for long time frames - Do not define causal techniques	- To project quantifiable parameters - To analyse adoption and substitution of technologies
Expert Opinion	- Expert forecasts can tap high quality models internalised by experts who cannot or will not make them explicit	- Difficult to identify experts - Forecasts often incorrect - Questions asked are often unclear - Design of capture of expert opinion can be unclear - If interaction of experts allowed, can often be guided by strong personalities	- Generation of forecasts where experts in the domain are available - Used for forecasting when limited data - Used when modelling difficult or impossible
Modelling	- Models can define future behaviour of complex technologies from the separation of important aspects from unessential data - Some models can account for incorporating human judgement - Building the model can identify key characteristics of technologies	- Complex models can provide confidence in an inaccurate output - Prioritise quantifiable parameters over qualitative, sometimes neglecting key parameters - Models with limited data used for development can be inaccurate and misleading	- To reduce complex systems to a manageable output - Identification of the behaviour of a system
Scenarios	- Can provide excellent forecasts using a variation of quantitative and qualitative data - The outputs can be complied form other forecasting techniques - Can present forecast information to a variety of users	- Can be inaccurate unless a strong platform is utilised and maintained	- Integration of quantitative and qualitative information from varied sources - Creation of forecasts when data is weak or limited - Highly suited for forecasting complex projects with high levels of uncertainty to audiences with low technical experience/ability

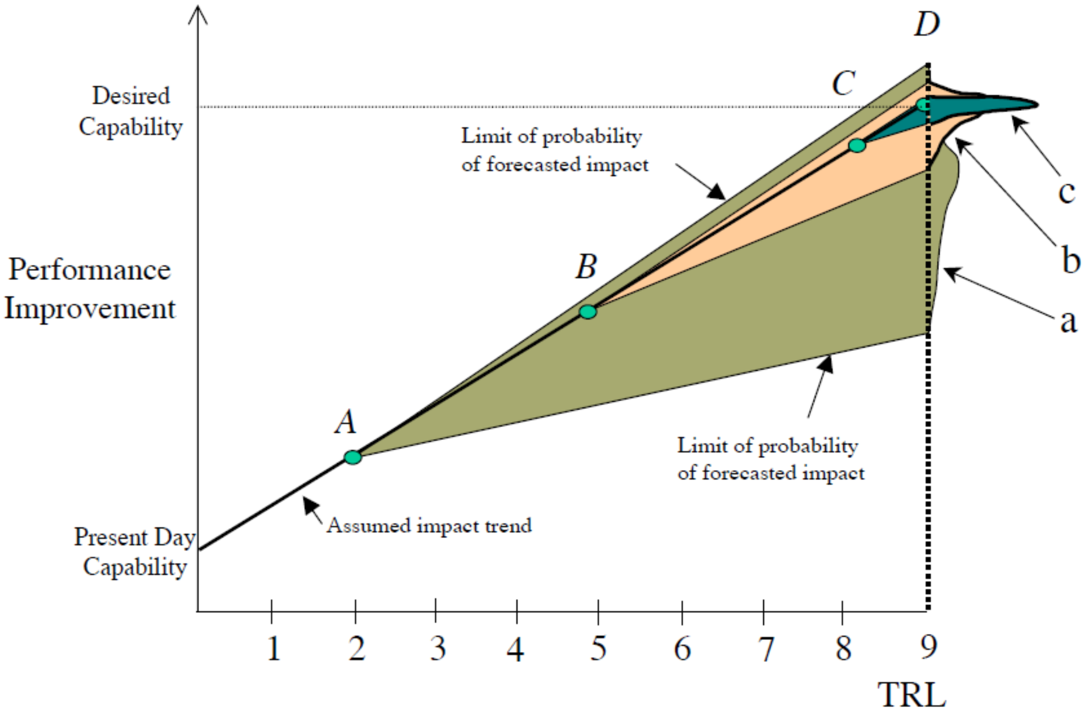

Figure 2-6 Example of Uncertainty in Forecasting a Technology Performance as a Function of TRL (Adopted from Kirby, 2001)

Point ‘A’ within the diagram defines a technology at the initial stages of development, TRL2. The desired capability of the technology at point ‘D’ is assumed using expert opinion, if the technology were successful. This is an estimate with low knowledge levels and could be lower, or higher than predicted, when the technology reaches full maturity. Kirby (2001) identifies that the technology development uncertainty is broken into two sources. The uncertainty of the technology itself is the first form and the second is from the forecast trend. Typically, the uncertainty reduces as knowledge builds and the technology matures and information is updated. Point ‘c’ within the diagram represents an increased level of knowledge at the high technological maturity level of TRL9. In contrary, point ‘a’ defines the lack of knowledge and high uncertainty distribution at a low level of technological maturity, TRL2. However, these distributions at the initial stages of development are based on expert opinion and are highly subjective.

2.4.4 Forecasting Methods and Toolsets

This Section so far has evaluated the main technology forecasting techniques and their suitability to the initial stages of development. TD uncertainty was discussed previously and defined the significant margins of uncertainty at the initial development stages. The purpose of this Sub Section is to evaluate any existing toolsets that try and identify or reduce the development uncertainty. When summarising, existing methods and toolsets within this domain are widely published by Kirby and Mavris (Kirby, 2001; Kirby and Mavris, 2002; Kirby and Mavris, 1999; Mavris, et al., 1998; Kirby and Mavris, 2000; Kirby et al., 2001; Kirby and Mavris, 2001; Kirby et al., 2006). Despite significant availability of research from these authors, the most relevant toolset is the Technology Identification Evaluation and Selection (TIES) framework published by Kirby (2001). This includes an 8 Step framework and for the purpose of this research, Step 6 Technology Identification and Step 8 Technology Selection are the most relevant. Step 6 of the framework included evaluation of technology development uncertainty, a point evaluated previously. Step 8 identified Technology Frontiers, designed to capture the uncertainty and present a tangible result. For each technology, the performance parameters were plotted against a predicted investment cost, with a probabilistic example illustrated in Figure 2-7. This author used the technology frontiers to assign budget limits and performance thresholds, allowing a clear visual identification of technologies providing the best value, illustrated in Figure 2-8.

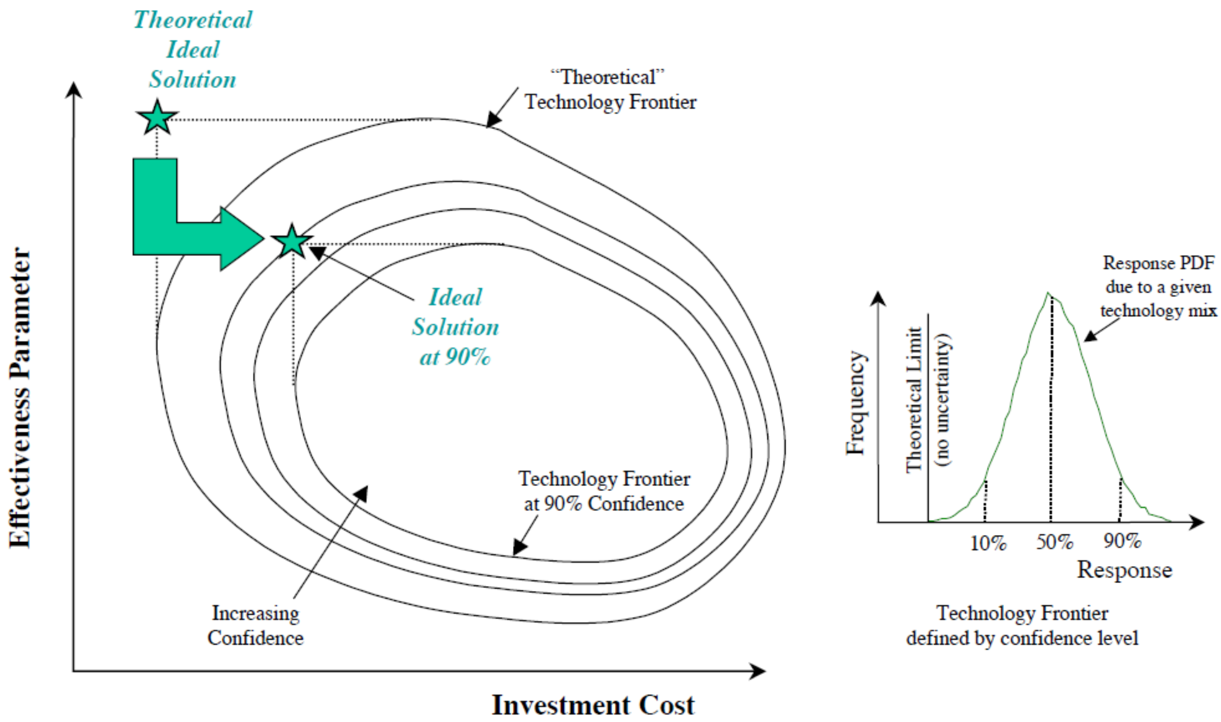

Figure 2-7 Example Probabilistic Technology Frontier (Adopted from Kirby, 2001)

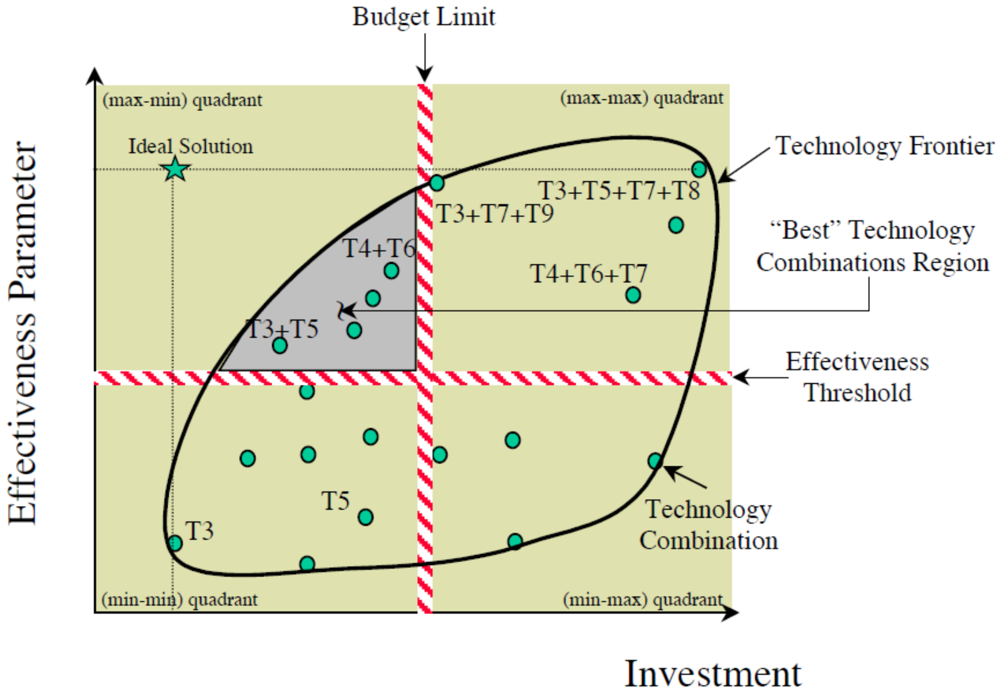

Figure 2-8 Technology Frontier for Identification of the Best Value Technologies (Adopted from Kirby, 2001)

However, this approach has only been applied for evaluation of generic aerospace technologies and is not applied to the manufacturing domain. Furthermore, assumptions were made for technology investment costs, not quantifying in a constructive format and the performance was also predicted using the decision maker's discretion.

2.5 State-of-the-Art Review

Figure 2-1 illustrated an overall Technology Management (TM) Framework used within the aerospace manufacturing industry. Technology Development (TD), Stage iii, was the focus of this research and was discussed in detail within Sub Section 2.2.2. Sub Section 2.2.3 defined how the aerospace manufacturing industry uses the TRL, or an adapted version, to standardise the development of AMTs (Chan et al., 2000; Evans, 2013; Rolls Royce, 2009; Ward et al., 2012).

When referring to state-of-the-art for AMT developments within the aerospace industry, a key provider is Advanced Manufacturing Research Centres and Universities (EPSRC Centres for Innovative Manufacturing, 2013; Rolls Royce, 2013; Lab for Integrated Metrology Applications, 2013; Rolls-Royce University Technology

Centre in Manufacturing Technology, 2013; Advanced Manufacturing Research Centre, 2013; Advanced Manufacturing Technology Research Centre, 2012; Advanced Forming Research Centre, 2014; National Composites Centre, 2014). Each of these utilise the TRL for development and maturity of novel AMTs. These state-of-the-art research facilities help to link companies, industrial sectors and universities (Catapult High Value Manufacturing, 2013; EPSRC Centres for Innovative Manufacturing, 2013; Rolls Royce, 2013). Further refinement can be placed towards high value Catapult manufacturing centres. The purpose of these centres is to enhance the manufacturing sector by assisting companies with by nurturing the development of novel technologies to reach commercialisation (Catapult High Value Manufacturing, 2013). Following the aerospace manufacturing industry and universities, Advanced Manufacturing Research Centres and the Catapult centres have standardised development and use of the TRL (Catapult High Value Manufacturing, 2013; EPSRC Centres for Innovative Manufacturing, 2013). Figure 2-9 identifies the Catapult centres role in the development of AMTs and their funding sources aligned to the TRL (Elsy, 2012).

The US has a similar research structure called the Advanced Manufacturing Technology Consortia (AMTech) Program and enables technology development research to support the US manufacturing industry (Advanced Manufacturing Technology Consortia, 2013). The Advanced Manufacturing Research centres, Catapult Centres and the Advanced Manufacturing Technology Consortia have not published how they estimate the development cost and perceived performance, at the initial stages of development.

Sub Section 2.2.4 discussed and analysed that there is currently a lack of understanding of existing AMT development cost estimation research available within the literature. To respond, Sub Section 2.3.3 detailed and described state-of-the-art cost models and toolsets available outside the AMT development domain. To understand further, regulatory standards were assessed. A key identified regulatory standard was the United States Government Accountability Office (GAO) cost estimating and assessment guide, applicable for developing and managing capital programme costs, with an overview illustrated earlier in Figure 2-3 (Leonard, 2009). A further regulatory standard is the NASA cost estimation handbook (NASA, 2008). This is a document designed for reference within and outside NASA’s cost estimation community.

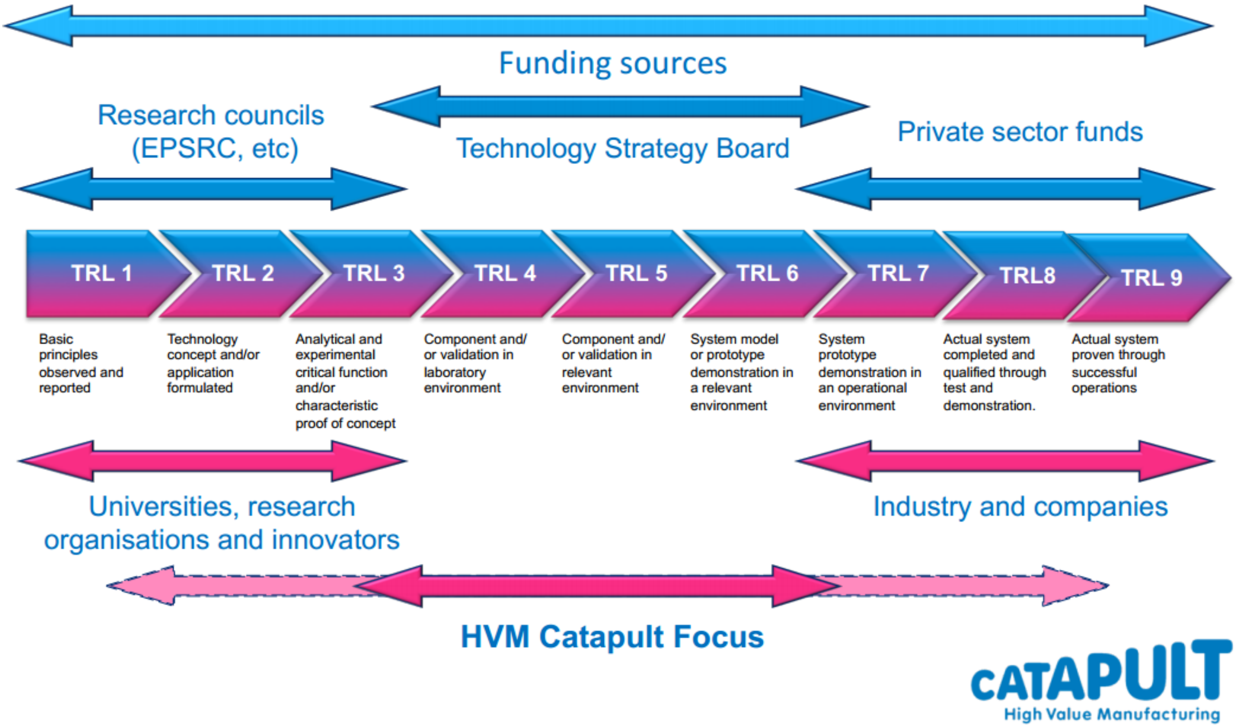

Figure 2-9 Catapult Involvement in Commercialising Innovation (Adopted from Elsy, 2012)

Sub Section 2.2.5 evaluated AMT performance evaluation techniques. While there was a significant quantity of literature for AMT performance evaluation, techniques did not perform the assessments at the early development stages for novel AMTs. In response, state-of-the-art forecasting methods and toolsets were discussed in Sub Section 2.4.3. To assess the domain further, regulatory standards were researched for performance evaluation of manufacturing technologies. This produced standards from the British Standards Institute (BSi) and the American National Standards Institute (ANSI). The most relevant standards are the BS ISO 22400-2[1] and identify key performance indicators for manufacturing operations. ANSI has produced standards for the performance validation of machining tools, using computer numerical controls systems and is numbered ANSI B5.54[2].

In summary, analysis of existing state-of-the-art has identified that manufacturing research centres and universities have standardised the TRL for development of novel AMTs. However, there is a lack of estimating development cost and resources at the initial stages of AMT development. Furthermore, there are no standards to support the development cost and resource estimation. For the evaluation of manufacturing technologies, there were available standards, although none are suited for assessment of AMTs at the initial development stages. This identifies that current techniques for the assessment of AMT development cost and resources are insufficient. Additionally, AMT performance evaluation techniques and standards are inadequate to evaluate and justify performance at the initial stages of development.

2.6 Summary of Knowledge Gaps

Figure 2-2 summarised the lack of existing literature within the management of AMT development and the justification of the R&T investment to develop and mature an AMT from concept to full demonstration. Within this summary, AMT development cost estimation and AMT performance forecasting were defined with a lack of existing knowledge. To respond, the theory of cost estimation and available state-of-the-art models from diverse domains were explored. Despite there being available models and toolsets to estimate development effort and cost from abstract domains, available models cannot be directly applied for estimation of AMT development effort and cost.

To acknowledge the lack of AMT performance forecasting at the initial stages of development, technology forecasting techniques and state-of-the-art models and toolsets were explored and analysed. This categorised the lack of suitable models and toolsets capable of forecasting the performance of technologies with inclusion of technology development uncertainty. A state-of-the-art review covering how international manufacturing research institutions, universities and catapult centres function, further clarified the lack of AMT development cost estimation and performance forecasting.

The following are the knowledge gaps summarised by this critical review of existing research and state-of-the-art:

There is a lack of understanding of how the aerospace manufacturing industry, advanced manufacturing research centres and universities manage AMT developments and justify the required R&T investment to mature.

[1]BS ISO 22400-2 *Automation systems and integration – Key performance indicators for manufacturing operations management*

[2]ANSI/ASME B5.54 *Methods for performance evaluation of computer numerically controlled machining centres*

A detailed analysis of existing literature and state-of-the-art identified the lack of documentation and understanding of techniques and methods used to justify the required R&T investment to mature a novel AMT from concept to full scale demonstration. This analysis also discovered that the aerospace manufacturing sector and state-of-the-art research hubs including Catapult centres and universities utilise the TRL to develop novel AMTs. However, there is a specific lack of understanding of how the resources and costs are allocated and estimated for the development of novel AMTs, with specific alignment to the TRL. Additionally, there is a lack of understanding of justification and estimation of the performance at the initial AMT development stages, when these can include non-quantifiable parameters.

Lack of models or toolsets capable of estimating AMT development effort and cost at the initial stages of development.

Despite availability of state-of-the-art models capable of estimating development effort and cost from other domains, there is a lack of knowledge of what drives the Non-Recurring effort and cost of novel aerospace AMTs. Furthermore, the lack of understanding is amplified from high levels of uncertainty from significant AMT process technological novelty and a lack of historical trend development patterns.

Lack of models or toolsets capable of forecasting novel AMT tangible and intangible performance at the initial stages of development.

Although there is availability of AMT evaluation techniques and methods, the literature analysis and state-of-the-art review has defined a lack of models and toolsets capable of forecasting novel AMT performance at the initial stages of development. Following development cost estimation, there are high levels of technological uncertainty, not allowing for application of generic trend analysis. Despite AMT evaluation models defining tangible and intangible performance, each did not capture and evaluate with inclusion of development uncertainty. Additionally, there is a lack of understanding and classification of aerospace AMT performance measures for comparison of a diverse range of novel AMTs at the initial stages of development.

Lack of framework or methodologies to indicate or quantify the development value of novel aerospace AMTs; providing the justification of the required R&T investment at the initial stages of development.

Evaluation of existing aerospace manufacturing TM techniques identified the lack of rigor from transitioning novel AMTs from the initial selection, to justify the investment required to launch into development research. This is further clarified from the lack of definition of how state-of-the-art international manufacturing research centres and universities justify their investments from both industry and government investment sources. In summary, research centres and industry have not published how they perform value analysis technique to evaluate novel AMTs at the initial development stages.

When evaluating value analysis research from the general aerospace technology domain, a key author suggested that their most important research recommendation should be in “the area of quantifying the amount of investment money needed to develop a technology” and recommended using the TRL (Kirby, 2001). This author recommends that quantifying the development investment and plotting against a performance effective parameter would provide the perfect technology value evaluation toolset.

To respond to these knowledge gaps, the following Chapter defines the development of a research methodology and explains the various research strategies contemplated.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

Chapter 2 defined the knowledge gaps in existing literature and in response; this Chapter identifies the research objectives, explains the research methodology development and describes the final research methodology. Section 3.2 specifies the research objectives; Section 3.3 defines available research approaches and selects the most suitable. Section 3.4 presents and details the five Phases of the final research methodology.

3.2 Research Objectives

A review of the literature and state-of-the-art in Chapter 2 identified the gaps in the existing body of knowledge, with the following objectives to address:

Phase 1. Understand current practice and state-of-the-art in the management of aerospace AMT development and the methods used to estimate, justify and allocate development investment. More specifically, outcomes must include:

- A fully documented review of existing AMT development management, cost estimation and performance forecasting methods used within R&T of the aerospace industry.
- A process map of the As-Is.
- Design of an enhanced management of AMT development process.

Phase 2. Develop a systematic approach capable of estimating novel AMT non-recurring development resources and hardware cost, at the early development stages. The outcome must include:

- A solution capable of meeting the requirements defined from the enhanced management of AMT development process, specified in Phase 1.

Phase 3. Develop a performance forecasting model capable of quantifying tangible and intangible performance for a diverse range of AMTs with varied applications, each at the initial development stages. This solution must include:

- A toolset capable of meeting the requirements specified within the enhanced management of AMT development process, defined in Phase 1.

Phase 4. The solution must guide users within an industrial R&T application to align the cost-benefit forecasts and provide development value advice, at the early stages of development. This must be capable for a generic range of aerospace AMTs with diverse applications. To meet these requirements the solution should:

- Be capable of meeting the specification formed from the enhanced AMT development process, defined in Phase 1.
- Provide a framework to control the toolsets developed in Phase 2 and 3.

Phase 5. Verify and validate the cost-benefit outputs and development value advice using detailed industrial case studies. This should include:

- An empirical study using the developed framework for assessment of novel AMTs with varied applications.
- A detailed statistical verification of each toolset developed in Phase 2.
- Verification of each toolset developed in Phase 3 using data from AMTs with known outcomes.
- An industrial validation using the responses from AMT development experts after utilising the solution within an industrial setting.

The 5 Phases of the research objectives are required to form a framework capable of assessing diverse AMTs with varied applications, forming a generic approach. Within this approach, fully external AMT vendors will not be considered as part of the solution.

The following Section analyses available research strategies, providing a platform for the final research methodology developed and followed.

3.3 Research Methodology Development

This Section describes approaches available for application to this research. A research strategy is then selected based on the aim, objectives and context.

3.3.1 Research Context

To define and develop a suitable research methodology, understanding the research context is determined as crucial. The primary focus of this research is the management of aerospace AMT development within industry and contributing research institutions. The second research domain is cost estimation, with a refinement to development cost. The final research focus is technology forecasting for evaluation of aerospace AMTs at the initial stages of development.

3.3.2 Research Purpose

Robson (1997) breaks the research purpose into three research categories:

- Exploratory research. This is applied when there are low levels of understanding and explores a new problem, structuring accordingly.
- Descriptive research. This approach aims to deliver an accurate description of person, events or situations.
- Explanatory research. This is aimed at identifying and explaining a problem, defining how and if there is a similarity in phenomenon.

Additional authors (Kumar, 2005; Romero Rojo, 2011) identified a further research purpose, termed Correlation Research. This technique aims to define a relationship between two or more characteristics of a phenomenon.

On detailed evaluation of each approach and aligning with the research aims, objectives and context, the most suitable technique is an amalgamation of exploratory and explanatory. The exploratory technique is suited to the initial stages of this research, with limited knowledge of the management of AMT development. Explanatory has an emphasis towards the later stages of this research by correlating the relationship between cost estimation, technology performance forecasting and AMT development.

3.3.3 Research Application

The research classification can be placed into two major categories, including pure research and applied research. Pure research, or basic research, is typically performed to elaborate existing knowledge and analyse the unknown. Applied research is normally a logical problem solving approach. This research aims to solve the problem of estimating the development cost of AMTs and in conjunction, forecast their performance at the initial development stages. Each is required to solve the AMT investment justification problem, categorising as applied research.

3.3.4 Types of Research Design

There are two types of research design, qualitative and quantitative (Kumar, 2005; Romero Rojo, 2011). Robson (1997) also references these as flexible, known as naturalistic and fixed designs, termed interpretive.

3.3.4.1 Qualitative Research

Qualitative research utilises data in the format of words and observations, typically not numerically formatted (Romero Rojo, 2011). This technique is structured on the exploratory research approach and typically uses surveys, observations and interviews to systematically collect data (Robson, 1997; Romero Rojo, 2011). This generates high involvement of the researcher, making the process flexible and reiterative (Easterby-Smith et al., 2002; Romero Rojo, 2011; Robson, 1997). The key strengths and weaknesses of this type of research are listed in Table 3-1.

Table 3-1 Strengths and Weaknesses of Qualitative Research

Qualitative Research	
Strengths	**Weaknesses**
- Direct confrontation with the world	- Large time scales
- Flexibility to incorporate diverse and unique experiences	- Difficulty performing validation and determining accurate results
- Evaluation of objects in completeness	- Confidentiality problems
- Direct interaction with participants	- Can become biased

When evaluating the available qualitative research strategies, the most suitable to this research include (Robson, 1997; Romero Rojo, 2011):

- Case study research. This involves an empirical analysis of a new specific phenomenon and evaluation of its real life environment, using numerous inputs of evidence.
- Ethnographic study. This analyses a group, community or organisation, how they are involved and perceive the world.
- Grounded theory study. This forms theories from the data captured within the study.

A comparative analysis of the qualitative research strategies is listed in Table 3-2. This research is applied to state-of-the-art in the aerospace AMT development domain and is in collaboration with large aerospace manufacturers and advanced manufacturing research centres, so there is direct access to real life information. From this analysis and the research application, part of this research is appropriately suited to the qualitative case study strategy.

Table 3-2 Comparison of Qualitative Research Strategies (Adopted from Robson, 1997)

Comparative Parameter	Case Study	Ethnography Study	Grounded Theory Study
Focus	- Detailed analysis of a single or multiple cases	- Providing an explanation of a cultural or social group	- Creating a theory structured around the data captured
Discipline origin	- Political science, sociology, evaluation, urban studies or other social sciences	- Cultural anthropology, sociology	- Sociology
Data collection	- Multiple document sources including: interviews, archival records, observations, physical artefacts	- Based on observations and interviews	- Interviews typically held with 20-30 individuals to perform in-depth analysis of categories
Data analysis	- Description, themes, assertions	- Description, analysis, interpretation	- Open coding, axial coding, selective coding, conditional matrix
Narrative form	- Detailed analysis of case(s)	- Description of cultural behaviour of group	- Theory or theoretical model

3.3.4.2 Quantitative Research

Quantitative research analyses data, typically in numerical form to quantify an object or phenomena (Romero Rojo, 2011; Robson, 1997). This research is placed into characteristics including (Burns, 2000; Romero Rojo, 2011): replication, operational definition, hypothesis testing and control. Replication determines if the data is repeatable, accurate and capable of forming the exact results. Operational identifies a need for categorisation of the terms. Hypothesis is formed and analysed using empirical tests. A quantitative research technique creates a controlled experiment and environment for the researcher, ensuring minimal bias. Generally speaking, the quantitative technique is formed using a fixed design, although this can create an inflexible process (Robson, 1997). Table 3-3 lists the key strengths and weaknesses.

Table 3-3 Strengths and Weaknesses of Quantitative Research

Quantitative Research	
Strengths	**Weaknesses**
- Repeatable results	- Abstract from everyday life
- Can verify the results	- Challenging to adapt to environmental changes
- Can provide precise results	- Does not capture personal experiences
- Can determine causal impacts	- Inflexible

From this analysis and the requirements to verify and validate the framework within an industrial setting; this research requires application of the following quantitative techniques: replication, operational definition and hypothesis testing. Hypothesis will be formed using the interviews with experts, historical data and the Delphi study, each using techniques within the qualitative research design. This requires the hypothesis of each model within the framework to be tested, namely multiple regression for the development cost models, validating model significance. Each performance forecasting model hypothesis will also require statistical verification using case study data from the aerospace manufacturing organisation. Each will feed into the framework to form development value.

3.3.5 Comparative Analysis of Qualitative and Quantitative Research

Easterby-Smith et al. (2002) and Romero Rojo (2011) each define that both qualitative and quantitative approaches must be considered when conducting research. However, both approaches are not typically applied at once and are normally aligned to different Phases of the research. Table 3-4 presents a comparison of qualitative and quantitative research. From this detailed analysis of each technique, the most suitable approach to achieve the aims and objectives of this research is a combination of qualitative and quantitative. This creates a flexible research approach, with the capability to verify and provide validity within the industrial setting.

Table 3-4 Qualitative and Quantitative Research Comparison (Adapted from Burns, 2000; Romero Rojo, 2011)

Comparative Parameter	Qualitative Research	Quantitative Research
Assumptions	- Construction using social reality	- Reality based on factual objectives
	- Interwoven variables difficult to dissect and measure	- Can perform identification and measure of variables
	- Events perceived using an informants' view point	- Events perceived using outsiders' view point
	- Dynamic format of evaluation	- Fixed format of evaluation
Purpose	- Evaluation	- Estimation
	- Contextualisation	- Generalisation
	- Understating interpretation of others	- Causal interpretation
Method	- Collecting data with observations and unstructured interviews	- Measuring data and testing
	- Concludes with hypothesis and grounded theory	- Initiates hypothesis and theory
	- Emergence and portrayal	- Manipulation and control
	- Inductive and naturalistic	- Deductive and experimental
	- Evaluation of data using informants' descriptions	- Statistical analysis
	- Data presented in informants' style	- Data presented using statistical techniques
	- Expressive write-up	- Abstract write-up
Researcher's role	- Researcher acts as instrument	- Research applies structured instruments
	- Personally involved	- Abstract
	- Empathetic understanding	- Objective

3.3.6 Data Collection Methods

Data collection involves the process of preparing and collecting data (Evans, 2013). The main data collection methods include: literature review, surveys, interviews and focus groups (Romero Rojo, 2011; Robson, 1997). A focus group is a type of interview consisting of a group of interviewees rather than a one-to-one (Robson, 1997). Each of these main data collection methods have been applied to this research, with the addition of the Delphi Method and continuous iterations for the development of each model and the final framework.

3.3.6.1 Literature Review

Romero Rojo (2011) and Burns (2000) describe a literature review as a method that provides stimulation of the mind, rather than a direct evaluation of existing research, that can form a restricted viewpoint. To perform a thorough literature review, existing ideas and knowledge should be evaluated, with the addition of methodologies used (Romero Rojo, 2011; Robson, 1997). Evans (2013) identifies that if possible, existing state-of-the-art from industry and standards to support the appropriate techniques should be defined and evaluated.

3.3.6.2 Surveys

A survey involves capturing data by asking participants suitable questions using questionnaires. There are three types of questionnaire used including: self-completion, face-to-face interview and telephone interview (Romero Rojo, 2011; Robson, 1997). In self-completion, the respondent receives the questionnaire by post or email. Face-to-face involves the interviewer asking the interviewee the questions within the questionnaire. In a telephone interview, the respondent is asked the questions and the results are recorded.

3.3.6.3 Interviews

The applicability of the interview process to capture data is determinant on the research type. Robson (1997) and Romero Rojo (2011) categorise three types of interview based on their standardisation and structure, including:

- Fully-structured interviews. These have fixed predetermined questions, normally in a set order with characteristics similar to the surveys discussed previously. This approach is typically utilised to capture opinions rather than qualitative research.

- Semi-structured interviews. This type of interview also has predetermined questions, although they have the flexibility of the interviewer to adjust the questions, the order asked and time spent on each. These adjustment factors build the rapport between the interviewer and interviewee. However, this flexibility can generate difficult and sluggish data analysis.
- Unstructured interviews. This uses open-ended questions that allow the interviewer to discuss and evaluate in detail and generate an excellent rapport between the interviewer and interviewee. This can discover unpredicted answers, although can lead to meandering interviews that lose the trail of thought. Analysis of the answers can become problematic from unstructured input data in a non-coherent format.

3.3.6.4 Delphi Method

The Delphi Method is a technique capable of reaching convergence on opinion with a number of experts (Valerdi, 2011). This research method is suited for novel research fields and exploratory studies (Romero Rojo, 2011; Grisham, 2009; Valerdi, 2005 and 2011). A fundamental driver for utilisation of the Delphi method within this research is the lack of AMT historical development data. The Wideband Delphi method operates in the same manor, although allows for group discussion between experts (Valerdi, 2005; Valerdi, 2011). This technique has been proven as an accurate and reliable method for reaching group consensus, involving unquantifiable criteria and utilising experts from a range of knowledge fields (Boehm et al., 2000; Valerdi, 2005; Valerdi, 2011; Romero Rojo, 2011).

3.4 Final Research Methodology

3.4.1 Research Approaches Selection

From the evaluation within the research methodology development discussed previously, the research approaches selected are illustrated in red within Figure 3-1.

The primary platform of the research approach adopted uses a case study research strategy. Within this technique, there are typically many sources of data collection (Romero Rojo, 2011; Robson, 1997; Yin, 2009; Eisenhardt, 1989). The data collection techniques utilised within this research is now discussed.

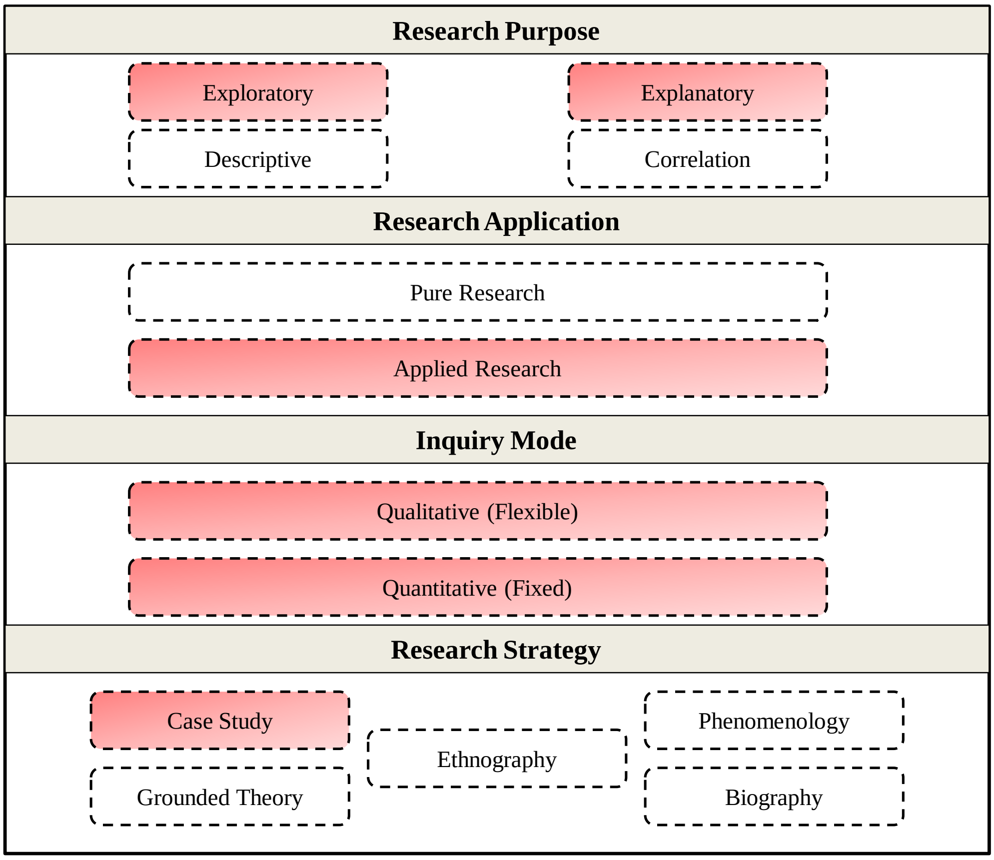

Figure 3-1 Research Approaches Selected

3.4.2 Final Research Methodology Design

The previous aspects of this Chapter have discussed the applicable theories of research methodologies and the suitability to this project. This research involves the capture of information throughout the research process, forming an inductive approach. To form a detailed understating of industry and allow the generation of a novel Cost-Benefit Forecasting Framework, a case study research strategy was selected. This will allow the approach to be tailored for the aerospace manufacturing industry. An outline of the final research methodology is presented in Figure 3-2. This identifies the five key Phases of the research including: 1) Contextual Understanding and Current Practice; 2) The Constructive Technology Development Cost Model (COTECHMO) Development; 3) The Performance Forecasting Model (PERFORMO) Development; 4) Cost-Benefit Forecasting Framework Development and 5) Industrial Verification and Validation, with each detailed as follows.

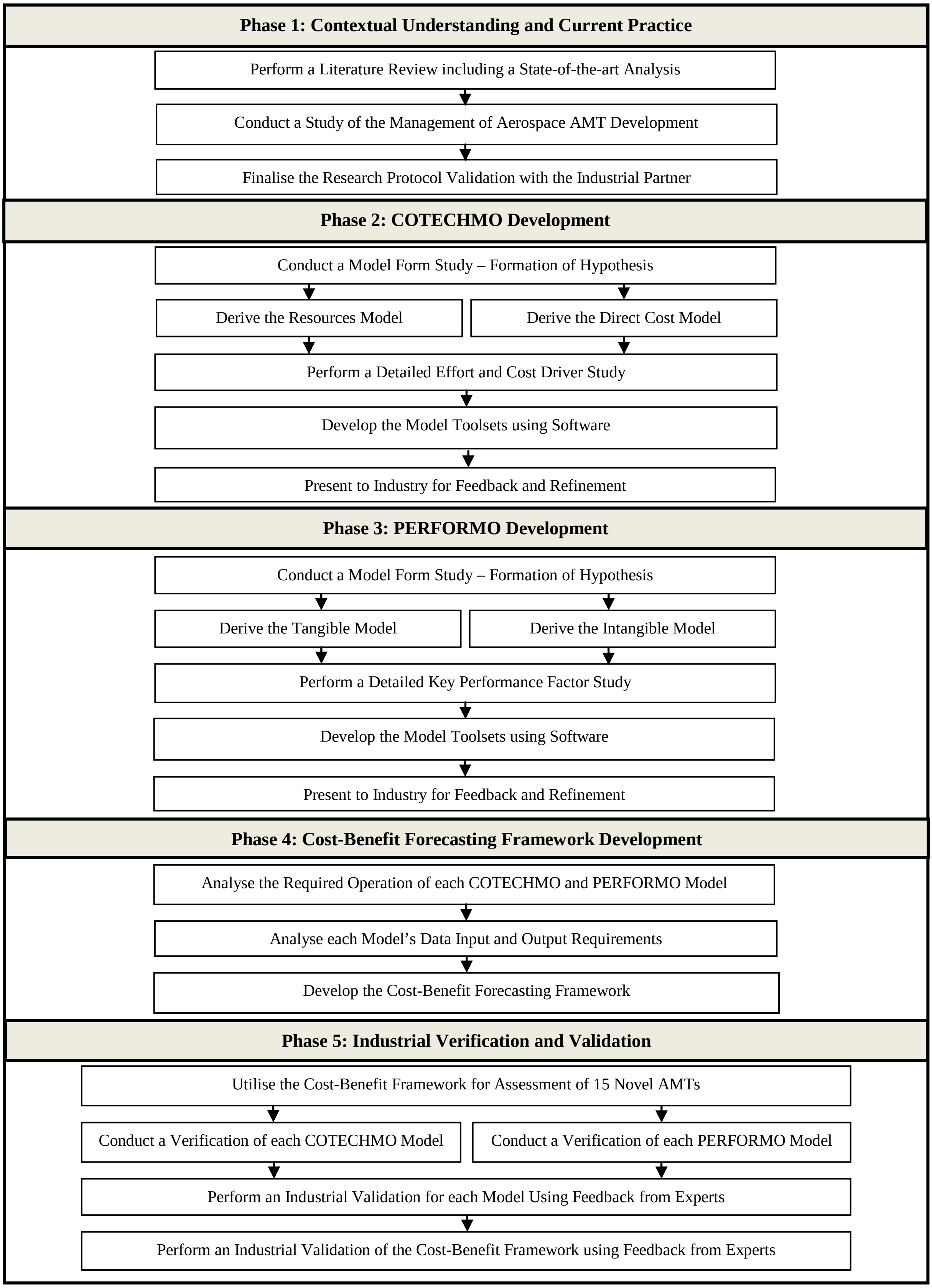

Figure 3-2 Research Methodology Adopted

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

The first step of this research Phase was to perform an extensive literature review and evaluate existing management of Advanced Manufacturing Technology (AMT), development cost estimation and performance forecasting techniques. From the lack of understanding within this review, detailed state-of-the-art analysis was performed on manufacturing research centres and institutions. This clarified the lack of standards available for this research.

From the insufficient understating presented in the existing body of literature, the next step involved performing a detailed study of existing techniques used within the aerospace manufacturing industry. The study was performed within large aerospace manufacturing organisations and state-of-the-art research centres, using a series of interviews and a review of internal documentation. This identified a lack of existing techniques within industry capable of managing AMT development and justifying the required R&T investment. Expert opinion was currently used for estimating AMT development effort and forecasting the performance, creating subjective and inconsistent results. The analysis was then used to design a new management of aerospace AMT development process map, piloted by the industry requirements. This formed the final research protocol and was validated with the industrial partner.

- **Phase 2: COTECHMO Development**

The validated research protocol identified the need for a cost estimation technique, capable of estimating the AMT non-recurring development effort to TRL6, in the form of resources (person-hours) and direct (hardware) cost. This Phase involved the development of two parametric ‘Constructive Technology Development Cost Models’ (COTECHMO).

The first step of the model development involved defining the detailed requirements. These were formed using semi-structured interviews with 18 experts from a large aerospace manufacturing organisation and 3 from outside. Cost estimation experts were selected and presented these detailed requirements, information and data available. This information and the cost experts were used to define a suitable approach and resolve the cost estimation problem. This formed an initial hypothesis and created the platform to perform a detailed driver study. This initially involved semi-structured interviews with 26 experts. A questionnaire was developed and piloted by industry and cost estimation experts, to finalise the drivers for each model and their qualitative rating descriptions. A two stage Wideband Delphi study was performed to reach consensus among 20 experts for the quantitative driver weightings. The final model forms, driver descriptions and weightings were used to build the two MS Excel COTECHMO models. These were enhanced using the feedback from an industrial partner. This provided the platform to verify and validate each model's statistical significance using data from a large aerospace manufacturer, discussed in Phase 5.

- **Phase 3: PERFORMO Development**

The validated research protocol defined in Phase 1 formed the requirements for a forecasting technique capable of predicting the tangible and intangible performance of diverse AMTs, at the initial stages of development. This Phase of the research responded with the development of two Performance Forecasting Model's (PERFORMO).

Determining detailed model requirements was the first step of model development. This was performed using semi-structured interviews with 17 experts from the aerospace manufacturing industry and 2 from outside. Decision making and performance evaluation experts were selected and presented the detailed requirements and the AMT information available at the initial development stages. Experts helped to define a suitable approach to resolve the performance forecasting problem, forming an initial hypothesis. These two separate models were used to perform a detailed Key Performance Factor (KPF) study. The first aspect of this study involved individual semi-structured interviews with 14 AMT development experts, to define KPFs. These were collated into a questionnaire to finalise KPFs for each model, collecting the responses from 13 experts. Qualitative ratings were finalised for the PERFORMO Intangible model using 9 AMT development experts.

The defined model forms, KPFs and Intangible model qualitative ratings were used to develop two MS Excel PERFORMO models. These were presented to an industrial partner and modified based on their feedback. The final models then formed the platform to perform verification and validation, detailed in Phase 5.

- **Phase 4: Cost-Benefit Forecasting Framework Development**

To acknowledge the industrial requirements categorised in Phase 1, each COTECHMO and PERFORMO model must be operated within an industrial setting and provide overall development value. This output must define which AMTs provide the business with the best development value, at the initial stages of development. To plot outputs from each model, the operation of each was fully documented including model calibrations. This formed the platform to create a detailed framework suitable for use within the assigned industrial setting. The final Cost-Benefit Forecasting Framework was then ready for the industrial verification and validation, discussed in the following Phase.

- **Phase 5: Industrial Verification and Validation**

Phase 5 performed a detailed industrial verification and validation of COTECHMO discussed in Phase 2, PERFORMO in Phase 3 and the Cost-Benefit Forecasting Framework in Phase 4. This defined if each aspect fulfilled the industrial requirements specified in Phase 1.

The first step involved an empirical case study with 15 novel AMTs within a large aerospace manufacturing organisation. These AMTs were evaluated using each stage of the developed Cost-Benefit Forecasting Framework with 10 AMT development experts. This produced final Development Value (DEVAL) outputs, identifying which AMT(s) provided the business with the best development value, forming an initial verification.

To systematically verify the framework's key aspects, each COTECHMO model was verified. To perform an initial verification of the COTECHMO Resources and Direct Cost models, the CER forecasting accuracy of each model was tested using PRED (Prediction Level) values. The industrial specification required the data to fall within PRED(20). A PRED(20) value specifies the forecast data to fall within 20% of the actual value. To further verify, statistical tests were performed on each model. This included a model significance *F*-test and a driver sensitivity analysis using *t*-values and *p*-values. From the limited AMTs available, each model was tested in reduced form.

The data from the 15 AMTs within the empirical study was used to verify each COTECHMO model. These AMTs were still within an aerospace manufacturing organisation R&T department and were not fully implemented within manufacturing operations. To verify each PERFORMO model, 8 AMTs with known conclusions were selected; 5 had been successfully implemented within manufacturing operations and 3 were unsuccessful. The 5 successful AMTs were ranked based on their actual data within operations. The

PERFORMO Tangible and Intangible models were used to forecast the performance. The forecast performance outputs from each model were checked for correlation with the ranking from the actual operations data.

The statistical verification discussed previously is a quantitative form of validation. The Cost-Benefit Forecasting Framework is aimed at an industrial practical environment. To further validate within the industrial setting, a questionnaire was developed for assessment of each COTECHMO and PERFORMO model. These questionnaires were tailored for evaluation of the Cost-Benefit Forecasting Framework, including the development value advice outputs and the overall operation. Each of these questionnaires used three applicability criteria proposed by Platts, Walter and Gregory (1990). This was successfully utilised by Evans, Lohse and Summers (2013) within the manufacturing domain including: feasibility, usability and utility. Feasibility defines if users can follow the methodology, usability determines if it’s easily followed and utility studies the output. The 10 AMT industrial experts who operated each model and the Cost-Benefit Forecasting Framework were asked to rank the detailed questions under each category. This provided validation of each model and the overall framework within its assigned industrial setting.

3.5 Summary

This Chapter has defined the research objectives. To acknowledge, the suitable research methods were reviewed and analysed for selection of the most suitable approach. The research methodology was then discussed in detail, including the granularity within each of the 5 Phases. These aim to structure the research and develop a suitable solution for the industrial application.

The following Chapter conducts a study into the management of aerospace AMT development, aiming to understand existing practice in R&T investment justification and allocation.

CHAPTER 4

A STUDY OF THE MANAGEMENT OF AEROSPACE ADVANCED MANUFACTURING TECHNOLOGY DEVELOPMENT

4.1 Introduction

A review of the literature, presented in Chapter 2, identified a lack of understanding how the aerospace manufacturing industry manages Advanced Manufacturing Technology (AMT) developments and justifies the required Research and Technology (R&T) investment to mature. This Chapter presents a detailed study into existing techniques used within the aerospace manufacturing industry. Each study was performed within large aerospace manufacturing organisations and state-of-the-art research centres, using a series of interviews and a review of internal documentation. The study uses the detailed industry analysis to design a new management of aerospace AMT development process map with the requirements identified. This forms the final research protocol and is validated by industry.

Section 4.2 presents the detailed research methodology followed for each stage of the study. The existing industrial process to manage AMT development at the early stages of development is presented in Section 4.3. Section 4.4 studies AMT development cost estimation techniques used at the initial stages of development. This is specifically aligned to Readiness Levels and assesses existing commercially available cost estimation software packages. In Section 4.5 performance forecasting techniques used at the initial stages of AMT development are studied and evaluated. Section 4.6 presents the proposed Management of Aerospace AMT Development Process Map. To conclude, Section 4.7 presents the Chapter summary and key observations.

4.2 Detailed Research Methodology

4.2.1 Detailed Research Methodology to Study the Management of Aerospace Advanced Manufacturing Technology Development

To determine existing practice in the management of AMT development within the aerospace manufacturing industry, a detailed research methodology was developed and is outlined in Figure 4-1.

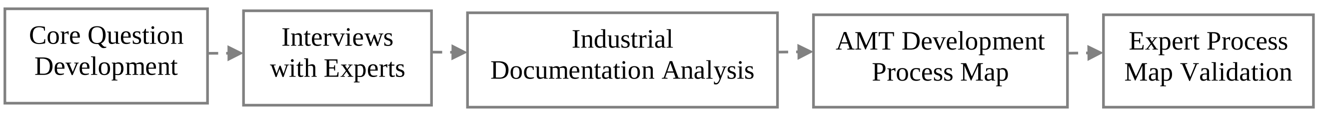

Figure 4-1 Detailed Research Methodology to Study the Management of Aerospace Advanced Manufacturing Technology Development

The first step involved the development of a questionnaire to understand existing practice in the management of AMT development, with the core questions presented in Table 4-1. The purpose of asking core questions was to understand the existing process flow using the experts listed in Appendix A.1, Table A1-1. Many of the experts presented industrial documentation to further explain the process and its mapping. This information was analysed after the interviews, to provide a full understating of the AMT development. The process map was drawn into an overview and presented back to the experts involved. This provided initial validation and presented any additional information to support the analysis, adjusting where required. The final AMT development process map with a detailed explanation of each stage is presented in Section 4.3.

Table 4-1 Core Questions to Study the Management of Aerospace Advanced Manufacturing Technology Development

Background Questions
What is your position and responsibility within the company?
What is your experience and background?
What level of exposure have you had in the development of new AMTs?
What other areas have you worked in?
Management of AMT Development
Describe the stages of AMT development within R&T?
What are the objectives within each stage?
How are the stages managed?
How is the budget allocated?
How are the manufacturing requirements formed?
How is the internal/external research capability selected?
How is the most suitable development expert selected?
How is the TRL used for planning of development?
What level of TRL is used within R&T?
How is the development cost estimated?
How is the performance forecast at the initial development stages?
Is there a value analysis performed to select the AMT providing the business with the best value?
How are AMTs delivered as a solution?

4.2.2 Detailed Research Methodology to Study Development Cost Estimation of Advanced Manufacturing Technology

From the detailed evaluation of the literature, cost estimation for the development of AMTs has had limited exploration. Therefore, a detailed evaluation was performed to identify how the aerospace manufacturing industry estimate AMT development cost using the detailed research methodology outlined in Figure 4-2.

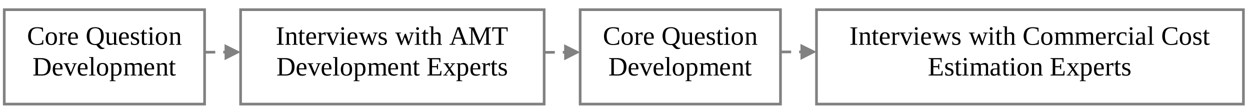

Figure 4-2 Detailed Research Methodology to Study Development Cost Estimation of Advanced Manufacturing Technology

A specific alignment was aimed at using the TRL, or equivalent, for the planning and estimating of cost, schedule and resources. A set of key core questions was developed with each listed in Table 4-2 and used to interview the experts from industry, listed in Appendix A.1, Table A1-2. The final cost estimation analysis of the aerospace manufacturing industry is presented in Section 4.4.

Table 4-2 Core Questions to Study Development Cost Estimation of Advanced Manufacturing Technology

Background Questions
What is your position and responsibility within the company?
What is your experience and background?
What level of exposure have you had in the development cost estimation of new AMTs?
What other areas have you worked in?
AMT Development Cost Estimation Process
Resources (person-months)
How do you estimate the development resources (person-months) at the initial stages of development?
Is the development team skill-set taken into consideration?
Is schedule taken into consideration for the estimate?
What cost drivers do you use?
Do you use a work breakdown structure?
How is the TRL used within the estimate?
What cost estimation techniques do you use?
Do you consider historical cases?
Is there a TRL historical database?
What is the expected accuracy?
Is there a known accuracy?
What are the limitations of the existing technique?
Direct (Hardware) Cost
How do you estimate the development hardware cost at the initial stages of development?
Do you use a work breakdown structure?
How is the TRL used within the estimate?
What cost estimation techniques do you use?
Do you consider historical cases?
What cost drivers do you use?
Is there a TRL historical database?
What is the expected accuracy?
Is there a known accuracy?
What are the limitations of the existing technique?

The industrial analysis identified that some areas of the manufacturing industry use commercially available cost estimation toolsets. To understand where these have been used and if they are applicable to AMT development, experts from commercially available cost estimation companies were interviewed. The core questions listed in Table 4-3 were asked to each of the experts listed in Appendix A.1, Table A1-3. To provide a detailed understanding, the software packages were evaluated with the experts presenting their software packages and the relevant characteristics. The output from this commercial cost estimation analysis is presented in Section 4.4.

Table 4-3 Core Questions to Determine Current Practice in Commercial Cost Estimation of AMT Development

Background Questions
What is your position and responsibility within the company?
What is your experience and background?
What level of exposure have you had in the development of new AMTs?
AMT Development Cost Estimation
Can you use your software toolsets to estimate AMT development person-months?
Can you use your software toolsets to estimate AMT development hardware cost?
What techniques are used within the toolset?
Is the TRL used as a factor?
How have these toolsets been previously aligned within the aerospace manufacturing industry?
What is the expected accuracy?
How are they calibrated?
What is their flexibility for the target application?

4.2.3 Detailed Research Methodology to Study Performance Forecasting of Advanced Manufacturing Technology at the Initial Stages of Development

Despite the availability of toolsets and techniques to forecast AMT performance, the existing body of literature identified a lack of techniques capable of quantifying performance at the initial development stages. At this stage, technological and development uncertainty is high, with an example aligned to the TRL presented in Chapter 2, Figure 2-6. From this limitation, a detailed analysis of how industry currently quantifies performance at the initial stages of development was conducted using the research methodology outlined in Figure 4-3. The first stage of this analysis involved the development of a questionnaire, with the core question listed in Table 4-4. Experts listed in Appendix A.1, Table A1-4 were interviewed with the final responses presented in Section 4.5.

Figure 4-3 Detailed Research Methodology to Study Performance Forecasting of Advanced Manufacturing Technology at the Initial Stages of Development

4.2.4 Detailed Research Methodology for the Design of an Enhanced Management of Advanced Manufacturing Technology Development Process

From the detailed evaluation of the literature and industry, a new management of AMT development process map was designed using the research methodology outlined in Figure 4-4. To validate, the new AMT development process map was presented to the experts listed in Appendix A.1, Table A1-5. This formed the finalised research protocol to meet the industrial requirements and provide the platform to structure the research. The final developed process map is illustrated in Figure 4-6, with each stage detailed in Section 4.6.

Figure 4-4 Detailed Research Methodology for the Design of an Enhanced Management of Advanced Manufacturing Technology Development Process

Table 4-4 Core Questions to Study Performance Forecasting of Advanced Manufacturing Technology at the Initial Stages of Development

Background Questions
What is your position and responsibility within the company?
What is your experience and background?
What level of exposure have you had in performance forecasting of new AMTs?
What other areas have you worked in?
AMT Performance Forecasting Process
How do you estimate the tangible performance at the initial stages of development?
How do you estimate the intangible performance at the initial stages of development?
Are these quantified outputs?
How do you compare diverse AMTs?
How do you capture uncertainty?
What metrics do you use?
What key performance factors do you use?
Do you compare to a baseline?
How is the TRL used within the forecast?
What forecasting techniques do you use?
Are historical trends taken into consideration?
Do you consider historical cases?
Is there a TRL historical database?
What is the expected accuracy?
Is there a known accuracy?
What are the limitations of the existing techniques?
What would be the most suitable breakdown for evaluation of AMTs?
How the performance is amended as the TRL maturity progresses?

4.3 A Study of the Management of Aerospace Advanced Manufacturing Technology Development

From the lack of understanding of how AMT development is managed within an R&T context, a study was conducted to define a detailed process map and the information flow. An overview of the existing AMT development process map is presented in Figure 4-5, derived from a focus of experts from 'Organisation A.' This large aerospace manufacturing organisation has a direct collaboration with state-of-the-art manufacturing research centres, with experts from each external research centre contributing and validating the top level process map. Each of the 8 stages is described in detail in the proceeding Sub Sections.

4.3.1 Stage 1 - Define Research and Technology Programme

The first aspect of managing a new AMT development is defining the R&T programme. The function of this process is to deliver the R&T plan and contracts, based on developing and maintaining a comprehensive R&T strategy, guided by a robust partnership and funding model. Key objectives of the R&T programme process include:

- Determine and maintain R&T Strategy:
    - Technology requirements and needs
    - R&T vision, goals and objectives
    - R&T Work Breakdown Structure (WBS) including risk and time bound budget
    - Internal/external partnerships
- Secure external funding
- Manage partnerships
- Define and maintain R&T plan:
    - Roadmap
    - Estimated budget plan over 5 years
    - Estimated cost of completion
    - Resource requirements
    - Risk assessment
    - Partnership elements
    - External funding elements

These objectives form a top level view for the R&T programme. AMT development becomes more specific to deliver solutions to the R&T programme from a manufacturing perspective. This forms the discussion point for the next stage.

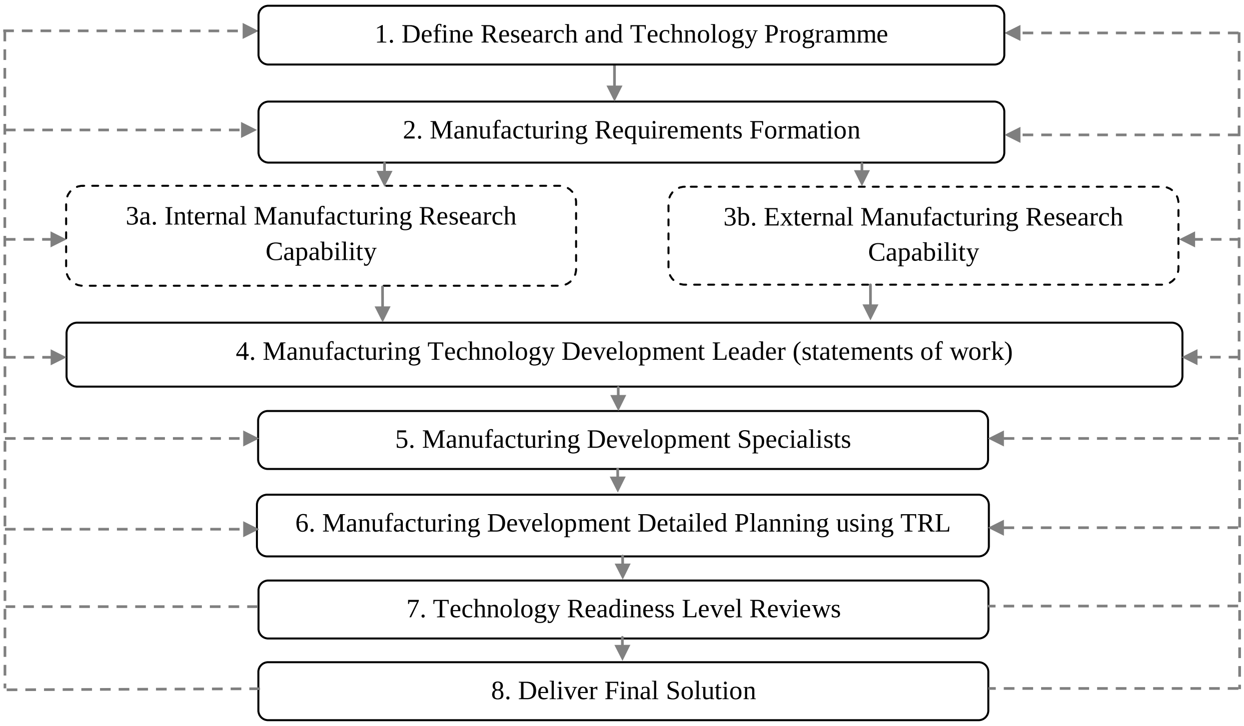

Figure 4-5 Eight Stages of the Management of Advanced Manufacturing Technology Development

4.3.2 Stage 2 - Manufacturing Requirements Formation

Manufacturing requirements formation is a subdivision within the R&T programme discussed previously and forms the manufacturing strategy. Within the aligned R&T programme, technologies are broken down into Technology Products and include Technological Streams. The R&T manufacturing division can sub feed into the Technological Streams to enable new designs, product generation or enhance existing operations. When evaluating from a general perspective, internal manufacturing customers typically feed into the following technology themes:

- Legacy technologies. This involves AMTs aimed at enhancement of existing operations. These are ‘pull’ technologies and don’t require architectural changes.
- Enabling technologies. These technologies enable manufacture where existing capability can’t function or perform in an efficient manner. A typical example would be the manufacture of a composite wing where existing technologies are not capable, requiring the development of an enabling technology.

- Disruptive technologies. Technologies that are disruptive are entirely new and allow for the manufacture of an exclusively new product, not suitable for implementation into existing manufacturing operations. An example could include technologies that form part of a new manufacturing philosophy to manufacture an entirely new wing structure.

Internal manufacturing customers from each of the above technology breakdowns form their specific detailed requirements. These requirements form the platform for alignment to the suitable internal or external research facility, with the appropriate resources and capability. This decision is based on expert judgement, typically of a manufacturing research manager. There can be multiple development research facilities aimed to meet the requirements at this stage.

4.3.3 Stage 3a and 3b - Internal/External Manufacturing Research Capability

Assignment of the manufacturing research to achieve the manufacturing requirements is based on evaluation of internal and external manufacturing research capability. If there is not capability of resources and manufacturing development facilities internally, the research is proposed to an external manufacturing research institution or centre. Typical research centres were a discussion point presented in Chapter 2, Section 2.5. The external manufacturing research capabilities are aligned with an internal manufacturing technology development leader, discussed in the following stage.

4.3.4 Stage 4 - Manufacturing Technology Development Leader (statements of work)

A manufacturing technology development leader is assigned at this stage to lead the development and if required, form collaboration with the external research institution or centre. Either way, this technology development leader takes control of overseeing the development and the best approach to meet the desired customer requirements. At this stage, selection of the AMT is created using expert opinion and is highly subjective. Despite there being a broad breakdown of resources, costs and schedule, each is not broken down using the TRL and are allocated using expert opinion. Furthermore, performance at this stage is estimated using expert opinion and at best case, estimating an economic business case if the technology were developed successfully.

4.3.5 Stage 5 - Assigning Manufacturing Development Specialists

The manufacturing technology development leader assigns a manufacturing development specialist to take ownership of the technology development. This is normally a specialist in the assigned manufacturing development field and where appropriate, collaborates with the external research institution or centre.

4.3.6 Stage 6 - Manufacturing Development Detailed Planning using TRL

The manufacturing development specialist is required to generate a detailed plan for development of the technology using the TRL. The estimates are required in the following format:

- Resources. Estimation of the resources in person-hours required to develop the technology for its direct application to full scale, TRL6, using the TRL for each incremental development stage. This is highly subjective and is fully based on the expert’s opinion, detailed and elaborated on in Section 4.4.
- Direct (Hardware) Cost. For the development of AMTs this is predicted by estimation of the hardware required to develop and prove the AMT at full scale, TRL6. This is estimated using expert opinion and where applicable, help is requested from the aligned external research institution or centre. Detail of how this estimate is performed is presented in Section 4.4.
- Performance Estimation. The performance is estimated from a perspective of time, cost or quality. These estimates are based on expert opinion and how the technology could potentially meet the specified manufacturing requirements. There is no modular toolset currently available for evaluation of diverse AMTs at the initial stages of development. A detailed evaluation of existing AMT performance forecasting techniques is presented in Section 4.6.

4.3.7 Stage 7 - Technology Readiness Level Reviews

Once the planning task is complete, the technology is matured using the TRL with the required investment and resources. This is a continuous approach with one TRL maturity gate typically achieved each year. The TRL within R&T operates from TRL1-6. At each TRL gate the technology can be deemed unsuccessful based on its predicted value to the business from the evaluation of an expert panel. TRLs were presented in detail within Chapter 2, Sub Section 2.2.3.

4.3.8 Stage 8 - Deliver Final Solution

If a technology is successfully developed and matured through R&T from TRL1-6, the internal customer decides whether to invest and implement the technology into its assigned manufacturing application. Within the aerospace manufacturing industry, this is regarded as the technology handover. At this stage a fully detailed business case is required and the cost of investment in the AMT hardware and implementation. This is created using a CapEX, a capital expenditure business case. This can require the hardware and implementation cost to be paid back in two years for legacy applications.

4.4 A Study of Development Cost Estimation of Advanced Manufacturing Technology

4.4.1 Interviews with Advanced Manufacturing Technology Development Experts

The focus of the first stage of the cost estimation study is to understand exactly how development experts estimate the development resources (person-hours) and direct (hardware) cost. This level of granularity is required at stage 6 of the process map illustrated in Figure 4-4. From the detailed analysis of the process map and the information flow within, from stages 1-5, estimation is vague and imprecise and based on brief statements of work and not broken down using the TRL.

- Resources

The first stage involved understanding how each expert currently estimates the AMT development resources (person-hours) at the initial stages of development. The first step involved the development specialist identifying who and how many people are involved in the development. A schedule was then allocated for each TRL per quarter, with experts identifying that a typical development would take 1 year for a TRL maturity gate. The schedule was estimated based on expert judgement and alignment to meet the development requirements within the R&T programme. Following this, a Work Breakdown Structure (WBS) was formed and consisted of the tasks broken down for each TRL gate, assigning the development team using person-hours. This was based entirely on expert judgement and made little reference to the development team skill-set. On completion of these tasks, a final estimate was generated for each TRL gate. For the purpose of this estimate within the R&T programme, the estimate is required to TRL6, the level an AMT is handed over to manufacturing engineering for full implementation.

Experts identified that they did not consider historical development cases, although they did make reference to a TRL schedule nominal value of 1 year per TRL gate. Experts noted a key point in the existing technique from having a poor accuracy of ± 65% and with a lack of a TRL historical database, mistakes are typically replicated. In summary, there is no constructive technique to estimate the development resources in person-hours and the existing process relies on the opinion of experts, creating subjective and inconsistent results.

- Direct (Hardware) Cost

The second stage involved identifying how experts estimate the development direct (hardware) cost to prove an AMT at full scale demonstration, TRL6. The first step defined the required equipment to assess the AMT process. This was then listed into a WBS and assigned to the requirements of each TRL gate. If the development was performed in collaboration with a research centre, they helped to estimate the price of the hardware. Industrial experts identified that there was little reference made to historical development cost for the estimate. TRL4 was identified as a crucial task requiring full scale equipment to demonstrate. Following the resources estimate discussed previously, experts identified there is currently no constructive technique to estimate development hardware cost. Experts identified that the current cost estimation technique has accuracies of ± 80% and following the resource estimation analysis, from the lack of historical data capture, accuracy is not likely to refine. To summarise, this cost estimation process relies entirely on expert opinion and is inaccurate with minimal repeatability.

4.4.2 Interviews with Commercial Cost Estimation Experts

When interviewing experts within the aerospace manufacturing industry, many made reference to commercial cost estimation packages, namely from Trueplanner by PRICE® Systems and SEER® by Galorath Incorporated. To review these toolsets and their suitability for the assigned AMT development estimation application, experts from each company were interviewed. Each company had resource and hardware estimation software packages. The development resource and hardware cost estimation toolsets were not a primary focus of each and were only an allocation of the overall manufacturing lifecycle cost. Furthermore, each did not align to the TRL for manufacturing development and only had this as an ‘add on’ feature within the WBS, requiring the user to input manually. Each company was keen to collaborate and aim to resolve the AMT development cost estimation problem, stating they believed the parametric approach was most suited.

4.5 A Study of Performance Forecasting of Advanced Manufacturing Technology at the Initial Stages of Development

The primary focus of this study is to understand how industry forecasts the performance of novel AMTs at the initial stages of development, to assign the required R&T investment to mature through the TRL gates. At this stage of development, experts can be required to provide a general business case if the AMT was developed successfully. This business case is formed using expert opinion and is based entirely on tangible perspectives. Within the business these tangible factors feed into time, cost and quality. A key economic factor used for assessment in legacy technologies is the recurring cost and requires the technology to be paid back within two years after implementation. Nevertheless, this analysis is highly subjective at the initial stages of development and is based entirely on expert opinion from an assigned baseline. Legacy technologies normally have target baseline data available. Enabling and disruptive technologies don't normally have a conceptual application baseline; hence, quantified outputs at the initial development stages have higher levels of uncertainty when compared to legacy applications and are inherently subjective. Intangible performance enhancements were identified as problematic from not feeding into the time, cost and quality format. AMTs can be driven by intangible metrics and are extremely difficult to justify R&T investment at the initial development stages. These are predominantly estimated using expert opinion.

There is an economic assessment technique available when an AMT has already entered in the TRL. This evaluation is called Technology Value Analysis (TeVA) and evaluates the technology at the maturity gates using an economic 'Tangible' Net Present Value (NPV) analysis. Data is required of a detailed target application with a baseline; something more suited to the legacy technologies and not suited to the initial stages of development. In summary, there are no existing toolsets within the aerospace manufacturing industry capable of forecasting the tangible and intangible performance of novel AMTs at the early stages of development. The existing approaches are based on expert opinion or economic analysis and are highly subjective.

4.6 Design of an Enhanced Management of Advanced Manufacturing Technology Development Process

The detailed analysis of existing AMT development management, cost estimation and performance forecasting identified the problems with the current techniques used within R&T of the aerospace manufacturing industry. A new process map was designed for the management of AMT development and is illustrated in Figure 4-6.

Stages coloured red indicate an enhanced aspect of the existing process map, described earlier in Section 4.3. The enhanced stages are discussed in the proceeding Sub Sections.

4.6.1 Stage 3a - Development Cost Estimation

Section 4.3 identified that there is currently no suitable cost estimation toolsets for the estimation of development resources and hardware costs of AMTs within industry and commercial software packages. Therefore, experts defined that a toolset capable of estimating the development resources (person-hours) and hardware cost with an accuracy of ±20% would extensively enhance the existing R&T manufacturing development process. For this toolset to be effective it must be capable of estimating development resources in person-hours and direct (hardware) cost of diverse AMTs with varied applications.

4.6.2 Stage3b - Performance Forecast

From the lack of performance forecasting toolsets for the initial stages of development identified within Section 4.4, experts determined that quantification of the performance from ‘Tangible’ and ‘Intangible’ perspectives would advance AMT selection. Following the cost estimation requirements, the toolset must be capable of quantifying tangible and intangible performance for a diverse range of AMTs at the early stages of development. Experts clarified how quantification of each would reduce the risk of developing novel AMTs and help select the most suitable to align with the specified manufacturing requirements.

4.6.3 Stage 4 - AMT Development Value

From the limited value analysis toolsets identified within the literature and industry, experts stated that plotting the estimated development resources and cost against the forecast tangible and intangible performances would generate an excellent assessment of R&T development value. This analysis then supports allocation of the required R&T investment within the R&T programme.

4.7 Summary and Key Observations

Section 4.2 provided a process map of the existing AMT development research process. The primary focus was on a large aerospace manufacturing organisation and alignment with manufacturing research centres, illustrated in Figure 4-4. Within stages 2 to 4 of this process map, the decision of the most suitable research capability, whether internal or external, is based entirely on expert opinion. This decision can become biased and often the technology with the best value to the business is not selected. At these early stages of the AMT development process, a detailed evaluation of the development effort in resources (person-hours) and direct (hardware) cost is not estimated using the TRL. This is not performed until stage 6 of the process map, where the technology manufacturing development specialist is required to generate a detailed development plan with expert opinion using the TRL. Following the estimated development resources (person-hours) and direct (hardware) cost, the performance is not fully estimated until stage 6 and uses subjective expert opinion. As development progresses, this performance is regularly incorrect and technology development is ceased after heavily investing in resources and cost to develop the AMT process. Additionally, many AMTs have 'Intangible' benefits driving the manufacturing development and are not selected from tangible assessments only evaluating economic parameters.

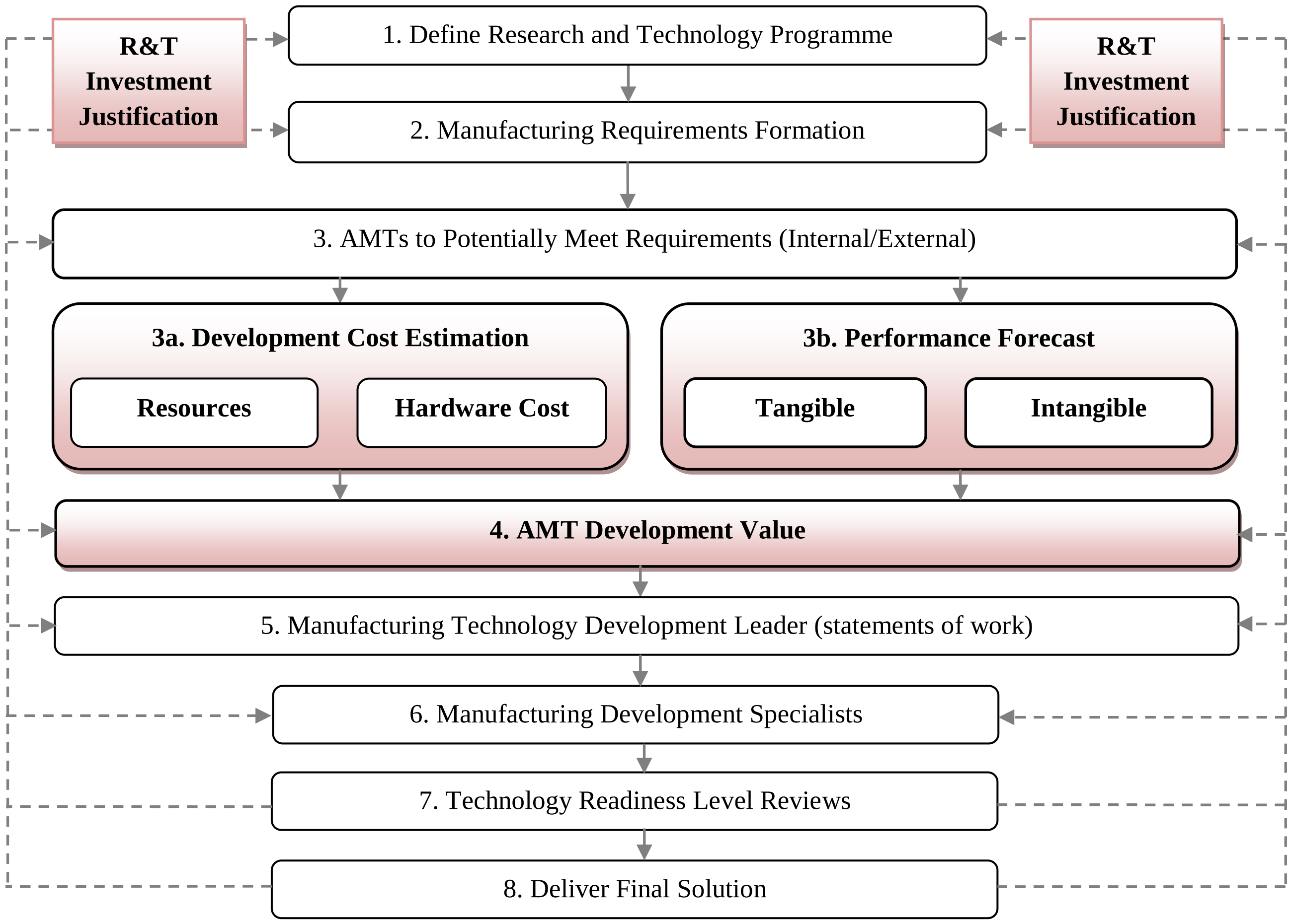

Figure 4-6 Enhanced Management of Advanced Manufacturing Technology Development Process

Section 4.6 presented a new design of the management of AMT development process map. The first requirement formed by industry was for the generation of two cost models. The first must be capable of estimating AMT development resources (person-hours). The second must be capable of estimating AMT development hardware cost. Each must be capable of forecasting to TRL6 and have an accuracy within 20% of the actual value, or Prediction Level PRED(20). Each must be capable of forecasting for a diverse range of AMTs. To respond to these requirements, Chapter 5 presents the development of two Constructive Technology Development Cost Models (COTECHMO).

Section 4.6 also detailed requirements for two performance forecasting models. The first must be capable of estimating tangible performance and the second intangible performance. Each must be capable of forecasting for a diverse range of AMTs. To respond, Chapter 6 presents the development of two Performance Forecasting Models (PERFORMO).

Experts identified that there is a lack of existing development value analysis toolsets. To justify R&T investment, plotting the development resources and cost against the tangible and intangible performance would provide an excellent development value assessment. This requires a systematic guide for users to follow and create the cost-benefit analysis. Chapter 7 presents a cost-benefit forecasting framework capable of fulfilling these industrial requirements. To prove the frameworks capability within an industrial setting and meet the detailed requirements, verification and validation within a large aerospace manufacturing organisation is presented in Chapter 8.

CHAPTER 5

THE CONSTRUCTIVE TECHNOLOGY DEVELOPMENT COST MODEL (COTECHMO)

5.1 Introduction

A review of the literature, presented in Chapter 2, identified a lack of systematic methodologies for estimating development effort (person-hours) and direct (hardware) cost for aerospace Advanced Manufacturing Technology (AMT), at the early development stages. Chapter 4 identified the current practice for forecasting AMT development effort and cost, with a focus on Research and Technology (R&T) of the aerospace manufacturing industry. This identified that industry use expert judgement for forecasting new AMT development effort and cost, creating subjective results with poor accuracy and repeatability. The analysis also acknowledged that enhancing the accuracy and repeatability of the existing AMT development estimation would strengthen the allocation and justification of the required R&T programme investment. In response, Chapter 4 developed a modified process map, illustrated in Figure 4-6. Aerospace manufacturing R&T divisions and research centres operate the Technology Readiness Level (TRL) for development of all AMTs. Despite the TRL structure being readily available, there is a lack of integration of this platform into forecasting development effort and cost.

This scenario has triggered an opportunity to develop two cost models capable of estimating AMT development effort and cost at the initial maturity stages. Therefore, this Chapter presents the development of two parametric 'Constructive Technology Development Cost Models' (COTECHMO). The first is the 'COTECHMO Resources' model that forecasts aerospace AMT development effort in person-hours. The second, the 'COTECHMO Direct Cost' model, is for forecasting the development cost in the form of aerospace AMT process hardware. Each model is capable of forecasting the R&T non-recurring development effort to TRL6, illustrated in Figure 5-1. At TRL6 the AMT must be proven at full scale and beyond TRL6 is transitioned from R&T for implementation into manufacturing. This requirement was detailed from the industry evaluation presented in Chapter 4.

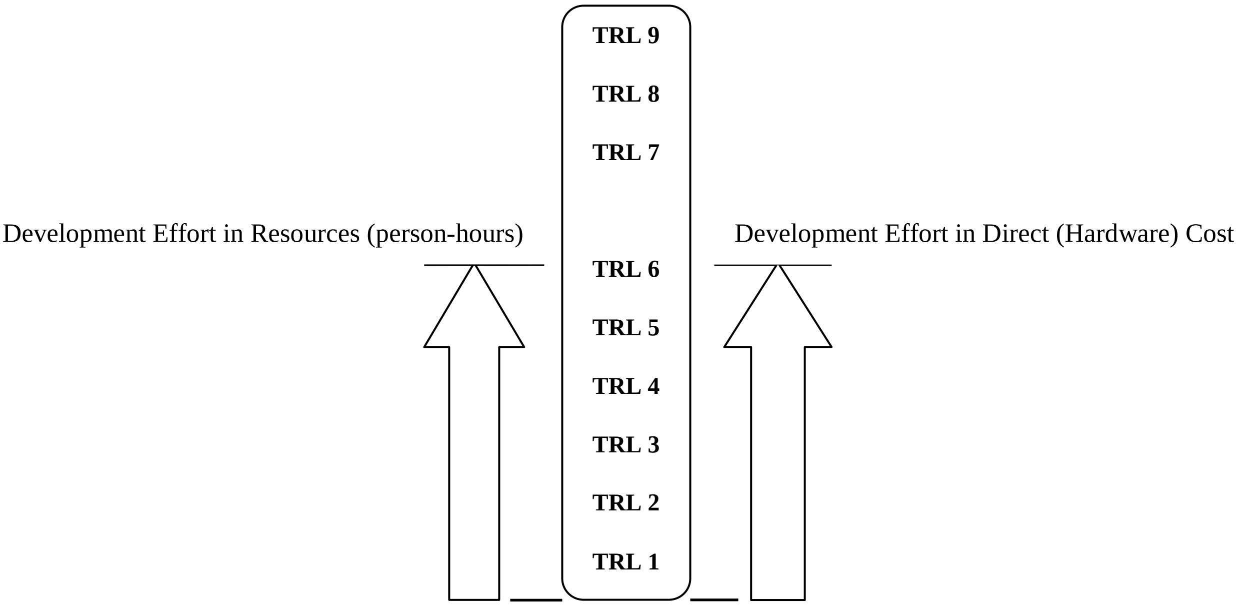

Figure 5-1 Development Effort and Cost TRL Alignment

Each COTECHMO model provides aerospace manufacturing R&T with the ability to forecast AMT development effort and cost at the conceptual stages, using the TRL as a data capture platform.

This Chapter is organised in the following structure. Section 5.2 describes the detailed research methodology used for the development of the two COTECHMO parametric cost models. Section 5.3 presents the results from the model requirements evaluation and Section 5.4 presents the final results from the COTECHMO model form study. Section 5.5 captures the results from the expert analysis to define size and effort drivers for the developed COTECHMO Resources model. Section 5.6 details the final results from the expert analysis to define the size and cost drivers for the COTECHMO Direct Cost model. Within Section 5.7, a detailed development structure was followed to create the two COTECHMO parametric forecasting models in MS Excel. The Chapter concludes in Section 5.8 with the summary and key observations.

5.2 Detailed Research Methodology

Figure 5-2 presents an overview of the research methodology used for the development of the two COTECHMO models. This feeds into Phase 2 of the overall research methodology presented in Chapter 3, Figure 3-2. The detailed research methodology was identified from the literature and subsequently initially validated with from AMT development and the cost estimation community.

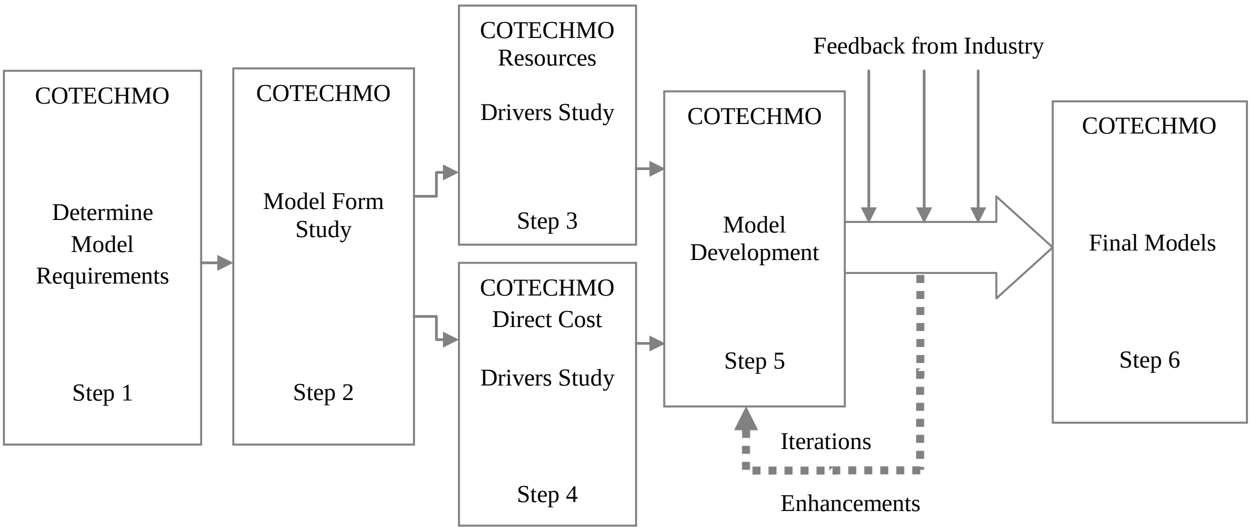

Figure 5-2 Detailed Research Methodology for COTECHMO Development

5.2.1 Detailed Research Methodology to Determine COTECHMO Model Requirements

Step 1 of the research methodology involved investigation of the industrial requirements and determined the model needs from each of the aerospace manufacturing organisations. This was performed using semi-structured interviews and industrial document analysis, detailed within Chapter 4. The evaluation provided a platform for the current cost estimation practice for aerospace AMT development, from a range of aerospace manufacturing companies and research institutions. A lack of resource and cost estimation processes, methods and models were identified for AMT development, forming the initial platform to determine the model requirements. These were formed using semi-structured interviews, with the duration of each averaging two hours. There were 18 experts selected from the aerospace manufacturing organisation and 3 from outside, although the experts from outside the organisation had a direct collaboration for AMT development. The experts were selected for their expertise in developing a range of aerospace AMTs and knowledge of the existing R&T development infrastructure. Each expert involved with determining the COTECHMO requirements is listed in Appendix A.2, Table A2-1, with the final model requirements presented in Section 5.3.

5.2.2 Detailed Research Methodology for COTECHMO Model Form Study

The COTECHMO requirements defined by experts in Step 1 of the detailed research methodology formed the model requirements from a manufacturing development perspective. Each of the AMT development experts involved with the initial requirements definition were not experienced in cost engineering and cost estimation. To fulfil this void and meet the model requirements, cost engineering and cost estimation experts were selected. These experts were selected for their expertise in cost engineering and cost estimation, having solved similar problems from different domains. The experts were used to help assist with the generation of an appropriate model form for each COTECHMO forecasting toolset. The cost estimation and cost engineering experts were presented with the detailed requirements specified for each model. This was carried out using brainstorm workshops and semi-structured interviews, by presenting the requirements, data and information available to develop each COTECHMO model.

Further networking and expert feedback was carried out by presenting the model requirements at leading conferences, industrial and academic institutions including: Association of Cost Engineers (ACostE), Society of Cost Analysis and Forecasting (SCAF), IEEE Aerospace Conference, Airbus Internal PhD Day, SAE Aerospace Conference and The University of Arizona. The final experts involved with the development of each COTECHMO equation form are listed in Appendix A2, Table A2-2.

To further validate the selected model forms for each parametric equation, the final equations were presented to the AMT development experts involved with determining the model requirements. The AMT development experts identified if they converged with the operational requirements. Further to this initial validation, each model form was presented at the Low Cost Manufacturing and Assembly of Composite and Hybrid Structures (LOCOMACHS) project launch meeting, including experts from a range of aerospace manufacturing fields. Feedback from each of the 21 industrial partners was excellent, with many interested in utilising each COTECHMO model for the project's cost and resource management

5.2.3 Detailed Research Methodology for COTECHMO Size, Effort and Cost Drivers Study

From the results of the model requirements and model form discussed previously in Step 1 and 2, a detailed study was conducted to identify size, cost and effort drivers for the COTECHMO Resources and Direct Cost model. This study is explained in the following Sub Sections.

5.2.3.1 Detailed Research Methodology for Size, Effort and Cost Driver Semi-structured Interviews

For the initial stage of the size, effort and cost drivers study, 26 AMT development experts were individually interviewed to initially define what drives effort and cost. Experts were asked to brainstorm, for AMTs they had developed, key drivers for the development effort in the form of person-hours (effort drivers) and Direct Cost (cost drivers), each to TRL6.

On completion of capturing the general cost and effort drivers, the model form was explained in more detail, identifying the functional size for the Resources model and the physical size for the Direct Cost model. Each was asked to identify if they thought any of their general cost and effort drivers fed into any of the size drivers. These were clustered into size and effort drivers for the Resources model and size and cost drivers for the Direct Cost model, with confirmation from the AMT development expert involved. This study was carried out with the selected 26 experts, with an average of 2.5 hours, totalling 65 hours. The final results from the AMT experts were compiled and evaluated with 4 cost estimation experts, totalling 85 years' experience. Many cost and effort drivers cross referenced and were similar in definition, so were collated into an overall list in the form of a questionnaire. This was used within the workshops, discussed in the following.

5.2.3.2 Detailed Research Methodology for Size, Effort and Cost Driver Workshops

From the compiled responses of the semi-structured interviews described previously, a questionnaire was developed to define a final set of cost, effort and size drivers for both the Resources and Direct Cost model.

Round 1 involved a detailed discussion of the questionnaires with 21 AMT development experts. This included the size, effort and cost drivers compiled from the semi-structured interviews discussed previously. These questionnaires were edited by adding the descriptions of the finalised drivers from the expert analysis and adding a rating scale, shown in Appendix A.3 and A.4. The rating scales were discussed and assigned descriptions with the experts, forming Round 2. Historical AMT development data was utilised where appropriate to identify a nominal case and help with the qualitative rating of each driver. This involved analysing past project development data and methodically running through each cost, effort and size driver for both models. This aspect was regarded as vital for the numerical weighting of each rating, defined within the Wideband Delphi study that follows. Inaccurate definitions and ambiguity for each rating could lead to highly subjective weightings, creating an inaccurate model.

5.2.3.3 Wideband Delphi Methodology for Size, Effort and Cost Drivers

The results of the semi-structured interviews and two workshops defined suitable circumstances for deploying the Wideband Delphi method. This method quantified the weightings for each size, cost and effort driver. The

Wideband Delphi method has been proven within the cost estimation domain as an accurate and reliable method for reaching group consensus, involving unquantifiable criteria and utilising experts from a range of knowledge fields (Valerdi, 2005 and 2011; Boehm et al., 2005). The fundamental aims and objectives of the Wideband Delphi study are:

- Agree consensus from a number of experts
- Identify the distribution for both development effort and cost, across the relevant categories
- Validate each driver within the model
- Assist with the model refinement

An overview of the Wideband Delphi study performed for each COTECHMO model size, effort and cost driver is presented in Figure 5-3.

The first aspect involved the development of a questionnaire for use within the first Round for each COTECHMO model. Each listed the finalised cost, effort and size drivers, aligned with their respective qualitative ratings. Appendix A.5 and A.6 detail the questionnaires used for each model, presented in edited form from Round 2 of the Wideband Delphi study, with inclusion of the mean weightings from Round 1. The questionnaire was initially validated with a research manager and 4 cost estimation experts. The cost estimation experts recommended the use of a scale ranging from ‘Very Low’ through to ‘Very High.’ Each of the cost estimation experts agreed that the cost and effort drivers for each model should be clustered into common themes, to make the assessment as logical as possible. A total of 21 AMT development experts engaged in Round 1 of the Wideband Delphi survey and the responses were evaluated. For this detailed evaluation, the mean value of the responses was calculated for each rating and aimed to reach consensus within ±10% of the mean. This was a recommendation made by the cost estimation experts involved with the model development, listed in Appendix A.2, Table A2-1.

The outcome from Round 1 was presented at a second Round, including 20 AMT development experts, of which 18 had participated in Round 1. The purpose of Round 2 was to try and reach consensus within the ±10% of the mean values provided from Round 1. The experience level in years for each AMT development expert is listed in Table 5-1. Each was asked to fill in the edited Round 1 questionnaires, shown in Appendix A.5 and A.6, either corroborating the results or correcting them. Consensus was reached after discussion, forming the final weightings used within the COTECHMO Resources and Direct Cost models, with the results presented later in Sub Sections 5.5.3 and 5.6.3.

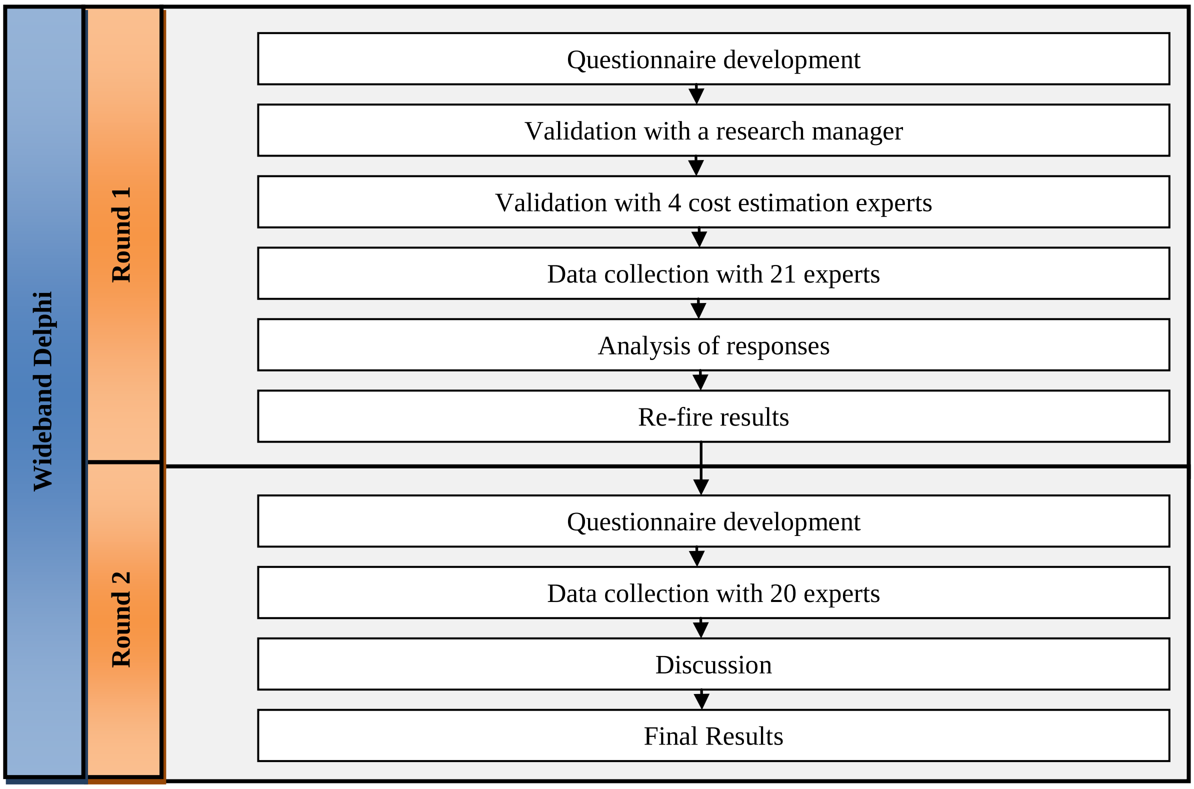

Figure 5-3 COTECHMO Size, Effort and Cost Drivers Wideband Delphi Study

5.2.4 Detailed Research Methodology for COTECHMO Model Development

For the development of each COTECHMO model a systematic methodology has been followed, with an overview illustrated in Figure 5-4. Phase 1 produced an in depth understanding of AMT development and its maturity assessment platforms, the varied types of AMTs and cost estimation. This created the requirements for each model development and the most appropriate equation form to solve the problem. A detailed study into the novel size, cost and effort drivers for AMT development completed Phase 1 of the study.

- Phase 2 involved the development of two prototype models, one to forecast AMT development resources in the form of person-hours and the other development direct (hardware) cost. Each model was developed in MS Excel and iteratively enhanced based on expert feedback. The final Phase involved quantitatively and qualitatively verifying and validating the developed models, detailed within Chapter 8.

Table 5-1 Expert Experience Level for Wideband Delphi Study

Round 1		**Round 2**	
Experience Level in Years	Number of Experts	Experience Level in Years	Number of Experts
< 5	8	< 5	8
5 - 9	5	5 - 9	4
10 - 19	6	10 - 19	6
20 - 29	1	20 - 29	1
30+	1	30+	1

5.3 COTECHMO Model Requirement Results

The experts listed in Appendix A.2, Table A2-1 defined the detailed industrial model requirements. Each expert identified the information available at the initial stages of development for an aerospace AMT and stated the need for two models. The first must be capable of estimating development resources in person-hours to TRL6, the second to estimate development direct (hardware) cost to TRL6. Each model will be utilised within an R&T function and must provide a robust forecasting process with the following requirements:

- Usability

Each forecasting model should be easy to use, with a clear user interface, utilising software already in operation within R&T of the aerospace manufacturing industry.

- Accuracy

Each model must be proven to have an accuracy of 20% of the actual data, termed PRED(20), for 10 or more diverse AMTs with varied applications.

- Calibration

The models must be capable of calibration as AMT historical development data increases and must retain, or enhance existing accuracy.

- Flexibility

Each model should be capable of forecasting development person-hours and hardware cost for a diverse range of AMTs within R&T.

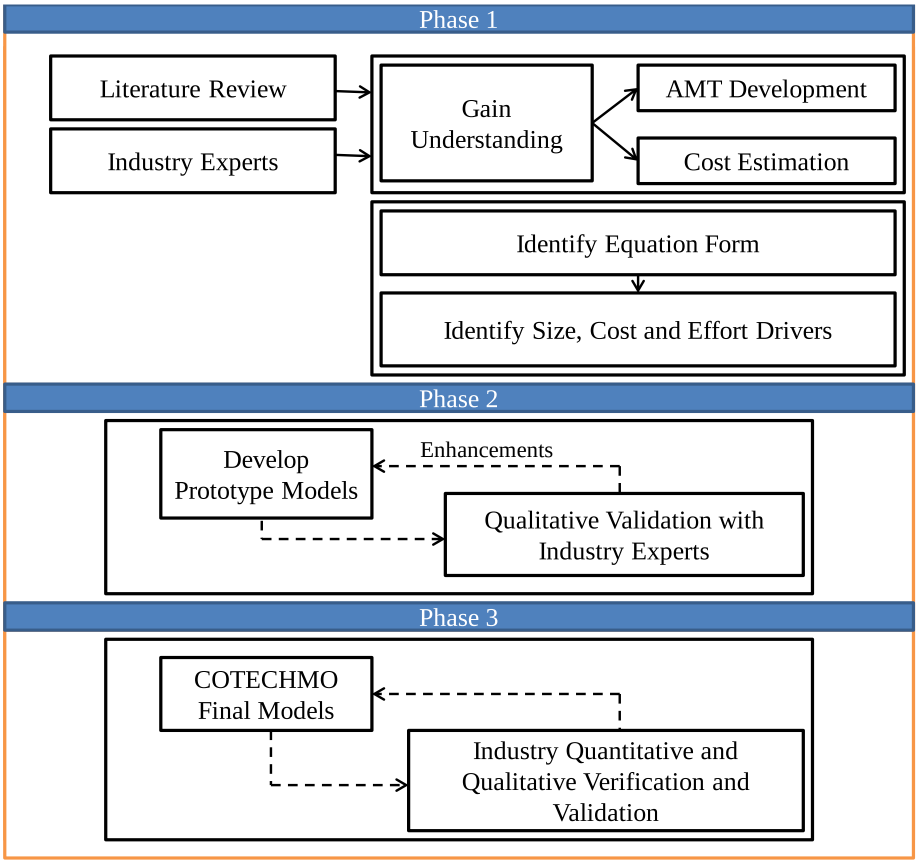

Figure 5-4 Research Methodology for COTECHMO Development, Verification and Validation

5.4 COTECHMO Model Form Study Results

The model requirements Section discussed previously has identified the need for two forecasting models. Using the experts listed in Appendix A.2, Table A2-2, a general model breakdown was developed. This categorises non-recurring development effort and cost to develop an AMT as a function of TRL, illustrated in Figure 5-5. The red area of the diagram relates to the COTECHMO Resources model and green the Direct Cost model. The diagram is for illustration purposes only and is not based on a scale.

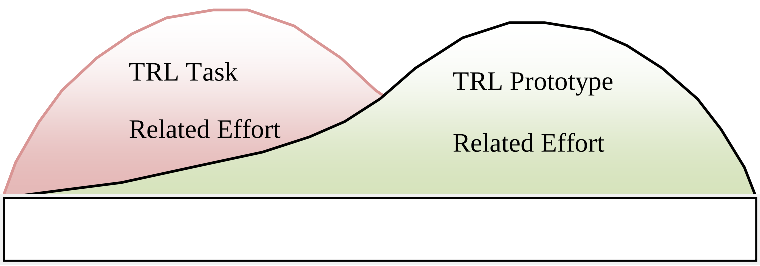

Figure 5-5 Non-recurring Development Effort as a Function of TRL

The ‘TRL Task Related Effort’ relates to the resources in person-hours required to develop the AMT and prove using the TRL development documentation. These resources have specific activities to prove the AMT and successfully progress through each TRL assessment. The COTECHMO Resources model estimates this development effort, with the final model mathematical notation presented within Sub Section 5.4.1.

The ‘TRL Prototype Related Effort’ is the cost of the hardware required to prove and demonstrate the AMT at full scale (TRL6). This is forecast with the COTECHMO Direct Cost model, derived and discussed in Sub Section 5.4.2.

5.4.1 COTECHMO Resources Derivation

The final COTECHMO Resources model form was developed in collaboration with the cost estimation/engineering experts listed in Appendix A.2, Table A2-2. The model forecasts development effort (person-hours) to prove an aerospace AMT at full scale for the direct application (TRL6).

When evaluating the overall COTECHMO Resources model Cost Estimating Relationship (CER), distinction must be made between the size and effort drivers, with full definitions presented later in Section 5.5. The two parameters defined within the model are: additive and multiplicative, introduced in Equation 5.1.

$$PH = A * (Size) * (EM) \qquad \text{(Eqn. 5.1)}$$

Where:

PH = person-hours (effort in resources)

A = calibration factor

Size = size drivers counting the AMT process functional size (additive)

EM = effort multipliers impacting AMT development effort (multiplicative)

Drivers feed into the size and effort aspects of the equation based on the following descriptions:

1. Factors that impact development effort in an additive form are additive. Adding a geometric requirement, process step or test piece has an additive impact on the AMT process development

functional size. An example would be adding 20 more nominal geometric requirements to a process with a total of 100, generating a 20% increase in functional size.

2. A factor is multiplicative if it impacts the entire AMT development in a multiplicative configuration. For example, reducing the requirements understanding to a 'Very Low' rating for the development team, with a process functional size of 100, would impact the overall development by 50%. Similarly, reducing the requirements understanding to the same level for a process with a functional size of 500, would also impact development effort by 50%.

Equation 5.2 is the final COTECHMO Resources Parametric CER and is broken down into three size drivers (predictors) and thirteen effort drivers (effort multipliers), with Figure 5-6 illustrating the overall operation of the model. The final list of drivers feeding into the model is presented in Section 5.5.

$$PH = A \cdot \left(\sum_{k} \omega_e \emptyset_e + \omega_n \emptyset_n + \omega_d \emptyset_d \right) \cdot \prod_{j=1}^{13} EM_j$$

Where: (Eqn.5.2)

PH = person-hours (effort in resources)

A = historical data calibration factor

k = number of geometric requirements, number of process steps, number of test pieces

ω = weight

e = easy

n = nominal

d = difficult

$\emptyset$ = size driver count. The final size drivers are listed in Table 5-35, with their relative rating and weightings.

EM_j = represent the effort multipliers, with each set to a nominal value of 1.0. The impact of an individual effort multiplier is the range of the highest to the lowest, indicated by the Effort Multiplier Ratio (EMR), listed in Table 5-37.

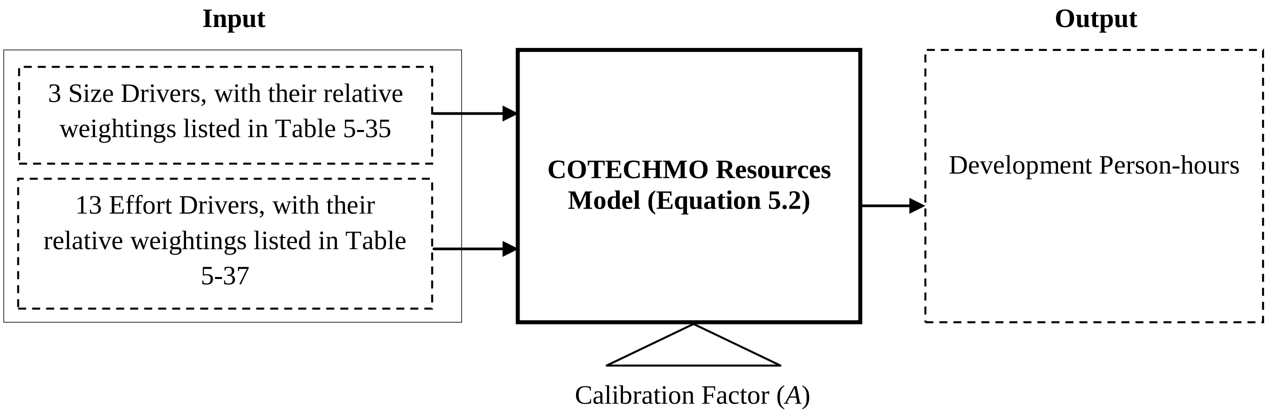

Figure 5-6 COTECHMO Resources Model Operation

5.4.2 COTECHMO Direct Cost Derivation

The final COTECHMO Direct Cost model form was developed in collaboration with the cost estimation/engineering experts listed earlier in Appendix A2, Table A2-2. The model forecasts development effort in direct (hardware) cost, to prove an aerospace AMT process at full scale for the direct application (TRL6). When evaluating the overall COTECHMO Direct Cost model CER, distinction must also be made between the size and cost drivers. The COTECHMO Direct Cost model's equation form is different to the Resources model. This model uses additive (physical size) and multiplicative (development complexity), shown in Equation 5.3.

$$DC = A * (Size) * (CM) \qquad \text{(Eqn. 5.3)}$$

Where:

DC = development cost (€)

A = calibration factor

Size = physical hardware size of the AMT process in volume (additive)

CM = cost multipliers that impact AMT development direct cost (multiplicative)

The equation form in this model uses size as a function of volume (physical), rather than the functional size (additive) used by the Resources model discussed previously. Equation 5.4 is the final COTECHMO Direct

Cost parametric CER and is broken down into one size driver (predictor) and thirteen cost drivers (cost multipliers), with Figure 5-7 showing the overall model operation.

$$DC = A \cdot (x, y, z) \cdot \prod_{j=1}^{13} CD_j$$

Where: (Eqn.5.4)

DC = development cost (€)

A = historical data calibration factor

x = width of the AMT process hardware

y = length of the AMT process hardware

z = height of AMT process hardware

CD_j = represent the cost multipliers, with each set to a nominal value of 1.0. The impact of an individual cost multiplier is the range of the highest to the lowest, indicated by the Cost Multiplier Ratio (CMR), listed in Table 5-65.

The Direct Cost model is broken down into the physical size of the AMT process hardware and thirteen cost drivers (cost multipliers), with the final results detailed in Section 5.6.

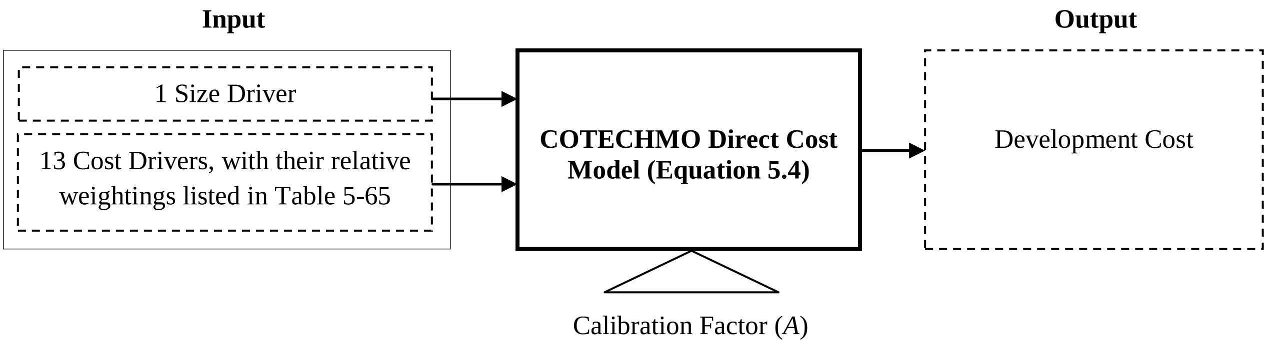

Figure 5-7 COTECHMO Direct Cost Model Operation

5.5 COTECHMO Resources Model Size and Effort Drivers Study Results

The COTECHMO Resources size and effort drivers feed into the CER presented in Equation 5.2. The proceeding Sub Sections are the final outputs from the detailed research methodology.

5.5.1 Resources Model Size Drivers

The size drivers were defined using semi-structured interviews and two rounds of workshops, described in Sub Sections 5.2.3.1 and 5.2.3.2. These finalised size drivers then feed into the two stage Wideband Delphi Study, with an overview presented earlier in Figure 5-3.

The size drivers form the additive part of the CER presented in Equation 5.2 and quantify the functional size of the AMT process for its assigned manufacturing application. Functional size is a technique widely used within software cost estimation and typically uses Application Points (AP), Software Lines of Code (SLOC) or Function Points (FP). These techniques allow the measuring and adjustment, based on the operating platform and language used. This technique was successfully adapted by Valerdi (2005) for application to systems engineering cost estimation. Using a similar approach to Valerdi (2005), this technique has been adapted for AMT development effort. The following size drivers were defined within this study: number of geometric requirements, number of process steps and number of test pieces. The three size drivers capture nine possible amalgamations of weight. Each of the size drivers are counted and adjusted based on the complexity of the requirement and have discrete weights, ω, categorising each of the requirement values as ‘easy,’ ‘nominal’ and ‘difficult.’ The quantities of each size driver, $\emptyset$, can have any value input, depending on the number of geometric requirements, number of process steps and number of test pieces. Weighting the sum of factors has similarity when compared to the software function technique, typically utilised within software cost models (Albrecht and Gaffney, 1983) and for application to systems engineering cost estimation (Valerdi, 2005). Logically speaking, the higher the complexity of the process requirement, the greater the assigned weight. Each size driver is listed in Tables 5-2 to 5-7, with elaboration on each definition to keep subjectivity to a minimum. The rating scales are included within each Table for the driver complexities, finalised from the semi-structured interviews and two workshops. The input requirements listed within Table 5-2 to 5-7 are quantitative parameters counted from the early development documentation at TRL1-2. When analysing such detail at the initial development stages, these sources may not be available in high levels of detail. In this scenario, surrogate sources of data are needed, with typical sources including data from similar AMT developments.

Table 5-2 Number of Geometric Requirements Definition

Number of Geometric Requirements The number of requirements taken from the AMT process customer specification. These can be quantified by counting the conceptual application documentation.

Table 5-3 Number of Geometric Requirements Rating Scale

Easy	Nominal	Difficult
- Lower geometric requirements than existing accuracy.	- Replicating existing geometric process accuracy.	- Higher than existing geometric process requirement accuracy.

Table 5-4 Number of Process Steps Definition

Number of Process Steps The number of process steps counted from the customer application specification to prove the AMT process at full scale, TRL6.

Table 5-5 Number of Process Steps Rating Scale

Easy	Nominal	Difficult
- Lower than existing process step complexity.	- Replicating existing process step complexity.	- Higher than existing process step complexity.

Table 5-6 Number of Test Pieces Definition

Number of Test Pieces The number of process steps counted from the customer application specification to prove the AMT process at full scale, TRL6.

Table 5-7 Number of Test Pieces Rating Scale

Easy	Nominal	Difficult
- Lower than existing test piece complexity.	- Replicating existing test piece complexity.	- Higher than existing test piece complexity.

5.5.2 Resources Model Effort Drivers

The final effort drivers were defined using semi-structured interviews and two rounds of workshops, following the detailed research methodology described in Sub Sections 5.2.3.1 and 5.2.3.2. These finalised effort drivers were then used in a Wideband Delphi study, with an overview presented earlier in Figure 5-3.

The effort drivers feed into the multiplicative part of the CER presented in Equation 5.2. From impacting the whole AMT development in a multiplicative configuration, these drivers are also referenced as effort multipliers. These drivers are qualitative, so assigning a rating is more challenging than the size drivers previously discussed. To help assist, each driver was placed into the following common themes:

- Development Team Factors. Drivers that capture the skill set and comprehension of the development team.
- Demonstration and Application Factors. Drivers that capture the complexity of the process and its target application.
- Project Factors. Drivers that capture the project requirements.
- Product Rate Factor. The driver that captures the required production rate of the assigned product.

The rating scales were defined by experts and included: Very Low, Low, Nominal, High and Very High. A rating of Nominal has no impact on the driver with an assigned multiplier value of 1.0. Weightings above and below 1.0 were assigned based on their individual polarity, defined within the two stage Wideband Delphi study, presented later in Sub Section 5.5.2. This polarity approach used within the Wideband Delphi method was defined by experts in the initial model form study, discussed in Section 5.4. For example, a development team ‘TRL pack experience’ driver set to ‘very low’ would multiply by 1.48. This indicates a 48% increase in development effort for that individual driver from the nominal value of 1.0.

5.5.2.1 Development Team Factors

The development team factors represent the skill set, knowledge and understanding of the team assigned to develop the AMT. For each of the development team drivers, a higher weighting creates a greater reduction in development person-hours. There are five development team factors with ‘Product Application Experience’ generating the greatest multiplicative impact.

Table 5-8 TRL Pack Experience Definition

TRL Pack Experience The level of familiarity of the development team from compiling successful Technology Readiness Level development (TRL) documents.

Table 5-9 TRL Pack Experience Rating Scale

Very Low	**Low**	**Nominal**	**High**	**Very High**
Completely unfamiliar with the TRL pack.	Familiar with the TRL pack from colleagues/suppliers/TRL reviews although not utilised for own development.	Utilised the TRL pack to successfully transition from one TRL gate to the next.	Successfully developed 1 development to TRL6.	Successfully complete > 1 development to TRL6.

Table 5-10 Product Application Experience Definition

Product Application Experience The level of product knowledge for the direct application e.g. understanding the existing aircraft manual sealant application to develop an automated manufacturing technology solution.

Table 5-11 Product Application Experience Rating Scale

Very Low	**Low**	**Nominal**	**High**	**Very High**
Unfamiliar with existing product manufacturing techniques.	Low level of understanding of existing product manufacturing techniques, many unfamiliar areas.	Fully familiar with existing product manufacturing.	Worked on the development of the existing product manufacturing.	Worked on the development and implementation of the existing product manufacturing.

Table 5-12 Process Experience Definition

Process Experience The level of experience of the development team in the manufacturing process domain e.g. direct automation development experience.

Table 5-13 Process Experience Rating Scale

Very Low	**Low**	**Nominal**	**High**	**Very High**
Unfamiliar with the process domain.	Low familiarity of the process domain.	Familiar with the process domain.	Worked on the development of a similar process.	Successfully developed and implemented a similar process.

Table 5-14 Requirements Understanding Definition

Requirements Understanding The understanding of the requirements from the direct customer e.g. automated drilling hole requirements for their exact product.

Table 5-15 Requirements Understanding Rating Scale

Very Low	**Low**	**Nominal**	**High**	**Very High**
Poor: no understanding of requirements.	Minimal: many undefined areas.	Reasonable: some undefined areas.	Strong: few undefined areas.	Full understanding and documentation of requirements.

Table 5-16 Supplier Network Availability and Capability Definition

Supplier Network Availability and Capability Manufacturing process supplier availability and capability to develop the process.

Table 5-17 Supplier Network Availability and Capability Rating Scale

Very Low	**Low**	**Nominal**	**High**	**Very High**
No experience of similar developments.	Low experience of similar developments.	Some experience of a similar development.	Delivered similar developments but with some guidance contact.	Fully proven within the domain and having delivered similar developments with minimal contact.

5.5.2.2 Demonstration and Application Factors

The demonstration and application factors represent the assigned application for the AMT process and the specified demonstration requirements from the direct customer. This is typically from the R&T programme or manufacturing operations. For each of the development team drivers, a lower weighting creates a greater reduction in development person-hours. The datum complexity driver does not comply with the 5 scale rating.

Table 5-18 Datum Complexity Definition

Datum Complexity
Complexity of datum(s) for the manufacturing process application.

Table 5-19 Datum Complexity Rating Scale

Nominal	**High**	**Very High**
Datum's with low access restrictions.	Very complex: datum's with minimal access.	Extremely complex: no datum access.

Table 5-20 Test Piece Material Complexity Definition

Test Piece Material Complexity
Complexity of the test piece material to prove the manufacturing process at full scale application.

Table 5-21 Test Piece Material Complexity Rating Scale

Very Low	**Low**	**Nominal**	**High**	**Very High**
Very low complexity: material fully proven for manufacture on existing product with selected process.	Low complexity: material proven in 2> same domain of aerospace manufacture with selected process.	Medium complexity: material implemented in 1> same domain of aerospace manufacture with selected process.	Very complex: limited development and implementation of a similar material with selected process.	Extremely complex: material completely novel and not been developed before with selected process.

Table 5-22 Installation Complexity Definition

Installation Complexity
Installation complexity of the manufacturing process to prove at full scale. A very complex process would consist of many automation equipment installations.

Table 5-23 Installation Complexity Rating Scale

Very Low	**Low**	**Nominal**	**High**	**Very High**
Complexity of very low levels: much lower than existing process implementation and existing developments.	Low complexity: complexity slightly lower than existing process installation procedure.	Moderately complex: installation procedure similar to existing process to replace.	Very complex: installation procedure exceeds existing process.	Extremely complex: installation procedure exceeds existing process installation and similar developments.

Table 5-24 Degree of Process Novelty Definition

Degree of Process Novelty
Manufacturing process novelty for the direct application, e.g. automated assembly process from an automotive plant, now developed using the TRL for the aerospace domain.

Table 5-25 Degree of Process Novelty Rating Scale

Very Low	**Low**	**Nominal**	**High**	**Very High**
Process developed, implemented and proven throughout the aerospace industry.	Process developed, implemented and proven within 3> non-aerospace domains.	Process developed, implemented and proven in 1> non-aerospace domain e.g. automotive manufacture.	Process developed to low level (TRL3-6) in 1> non-aerospace domain.	Process not proven or developed in any domain, completely novel.

5.5.2.3 Project Factors

The project factors represent the requirements, documentation and location of the overall development project. For the required development schedule and manufacturing documentation of requirements, a higher weighting generates a reduction in development person-hours. For the location and variation of trials and tests, a lower weighting generates a reduction in development person-hours.

Table 5-26 Required Development Schedule Definition

Required Development Schedule
Required delivery from the customer for the development and deployment of the manufacturing process, proven at full scale for the direct application (TRL6). Very low is an accelerated schedule (schedule compression) with very high having a development schedule slower than the nominal.

Table 5-27 Required Development Schedule Rating Scale

Very Low	**Low**	**Nominal**	**High**	**Very High**
≤ 6 months per TRL gate milestone.	≤ 9 months per TRL gate milestone.	≥ 12 months per TRL gate milestone.	≥ 18 months per TRL gate milestone.	≥ 24 months per TRL gate milestone.

Table 5-28 Manufacturing Documentation of Requirements Definition

Manufacturing Documentation of Requirements
Specific documentation by Manufacturing Engineering for the development enhancement. Legacy (existing) products are typically documented to a higher level when compared to future aircraft manufacture.

Table 5-29 Manufacturing Documentation of Requirements Rating Scale

Very Low	**Low**	**Nominal**	**High**	**Very High**
Completely novel product with no documentation of exact requirements.	Completely novel product with some documentation of exact requirements at TRL1-3.	Legacy product already in manufacture with levels of documentation planned to TRL4-6.	Legacy product already in manufacture with documentation planned to implementation at TRL7-9.	Legacy product already in manufacture with fully detailed documentation.

Table 5-30 Location Variation of Trails and Tests Definition

Location Variation of Trials and Tests Variation of the trials and tests through the development process, to prove the manufacturing process to full scale (TRL6).

Table 5-31 Location Variation of Trails and Tests Rating Scale

Very Low	Low	Nominal	High	Very High
No location variation of resources, research and testing all carried out in one place.	Location variation of research resources within the same research institution but with different locations over site/complex/institution.	Location variation of research resources within the same county/state.	Location variation of research resources within the same country.	Location variation of research resources outside the same country.

5.5.2.4 Product Factor

The product factor captures the required production rate of the assigned product. A lower weighting generates a reduction in development person-hours.

Table 5-32 Production Rate Reduction Requirements Definition

Production Rate Reduction Requirements Required production rate reduction to prove the process at full scale demonstration, TRL6.

Table 5-33 Production Rate Reduction Rating Scale

Nominal	High	Very High
5% > increase in existing production rate.	10% > increase in existing production rate.	20% > increase in existing production rate.

5.5.2 Resources Model Size and Effort Driver Wideband Delphi Results

5.5.2.1 Size Drivers

The initial validation of the results from the Round 1 and 2 of the Wideband Delphi involved determining the percentage variation from each of the rounds calculated mean. This was calculated by taking the mean of Wideband Delphi Round 1 and calculating the percentage variation of the mean from Round 2. The final variation values and the mean from Round 1 and 2 are listed in Table 5-34. The variation % cells highlighted green indicate the two Rounds reached consensus within the ± 10% tolerance, specified from cost estimation experts used for the model development. The one cell highlighted red indicated a +20% variation from Round 1 to 2. However, this result was discussed in detail following Round 2, with experts agreeing on the final mean output from Round 2.

Table 5-34 Functional Size Driver Weightings from Wideband Delphi Round 1 and 2

	Relative Complexity Weights from Wideband Delphi								
Functional Size Drivers	**Easy**			**Nominal**			**Difficult**		
Wideband Delphi Round Number	**1(μ)**	**2(μ)**	**Variation %**	**1(μ)**	**2(μ)**	**Variation %**	**1(μ)**	**2(μ)**	**Variation %**
Number of Geometric Requirements	0.50	0.50	0.00	1.00	1.00	0.00	3.25	3.00	-8.33
Number of Process Steps	1.10	1.00	-10.00	2.00	2.00	0.00	3.70	4.00	7.50
Number of Test Pieces	0.40	0.50	20.00	1.10	1.00	-10.00	1.50	1.50	0.00

The final results from Round 2 of the Wideband Delphi process for each of the size driver weightings are shown in Table 5-35. The Table indicates that the 'Number of Process Steps' size driver, when rated at 'difficult,' has the highest impact on functional size. This requires 4 times the amount of effort, compared to the 'nominal' size drivers for both 'Number of Geometric Requirements' and 'Number of Test Pieces.'

Table 5-35 Finalised Functional Size Driver Weightings from Wideband Delphi Round 2

	Relative Complexity Weights		
Functional Size Drivers	**Easy**	**Nominal**	**Difficult**
Number of Geometric Requirements	0.5	1.0	3.0
Number of Process Steps	1.0	2.0	4.0
Number of Test Pieces	0.5	1.0	1.5

5.5.2.2 Effort Drivers

Following the initial validation of the results from Round 1 and 2 of the Wideband Delphi study for the size drivers, the percentage variation was calculated for each of the effort driver ratings. This was calculated by taking the mean of the responses from Round 1 and 2. The percentage variation was then calculated for each effort driver rating. The final variation percentages and the mean of the responses from Round 1 and 2 are listed in Table 5-36. Within the Table, the variation % cells highlighted green indicate the two rounds reached consensus within the ± 10%. The variation % cells highlighted red is outside the specification limit. The effort driver found to have the highest variation of responses between rounds was the 'Required Development Schedule.' This variation was from the judgments about overheads and increases in effort when a development schedule is compressed, or extended beyond the nominal value. Each of the effort drivers with a variation percentage outside the ± 10% specification limit were discussed post Round 2 and each reached consensus to form the final output.

The final results from Round 2 of the Wideband Delphi study for each of the effort driver ratings are listed in Table 5-37. The scales nominal value is set at 1.0 with the polarity depending on the assigned variability for that specific driver. The ratings for each of the effort multipliers have been systematically ranked based on their Effort Multiplier Ratios (EMR). The EMR identifies the variability of the driver and its individual influence on development person-hours.

Table 5-36 Effort Driver Weightings from Wideband Delphi Round 1 and 2

Rating	**Very Low**			**Low**			**High**			**Very High**		
Wideband Delphi Round Number	**1(μ)**	**2(μ)**	**Var %**	**1(μ)**	**2(μ)**	**Var %**	**1(μ)**	**2(μ)**	**Var %**	**1(μ)**	**2(μ)**	**Var %**
Product Application Experience	1.90	1.85	-2.70	1.30	1.36	4.41	0.76	0.77	1.30	0.55	0.60	8.33
Degree of Process Novelty	0.60	0.62	3.23	0.80	0.79	-1.27	1.40	1.36	-2.94	1.82	1.85	1.62
Process Experience	1.54	1.64	6.10	1.30	1.28	-1.56	0.61	0.81	24.69	0.51	0.65	21.54
Test Piece Material Complexity	0.59	0.65	9.23	0.70	0.81	13.58	1.20	1.22	1.64	1.47	1.50	2.00
Requirements Understanding	1.50	1.50	0.00	1.25	1.22	-2.46	0.80	0.81	1.23	0.65	0.65	0.00
Manufacturing Documentation of Requirements	1.54	1.50	-2.67	1.25	1.22	-2.46	0.74	0.81	8.64	0.64	0.65	1.54
TRL Pack Experience	1.40	1.48	5.41	1.20	1.22	1.64	0.86	0.82	-4.88	0.66	0.67	1.49
Supplier Network Availability and Capability	1.45	1.39	-4.32	1.11	1.18	5.93	0.77	0.85	9.41	0.70	0.72	2.78
Installation Complexity	0.60	0.76	21.05	0.90	0.87	-3.45	1.26	1.21	-4.13	1.36	1.47	7.48
Location Variation of Trials & Tests	0.78	0.76	-2.63	0.81	0.87	6.90	1.23	1.21	-1.65	1.49	1.47	-1.36
Production Rate Reduction Requirements	N/A	N/A	N/A	N/A	N/A	N/A	1.39	1.37	-1.46	1.90	1.87	-1.60
Required Development Schedule	1.90	1.66	-14.46	1.50	1.20	-25.00	1.25	1.13	-10.62	1.40	1.28	-9.38
Datum Complexity	N/A	N/A	N/A	N/A	N/A	N/A	1.10	1.13	2.65	1.20	1.28	6.25

Table 5-37 Finalised Effort Driver Ratings and Effort Multipliers for Resources Model from Wideband Delphi Round 2

Effort Driver Name	Very Low	Low	Nominal	High	Very High	EMR
Product Application Experience	1.85	1.36	1.00	0.77	0.60	**3.08**
Degree of Process Novelty	0.62	0.79	1.00	1.36	1.85	**2.98**
Process Experience	1.64	1.28	1.00	0.81	0.65	**2.52**
Test Piece Material Complexity	0.65	0.81	1.00	1.22	1.50	**2.31**
Requirements Understanding	1.50	1.22	1.00	0.81	0.65	**2.31**
Manufacturing Documentation of Requirements	1.50	1.22	1.00	0.81	0.65	**2.31**
TRL Pack Experience	1.48	1.22	1.00	0.82	0.67	**2.21**
Supplier Network Availability and Capability	1.39	1.18	1.00	0.85	0.72	**1.93**
Installation Complexity	0.76	0.87	1.00	1.21	1.47	**1.93**
Location Variation of Trials & Tests	0.76	0.87	1.00	1.21	1.47	**1.93**
Production Rate Reduction Requirements	------	------	1.00	1.37	1.87	**1.67**
Required Development Schedule	1.66	1.20	1.00	1.13	1.28	**1.29**
Datum Complexity	------	------	1.00	1.13	1.28	**1.28**

EMR = Effort Multiplier Ratio

5.6 COTECHMO Direct Cost Model Size and Cost Drivers Study Results

The COTECHMO Direct Cost model size and cost drivers feed into the CER presented in Equation 5.4. The proceeding Sub Sections are the final outputs from the detailed research methodology followed.

5.6.1 Direct Cost Model Size Driver

The size driver for the Direct Cost model captures the volume of the AMT process, not the functional size used within the Resources model. Subsequently, this model consists of one additive size driver and quantifies the physical volume of the AMT process for its direct manufacturing application. This driver does not require complexity weightings, thus is eliminated from the Wideband Delphi study. Care has been taken to ensure all complexities are captured within each of the 13 cost multipliers. When quantitative physical size values are not available at the initial stages of development, surrogate sources of data must be captured and include data from similar AMT developments.

5.6.2 Direct Cost Model Cost Drivers

Following the Resources model effort driver form, due to the qualitative nature of these multiplicative drivers, the rating is not as simple as the physical volume size driver discussed previously.

To help assist with the novel AMT cost driver definitions and ratings; each driver was placed into four themes:

- AMT Process Primary Factors. Drivers that capture primary process parameter requirements for the target application.
- AMT Process Secondary Factors. Drivers that capture the secondary parameters of the process for the targeted application.
- AMT Process External Factors. Drivers that capture external AMT requirements for the target application.
- Product Rate Factor. The driver that captures the required production rate of the assigned product.

Drivers fed into the above themes based on expert opinion and weightings were applied using the following rating scales: Very Low, Low, Nominal, High and Very High. These were defined from the semi-structured interviews and workshops**.**

5.6.2.1 AMT Process Primary Factors

The AMT Process Primary Factors represent the process complexity and demonstration requirements set at the initial stages of development. For each of the drivers within this theme, a higher weighting creates greater complexity and an increase in development direct cost. There are five AMT Process Primary Factors with 'Number of Geometric Accuracy Requirements' generating the greatest multiplicative impact.

Table 5-38 Number of Geometric Accuracy Requirements Definition

Number of Geometric Accuracy Requirements
The number of requirements taken from the manufacturing process customer specification. These can be quantified by counting the conceptual application documentation.

Table 5-39 Number of Geometric Accuracy Requirements Rating Scale

Very Low	**Low**	**Nominal**	**High**	**Very High**
All geometric accuracy requirements lower than existing.	2 > geometric accuracy requirements lower than existing process; none above existing.	3 > geometric accuracy requirements replicating existing process; none above existing.	3 > geometric accuracy requirements regarded as higher than existing process accuracy.	6 > geometric accuracy requirements regarded as higher than existing process accuracy.

Table 5-40 Number of Process Steps Definition

Number of Process Steps
The number of process steps can be counted from the customer application specification to prove the process at full scale.

Table 5-41 Number of Process Steps Rating Scale

Very Low	Low	Nominal	High	Very High
All process steps below existing complexity.	2 > process steps below existing complexity; none above existing.	3 > process steps replicating existing complexity; none above existing.	3 > process steps regarded as higher than existing complexity.	6 > process steps regarded as higher than existing complexity.

Table 5-42 Process Capability Requirements Definition

Process Capability Requirements
Process capability (Cpk) requirements for the direct application, identified within the process requirements specification.

Table 5-43 Process Capability Requirements Rating Scale

Very Low	Low	Nominal	High	Very High
Process capability $\geq$ 1.00 Cpk	Process capability $\geq$ 1.10 Cpk	Process capability $\geq$ 1.33 Cpk	Process capability $\geq$ 1.60 Cpk	Process capability $\geq$ 2.00 Cpk

Table 5-44 Degree of Process Novelty Definition

Degree of Process Novelty
Manufacturing process novelty for the direct application e.g. automated assembly process from an automotive plant, now developed using the TRL for the aerospace domain.

Table 5-45 Degree of Process Novelty Rating Scale

Very Low	Low	Nominal	High	Very High
Process developed, implemented and proven throughout the aerospace industry.	Process developed, implemented and proven within 3> non-aerospace domains.	Process developed, implemented and proven in 1> non-aerospace domain e.g. automotive manufacture.	Process developed to low level (TRL3-6) in 1> non-aerospace domain.	Process not proven or developed in any domain, completely novel.

Table 5-46 Installation Complexity Definition

Installation Complexity
Installation complexity of the manufacturing process to prove at full scale. A highly complex process would consist of many automation equipment installations.

Table 5-47 Installation Complexity Rating Scale

Very Low	Low	Nominal	High	Very High
Complexity of very low levels: much lower than existing process implementation and existing developments.	Low complexity: complexity slightly lower than exiting process installation procedure.	Moderately complex: installation procedure similar to existing process to replace.	Very complex: installation procedure exceeds existing process.	Extremely complex: installation procedure exceeds existing process installation and similar developments.

5.6.2.2 AMT Process Secondary Factors

The AMT Process Secondary Factors represent the process requirements that experts determined secondary and are separate from the Primary Factors discussed previously. For each of the drivers within this theme, a higher weighting creates greater complexity and an increase in development direct cost. There are four AMT Process Secondary Factors, with 'Automation Level Requirements' having the highest multiplicative impact.

Table 5-48 Manufacturing Environment Requirements Definition

Manufacturing Environment Requirements
Temperature requirements to prove the process accuracy at full scale application.

Table 5-49 Manufacturing Environment Requirements Rating Scale

Very Low	**Low**	**Nominal**	**High**	**Very High**
No process temperature control requirements.	Process requires temperature controlled ± 15%	Process requires temperature controlled ± 10%.	Process requires temperature controlled ± 3%.	Process requires temperature controlled ± 1%.

Table 5-50 Automation Level Requirements Definition

Automation Level Requirements
The level and novelty of the automated control used within the process.

Table 5-51 Automation Level Requirements Rating Scale

Very Low	**Low**	**Nominal**	**High**	**Very High**
No automated control required.	Semi-automated control required fully proven within the domain.	Process requires a fully automated control proven within the same domain.	Process requires a fully automated control proven in one non-aerospace domain.	Process requires state of the art fully automated control unproven in any domain.

Table 5-52 Test Piece Material Complexity Definition

Test Piece Material Complexity
Complexity of the test piece material to prove the manufacturing process at full scale application.

Table 5-53 Test Piece Material Complexity Rating Scale

Very Low	**Low**	**Nominal**	**High**	**Very High**
Very low complexity: material fully proven for manufacture on existing product with selected process.	Low complexity: material proven in 2> same domain of aerospace manufacture with selected process.	Medium complexity: material implemented in 1> same domain of aerospace manufacture with selected process.	Very complex: limited development and implementation of a similar material with selected process.	Extremely complex: material completely novel and not been developed before with selected process.

Table 5-54 Process Test and Verification Requirements Definition

Process Test and Verification Requirements
Process test and verification requirements to prove the manufacturing process at full scale demonstration, TRL6.

Table 5-55 Process Test and Verification Requirements Rating Scale

Very Low	Low	Nominal	High	Very High
Process already proven, very low levels of testing required.	Process proven within a similar domain so required testing lower than nominal cases.	Standardised test and verification procedure for a similar manufacturing process.	Test and verification procedure conducted within a similar domain.	Advanced test and verification procedure never performed before.

5.6.2.3 AMT Process External Factors

The AMT Process External Factors define external process requirements. A higher weighting for the AMT Process External Factors increases the AMT development direct cost. There are four AMT Process External Factors with 'Tooling Requirements' having the highest multiplicative impact.

Table 5-56 Metrology Requirements Definition

Metrology Requirements
Metrology monitoring requirements to prove the manufacturing process and meet the customer requirements e.g. process capability.

Table 5-57 Metrology Requirements Rating Scale

Very Low	Low	Nominal	High	Very High
No metrology required.	Low levels of metrology required all fully proven for application.	Replicating or utilising existing metrology process, fully proven for application.	Metrology process proven within 1 > similar process domains.	State of the art metrology process, not proven within any process domain.

Table 5-58 Human Factor Requirements Definition

Human Factor Requirements
Human Factor Requirements of the manufacturing process to meet the customer requirements e.g. safety cell around the process to comply with Human Factor Legislation.

Table 5-59 Human Factor Requirements Rating Scale

Very Low	Low	Nominal	High	Very High
No human factor requirements.	Low level of human factor requirements and all lower than existing process.	Replication of existing process human factor requirements.	Process human factors requirements exceed existing process but proven within a similar domain e.g automotive.	Advanced human factors requirements e.g. robot-human interaction.

Table 5-60 Tooling Requirements Definition

Tooling Requirements
The tooling and fixture requirements to support the manufacturing process.

Table 5-61 Tooling Requirements Rating Scale

Very Low	Low	Nominal	High	Very High
No tooling requirements.	Low complexity: low levels of tooling and fixture requirements all lower than existing process.	Existing complexity: tooling and fixture requirements replicating the existing process.	High complexity: tooling and fixture requirements exceed existing process; developed within a similar domain.	Extremely complex: tooling and fixture requirements state of the art; not developed before in any domain.

5.6.2.4 Product Factor

The final cost driver theme is the Product Factor. This driver represents the production rate reduction requirements. Following the form of the previous cost driver theme, a higher weighting generates an increase in development cost. This driver does not comply with the 5 scale rating system and only utilises: nominal, high and very high.

Table 5-62 Production Rate Reduction Requirements

Production Rate Reduction Requirements
Required production reduction rate to prove the process at full scale demonstration, TRL6.

Table 5-63 Production Rate Reduction Requirements Rating Scale

Nominal	High	Very High
5% > increase in existing production rate.	10% > increase in existing production rate.	20% > increase in existing production rate.

5.6.3 Direct Cost Model Wideband Delphi Results

The Direct Cost model form only requires weightings for the cost drivers as the size driver forms the volume of the AMT process.

5.6.3.1 Cost Drivers

Following the initial validation of the Wideband Delphi results for the Resources model, the percentage variation was calculated for each of the cost driver ratings for the Direct Cost model. The percentage variation and the mean of responses from Wideband Delphi Round 1 and 2 are listed in Table 5-64. Within the Table, variation % cells highlighted red are outside the specification limit of ± 10% and green cells are within. The cost driver with the highest variation of responses between rounds was ‘Number of Geometric Requirements’ and ‘Degree of Process Novelty.’ However, final consensus was reached to utilise the mean output from Round 2, despite the variation from Wideband Delphi Round 1. This was finalised through a discussion after Round 2, converging on the issues impacting the discrepancy. The final results from the two stage Wideband Delphi process for each of the cost driver ratings are shown in Table 5-65. The scales nominal value is set at 1.0 with the polarity depending on the assigned variability for that specific driver. The ratings for each of the cost multipliers have been systematically listed based on their Cost Multiplier Ratios (CMR). The CMR identifies the variability of the driver and its individual influence on AMT development direct cost.

Table 5-64 Cost Driver Weightings from Wideband Delphi Round 1 and 2

Rating	**Very Low**			**Low**			**High**			**Very High**		
Wideband Delphi Round Number	**1(µ)**	**2(µ)**	**Var %**	**1(µ)**	**2(µ)**	**Var %**	**1(µ)**	**2(µ)**	**Var %**	**1(µ)**	**2(µ)**	**Var %**
Number of Geometric Accuracy Requirements	0.50	0.40	-25.00	0.71	0.60	-18.33	1.58	1.60	1.25	1.90	1.87	-1.60
Degree of Process Novelty	0.58	0.50	-16.00	0.79	0.70	-12.86	1.69	1.49	-13.42	1.91	1.90	-0.53
Automation Level Requirements	0.60	0.60	0.00	0.80	0.81	1.23	1.55	1.60	3.13	1.84	1.90	3.16
Tooling Requirements	0.50	0.55	9.09	0.66	0.70	5.71	1.33	1.30	-2.31	1.66	1.60	-3.75
Number of Process Steps	0.61	0.67	8.96	0.83	0.82	-1.22	1.50	1.48	-1.35	1.82	1.85	1.62
Process Capability Requirements	0.71	0.67	-5.97	0.81	0.82	1.22	1.43	1.48	3.38	1.89	1.85	-2.16
Test Piece Material Complexity	0.63	0.60	-5.00	0.73	0.72	-1.39	1.20	1.18	-1.69	1.40	1.39	-0.72
Metrology Requirements	0.62	0.60	-3.33	0.69	0.72	4.17	1.22	1.18	-3.39	1.45	1.39	-4.32
Production Rate Reduction Requirements	N/A	N/A	N/A	N/A	N/A	N/A	1.33	1.40	5.00	1.90	1.92	1.04
Human Factors Requirements	0.71	0.72	1.39	0.83	0.85	2.35	1.10	1.10	0.00	1.23	1.20	-2.50
Manufacturing Environment Requirements - temp	0.74	0.81	8.64	0.84	0.90	6.67	1.10	1.10	0.00	1.26	1.27	0.79
Installation Complexity	0.75	0.81	7.41	0.85	0.90	5.56	1.15	1.10	-4.55	1.30	1.27	-2.36
Process Test and Verification Requirements	0.87	0.81	-7.41	0.89	0.90	1.11	1.11	1.10	-0.91	1.16	1.27	8.66

Table 5-65 Finalised Cost Driver Ratings for the Direct Cost Model from Wideband Delphi Round 2

Cost Driver Name	**Very Low**	**Low**	**Nominal**	**High**	**Very High**	**CMR**
Number of Geometric Accuracy Requirements	0.40	0.60	1.00	1.60	1.87	**4.67**
Degree of Process Novelty	0.50	0.70	1.00	1.49	1.90	**3.80**
Automation Level Requirements	0.60	0.81	1.00	1.60	1.90	**3.17**
Tooling Requirements	0.55	0.70	1.00	1.30	1.60	**2.91**
Number of Process Steps	0.67	0.82	1.00	1.48	1.85	**2.76**
Process Capability Requirements	0.67	0.82	1.00	1.48	1.85	**2.76**
Test Piece Material Complexity	0.60	0.72	1.00	1.18	1.39	**2.32**
Metrology Requirements	0.60	0.72	1.00	1.18	1.39	**2.32**
Production Rate Reduction Requirements	-------	------	1.00	1.40	1.92	**1.92**
Human Factors Requirements	0.72	0.85	1.00	1.10	1.20	**1.67**
Manufacturing Environment Requirements	0.81	0.90	1.00	1.10	1.27	**1.57**
Installation Complexity	0.81	0.90	1.00	1.10	1.27	**1.57**
Process Test and Verification Requirements	0.81	0.90	1.00	1.10	1.27	**1.57**

CMR = Cost Multiplier Ratio

5.7 COTECHMO Model Development

Using the research methodology described in the COTECHMO model development, Sub Section 5.2.4, prototype COTECHMO Resources and Direct Cost forecasting toolsets were developed in MS Excel. This formed Phase 2 of the detailed research methodology illustrated in Figure 5-4 and involved qualitative validation with industry experts, enhancing from the feedback where applicable. The prototype models were presented to the AMT development experts listed in Appendix A.2, Table A2-1 individually and their feedback was implemented. Iterations of each COTECHMO model included:

- The use of a colour system to define effort increase or decrease e.g. a ‘Very Low’ rating for the effort driver ‘TRL Pack Experience’ should be colour coded red, indicating an increase in development effort.
- Hide the effort driver weightings, as this confused the AMT development experts utilising the model.
- Identify the clustering of the drivers within the model.
- Include a total composite effort or cost multiplier.

The models were then edited and refined using the constructive feedback and presented again to the same AMT experts. Each of the experts agreed that the models fulfilled the initial requirements defined in Section 5.3 and were suitable for use within an R&T function of the aerospace manufacturing industry. To further validate the models, they were presented at the Society for Cost Analysis and Forecasting (SCAF) to generate feedback from cost estimation experts. The analysis provided excellent feedback with no further iterations. Each version of the model was also presented at the Low Cost Manufacturing and Assembly of Composite and Hybrid Structures (LOCOMACHS) launch meeting, with exceptional feedback from the 21 industrial partners. This initial model validation then formed a suitable platform to test each model for new AMT evaluation and verify and validate using 15 case studies within a large aerospace manufacturing organisation, a detailed discussion point for Chapter 8.

The final developed MS Excel COTECHMO Resources model user interface is shown in Chapter 7, Figure 7-4. This interface forms part of the Cost-Benefit Forecasting Framework, with the operation fully described in Chapter 7, Section 7.4.3, Step 3A.

The final MS Excel COTECHMO Direct Cost model user interface is shown in Chapter 7, Figure 7-7. This interface forms part of the Cost-Benefit Forecasting Framework, with the operation fully described in Chapter 7, Sub Section 7.4.4, Step 3B.

5.8 Chapter Summary and Key Observations

This Chapter has presented the development of two parametric cost models. The first model is for estimating the AMT development resources in person-hours to TRL6. The second model is for estimation of development direct (hardware) cost to prove an AMT, also to TRL6.

The detailed research methodology followed for each model development was presented in Section 5.2. In Section 5.3 the model requirements from the aerospace manufacturing industry were detailed. Section 5.4 presented a categorisation of non-recurring development effort and cost as a function of TRL. This formed the platform for the model derivation, breaking down into resources (person-months) and direct (hardware) cost equation forms. Section 5.5 performed a size and effort driver study for the Resources model, including a two stage Wideband Delphi study for the weighting of each driver. The quantitative driver weightings were finalised after reaching consensus after 2 Rounds. Section 5.6 presented the results from the Direct Cost model size and cost driver study. A two stage Wideband Delphi study was included for the weighting of each cost driver, achieving expert consensus after 2 Rounds. In Section 5.7 the models development in MS Excel was described, identifying the reiterations made using the industrial feedback. To verify and validate each model, a detailed industrial case study is performed in Chapter 8.

Each COTECHMO model presented within this Chapter is for quantifying the ‘x-axis’ of the example presented in Figure 5-8. To meet the industrial development value requirements defined in Chapter 4 and quantify the ‘y-axis,’ two performance models are developed and presented in the next Chapter.

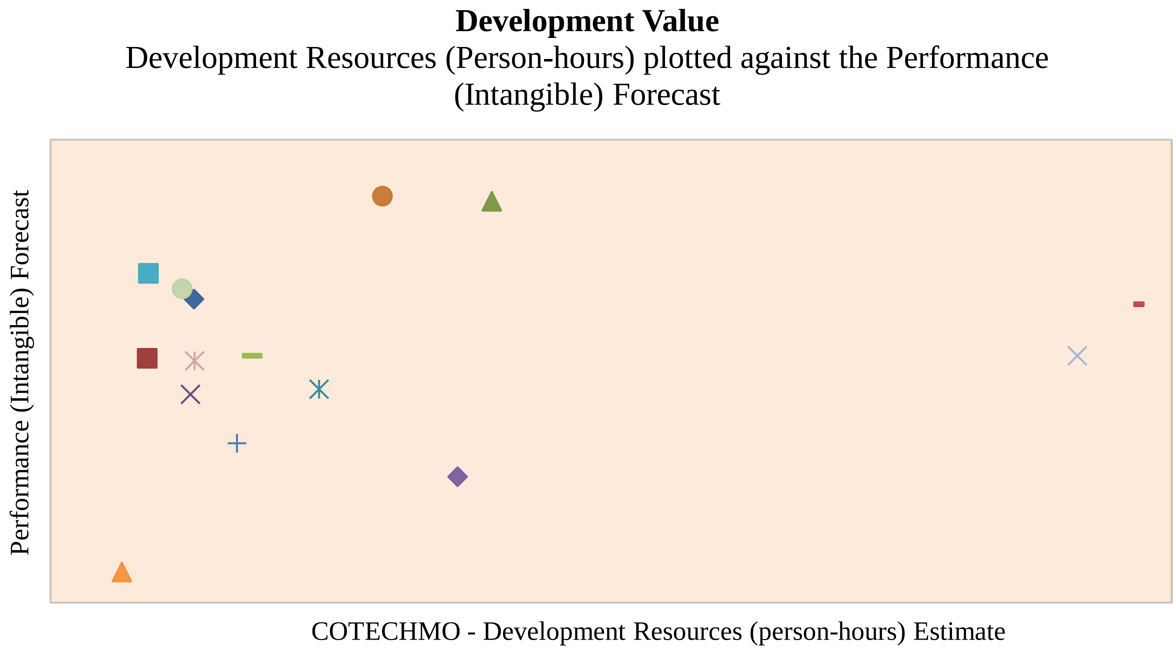

Figure 5-8 Example AMT Forecasting Required Output for Development Resources (Effort) and Performance

CHAPTER 6

THE PERFORMANCE FORECASTING MODEL (PERFORMO)

6.1 Introduction

A review of the literature in Chapter 2 identified a lack of systematic methodologies and processes to forecast tangible and intangible performance for aerospace Advanced Manufacturing Technologies (AMTs), at the initial stages of development. Chapter 4 identified the current practice for forecasting AMT performance at the early development stages, with a focus on Research and Technology (R&T) of the aerospace manufacturing industry. Performance at this stage is used to drive and allocate R&T investment. Currently, industry utilise expert judgement when forecasting AMT performance, consisting of subjective and inconsistent outputs, with incorrect decisions leading to unsuccessful AMT developments, reducing the future success of the manufacturing organisation. Furthermore, when a business evaluates an AMT at the initial development stages, assessments are typically made based on fully tangible perspectives and can fail to evaluate intangible performance parameters. These existing problems are amplified with high levels of AMT novelty at the early development stages, generating substantial uncertainty and risk. Chapter 4 generated a modified process map for justification of R&T investment, with a top level overview presented in Figure 4-6. Within this modified process map, performance forecasts of diverse AMTs with varied applications are required.

In response, two 'Performance Forecasting Models' (PERFORMO) have been developed and are presented within this Chapter. The quantified tangible and intangible performance forecast outputs feed into the 'y-axis' of the example illustrated in Chapter 5, Figure 5-8. The quantified 'x-axis' of the diagram was provided by COTECHMO, discussed in the previous Chapter. These outputs combined provide the aerospace manufacturing industry with the required information to justify R&T investment allocation. This was a requirement formed from the analysis of existing literature in Chapter 2 and industry in Chapter 4.

The first model developed is the PERFORMO Tangible model and is capable of forecasting the performance enhancement, or degradation, from a tangible perspective. This utilises performance metrics that are typically quantifiable and acknowledge development uncertainty. The second model developed is the PERFORMO Intangible model and is capable of forecasting AMT performance enhancement, or degradation, using intangible metrics. Capturing these subjective and classically unquantifiable metrics identifies the performance of an AMT when assessing from an intangible perspective. Chapter 4 identified these can form fundamental AMT development drivers and are not typically included within current 'Tangible' assessments, leading to incorrect AMT selections. Each PERFORMO model forecasts the performance to TRL9, the level an AMT is fully implemented into manufacturing operations. The models provide the aerospace manufacturing industry with the ability to forecast the AMT performance impact at the initial conceptual stages, using the TRL as a systematic historical data capture platform.

This Chapter is organised in the following structure. Section 6.2 describes the detailed research methodology used for the development of the two PERFORMO models. Section 6.3 captures the results from the detailed model requirements study. Section 6.4 describes the two model forms derived, with Section 6.5 and Section 6.6 finalising the Key Performance Factors (KPFs) for each forecasting model and the weighting format for each. Within Section 6.7, the development of the Tangible and Intangible models within MS Excel is discussed and their relative reiterations specified from industry. The Chapter concludes in Section 6.8 by summarising and defining key observations.

6.2 Detailed Research Methodology

Figure 6-1 presents an overview of the research methodology used for the development of the two PERFORMO models. This feeds into Phase 3 of the overall research methodology presented in Chapter 3, Figure 3-2. This methodology was identified from the literature and subsequently initially validated by AMT development experts within the aerospace manufacturing industry. To provide further initial research methodology validation, decision making experts from academia and industry were selected. Collaboration with each of the experts involved formed an iterative process, where experts would review and suggest enhancements that were put into practice appropriately.

6.2.1 Detailed Research Methodology to Determine PERFORMO Model Requirements

Step 1 of the methodology involved investigation of the industrial requirements and determined the model needs from each of the aerospace manufacturing organisations. This was performed using semi-structured interviews and industrial document analysis, detailed within Chapter 4. The evaluation provided a platform for the current performance forecasting practice for aerospace AMT development. This detailed assessment identified the lack of performance forecasting processes, methods and models for AMT development within the aerospace manufacturing sector, forming the initial platform to determine the model requirements. These were formed using semi-structured interviews, with an average duration of two hours. There were 17 experts from the aerospace manufacturing organisation and 2 from outside. Experts were selected for their expertise in developing a range of aerospace AMTs and knowledge of the existing R&T development infrastructure. Each expert involved with determining the PERFORMO requirements is listed in Appendix A.7, Table A7-1, with the final model requirements presented in Section 6.3.

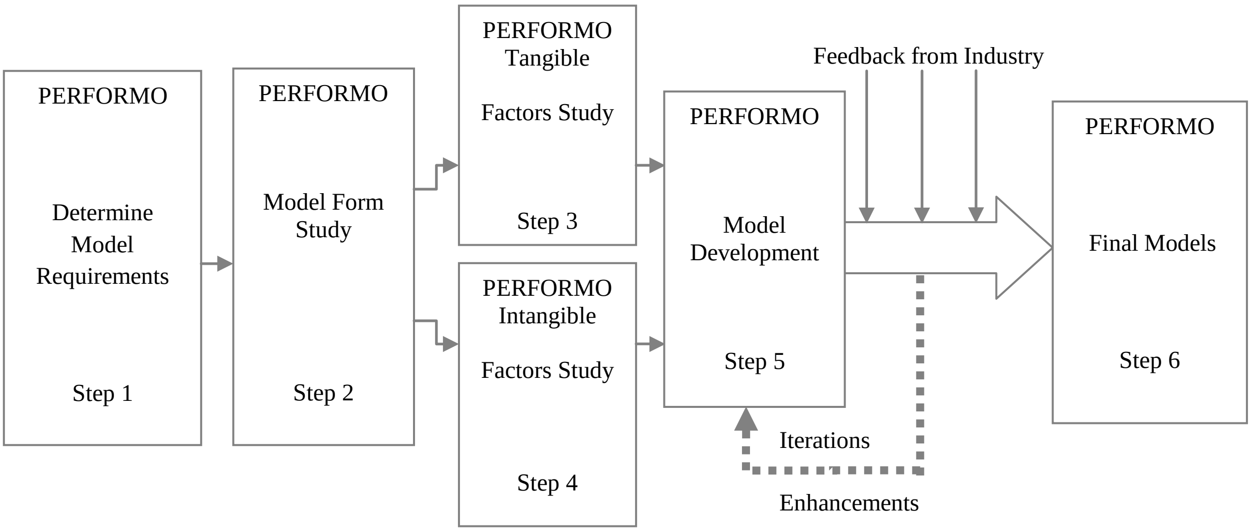

Figure 6-1 Detailed Research Methodology for PERFORMO Development

6.2.2 Detailed Research Methodology for PERFORMO Model Form Study

The PERFORMO requirements defined by experts in Step 1 of the detailed research methodology formed the initial model requirements. Despite extensive AMT development expertise, each had limited experience of performance forecasting at the initial development stages. To meet the initial requirements set previously and develop suitable models, performance forecasting and decision making experts were selected and formed Step 2. These experts helped define the most suitable model form for each PERFORMO forecasting model.

The performance forecasting and decision making experts were presented with the detailed requirements specified for each model. This was carried out using brainstorm workshops and semi-structured interviews by presenting the requirements, data and information available for the development of each model. Further networking and expert feedback was carried out by presenting the model requirements at leading conferences and academic institutions including:

- IEEE Aerospace Conference
- SAE Aerospace Conference
- The University of Arizona
- The University of Nottingham
- Cranfield University

Each included a number of performance forecasting and decision making experts who have covered similar problems within different domains; outside the AMT development application that the project is based. The experts directly involved with the development of each PERFORMO equation form are listed in Appendix A.7, Table A7-2.

To further validate the developed model forms for each performance forecasting model, they were presented to the AMT development experts listed in Appendix A.7, Table A7-1, clarifying fulfilment of the operational requirements. Following the COTECHMO model form initial validation, each PERFORMO model was presented at the Low Cost Manufacturing and Assembly of Composite and Hybrid Structures (LOCOMACHS) project launch meeting, including experts from a range of aerospace manufacturing fields. Feedback from the 21 industrial partners was excellent and many were interested in using the PERFORMO models for the project's AMT performance management.

6.2.3 Detailed Research Methodology for PERFORMO Key Performance Factors

From the results of the model requirements and model form discussed previously, a detailed study was conducted to identify Key Performance Factors (KPFs) for the PERFORMO Tangible and Intangible forecasting models. This study is illustrated in Figure 6-2 and explained in the following Sub Sections.

6.2.3.1 Detailed Research Methodology for PERFORMO Tangible and Intangible Key Performance Factor Semi-structured Interviews

For the initial stage of the Tangible and Intangible model KPF study, 14 AMT development experts were individually interviewed to define KPFs that are suitable for the evaluation of AMT performance. Each of the AMT development experts were asked to brainstorm general KPFs for AMTs they had developed, or were in the process of developing. These were recorded, initially breaking down into the PERFORMO Tangible and Intangible model forms.

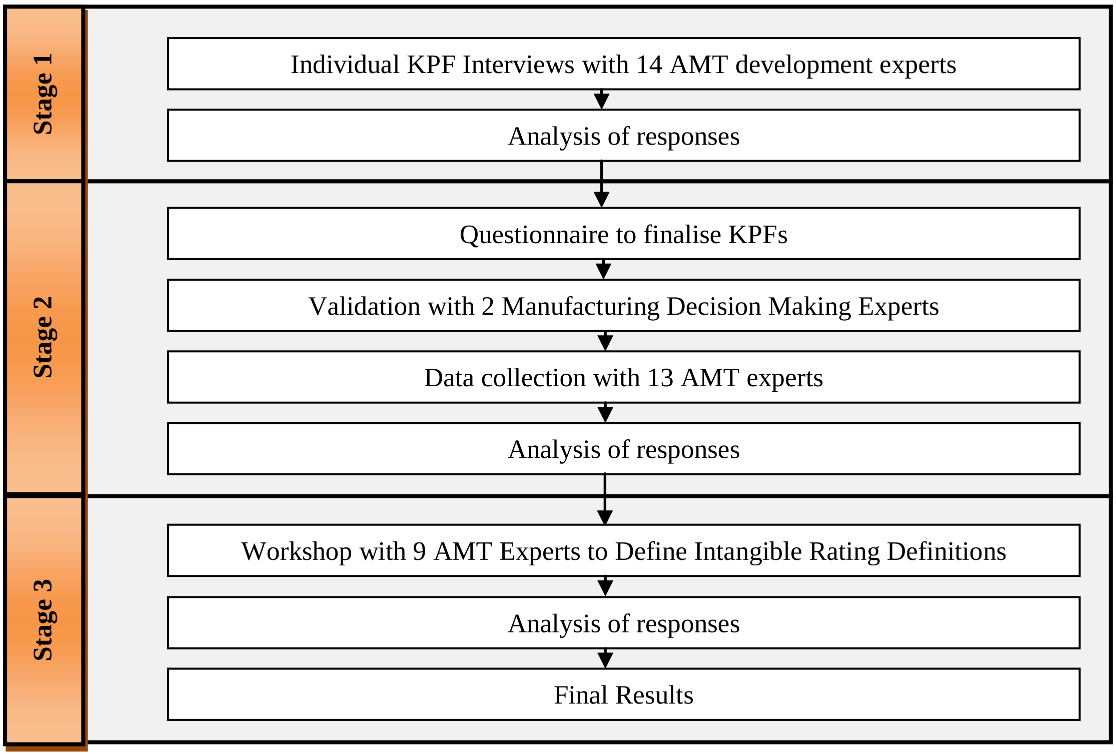

Figure 6-2 PERFORMO Key Performance Factors Study

On completion of capturing general KPFs, the model form was explained in more detail for the Tangible and Intangible models. The AMT development experts were asked if each of the KPFs they had identified could be quantified at the initial stages of development. Quantification of a KPF identified that it feeds into the Tangible model, with qualitative factors feeding into the Intangible model. The tangible KPFs were then clustered into time, cost and quality. The intangible KPFs were clustered into health and safety, flexibility, managerial/operations, risk and strategic. Each of the AMT expert inputs were compiled and evaluated with 2 manufacturing decision making experts, totalling 15 years' experience. Many KPFs cross referenced and were similar in definition, so were collated into an overall list.

6.2.3.2 Detailed Research Methodology for PERFORMO Tangible and Intangible Key Performance Factor Workshops

From the compiled responses of the semi-structured interviews conducted previously, a questionnaire was developed to define a final set of tangible and intangible KPFs. This formed Stage 2 of the research methodology illustrated in Figure 6-2 and 13 AMT development experts completed the questionnaire shown in Appendix A.8 and A.9, with the responses analysed.

The finalised KPFs from each model then allowed Stage 3 of the study to commence, although this was only performed for the Intangible model, as the tangible KPFs did not require ratings. This workshop was held with 9 AMT development experts using the questionnaire in Appendix A.9, with each expert defining and discussing the 'rating' definition for the KPFs. The final 'Very Low' to 'Very High' rating of each KPF was initially validated with the performance forecasting and decision making experts, listed in Appendix A.7, Table A7-2.

6.2.4 Detailed Research Methodology for PERFORMO Model Development

A systematic methodology was followed for the development of each PERFORMO model, with an overview illustrated in Figure 6-3. Phase 1 produced an in depth understanding of AMT development and its maturity assessment platforms. This also included understanding the varied types of AMT and the performance forecasting techniques used at the initial stages of development. Understanding of each was conducted through an extensive literature review and semi-structured interviews with a range of experts from industry, detailed within Chapter 2 and 4. This formed the platform and requirements for the development of each model to solve the problem. A detailed study into the novel KPFs to evaluate AMT performance at the early stages of development completed Phase 1.

Phase 2 involved the development of two prototype models, the first to forecast AMT tangible performance and the second to forecast the intangible performance. Each model was developed in MS Excel and iteratively enhanced based on expert feedback. The final Phase involved quantitatively verifying and validating the developed models, an evaluation discussed in detail within Chapter 8.

6.3 PERFORMO Model Requirement Results

The experts listed in Appendix A.7, Table A7-1 detailed and defined the industrial requirements. Each expert identified the information available for forecasting performance of a new AMT at the early development stages. This determined that quantification of the performance from 'Tangible' and 'Intangible' perspectives would advance AMT performance assessment. The models must be capable of quantifying tangible and intangible performance for a diverse range of AMTs with varied applications at the initial stages of development. Each model needs to be utilised within an R&T function and must provide the business with a robust forecasting process and obtain the following specified requirements:

- Usability

Each forecasting model should be easy to use, with a clear user interface, utilising software already in operation within R&T of the aerospace manufacturing industry.

- Accuracy

Each model must be verified with AMT cases that have already been developed within the aerospace manufacturing industry. The models must identify an AMT suitable for development and distinguish from an AMT that was determined unsuccessful. Each model must be further validated by expert opinion within the business using a proven industrial application assessment scale.

- Flexibility

Each model should be capable of forecasting performance for a diverse range of AMTs having varied applications, within R&T of the aerospace manufacturing industry and provide a coherent, comparable output.

- Uncertainty

The Tangible model must be capable of capturing the high levels of development uncertainty for novel AMTs.

6.4 PERFORMO Model Form Study Results

The model requirements Section discussed previously has identified the need for two performance forecasting models. Each model must be capable of forecasting the performance at the conceptual stages of development (TRL1-2) and predict performance when implemented into manufacturing operations (TRL7-9). Detailed within the model requirements discussed previously, capturing uncertainty is a key aspect of forecasting into the future. An example of forecasting performance as a function of TRL for generic aerospace technologies was presented by Kirby (2001) in Chapter 2 and illustrated in Figure 2-6. This illustrated the high technology development uncertainty distribution aligned with the TRL, a factor that is also applicable to the development of novel AMTs. The Tangible model aims to capture uncertainty using a three point estimate, described in the model's mathematical notation.

Using the experts listed in Appendix A.7, Table A7-2, AMT performance forecasting has been categorised into a tangible and intangible top level hypothesis. This provided the initial platform for the development of the two PERFORMO models.

The Tangible performance forecasting model is the first and captures quantitative input data, providing an overall performance output. The PERFORMO Tangible model mathematical notation is presented within Sub Section 6.4.1.

The Intangible performance forecasting model is the second and is capable of turning a subjective qualitative input into a quantified output. The PERFORMO Intangible model mathematical notation is conversed within Sub Section 6.4.2

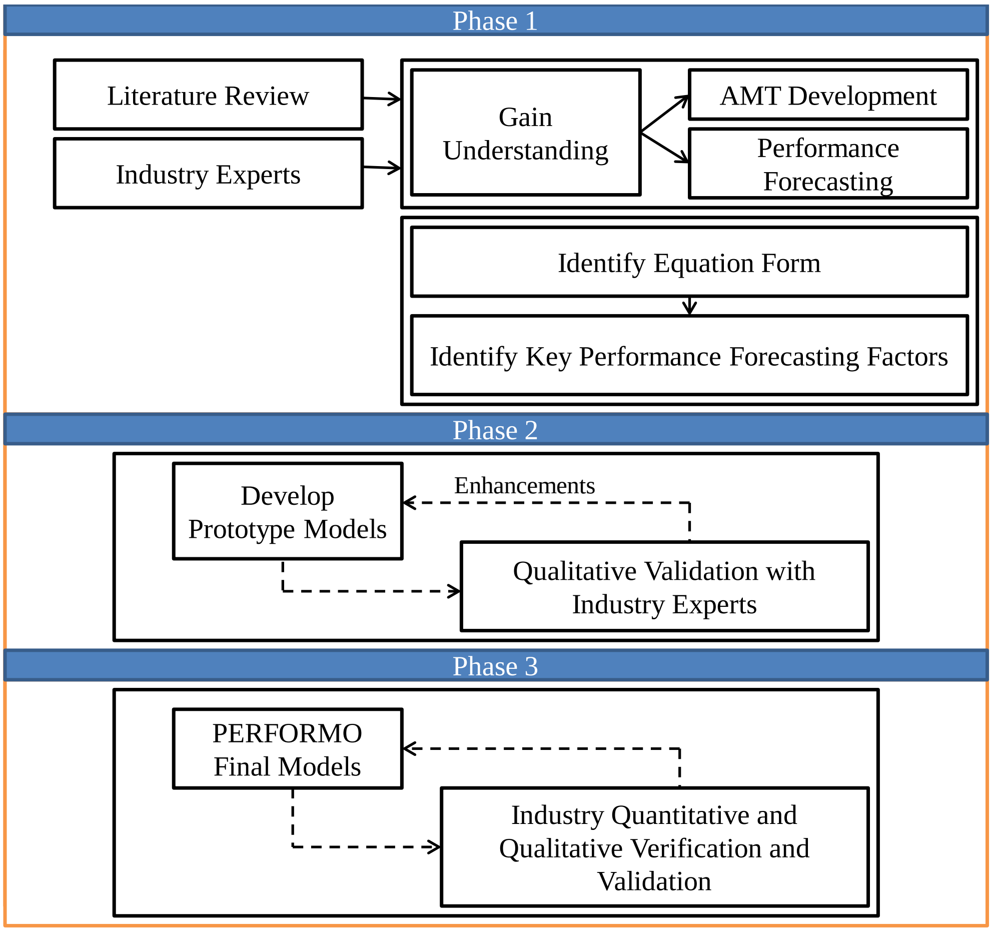

Figure 6-3 Detailed Research Methodology for PERFORMO Development, Verification and Validation

6.4.1 PERFORMO Tangible Derivation

The final PERFORMO Tangible model form was developed in collaboration with the performance forecasting and decision making experts listed in Appendix A.7, Table A7-2. The model forecasts AMT tangible performance to TRL7-9, the level an AMT is implemented into manufacturing operations. The model algorithm consists of three quantitative performance metrics: time, cost and quality. Each metric is broken down into

KPFs, with the time metric broken down into seven KPFs, the cost metric two KPFs and the quality metric three KPFs, with each listed and described within Section 6.5.

Equations 6.1, 6.2 and 6.3 identify how the time, cost and quality baselines are divided by the mean forecast performance for ten of the twelve KPFs. In contrary, 'Process Lifecycle Time' and 'Process Capability' KPFs have their mean forecast performance divided by a baseline, shown in Equations 6.4 and 6.5. A performance enhancement for these two KPFs has a larger value, not a reduction followed with the other ten KPFs. The mean forecast performance for each KPF is calculated using a 3 point estimate with a Beta-Project Evaluation and Review Technique Distribution (PERT), presented in Equations 6.6, 6.7 and 6.8.

$$Time_j = \frac{Time_{Baseline}}{Time_{Forecast\ \mu}} \quad \text{(Eqn.6.1)}$$

$$Cost_j = \frac{Cost_{Baseline}}{Cost_{Forecast\ \mu}} \quad \text{(Eqn.6.2)}$$

$$Quality_j = \frac{Quality_{Baseline}}{Quality_{Forecast\ \mu}} \quad \text{(Eqn.6.3)}$$

$$Time_j = \frac{Time_{Forecast\ \mu}}{Time_{Baseline}} \quad \text{(Eqn.6.4)}$$

$$Quality_j = \frac{Quality_{Forecast\ \mu}}{Quality_{Baseline}} \quad \text{(Eqn.6.5)}$$

Where:

$$Time_{Forecast\ \mu} = \frac{\text{minimum} + 4^{*}\ \text{most likely} + \text{maximum}}{6} \quad \text{(Eqn.6.6)}$$

$$Cost_{Forecast\ \mu} = \frac{\text{minimum} + 4^{*}\ \text{most likely} + \text{maximum}}{6} \quad \text{(Eqn.6.7)}$$

$$Quality_{Forecast\ \mu} = \frac{\text{minimum} + 4^{*}\ \text{most likely} + \text{maximum}}{6} \quad \text{(Eqn.6.8)}$$

Within the model, final outputs from Equation 6.1 - 6.5 are multiplied by the weighting of each KPF selected by the model user. This defines the importance of each KPF for the AMT selected for evaluation. The total weighting for each time KPF is presented in Equation 6.9, the KPFs weighting for cost in Equation 6.10 and the quality KPFs in Equation 6.11. Equation 6.12 categorises how the total weightings are normalised at 1 for all the KPFs combined, allowing comparison of a diverse range of AMTs.

$$\omega_{TimeKPFj} = (\omega_{Time\ KPF1} + \omega_{Time\ KPF2} + \dots \omega_{Time\ KPF7}) \qquad \text{(Eqn.6.9)}$$

$$\omega_{CostKPFj} = (\omega_{Cost\ KPF1} + \omega_{Cost\ KPF2}) \qquad \text{(Eqn.6.10)}$$

$$\omega_{QualityKPFj} = (\omega_{Quality\ KPF1} + \omega_{Quality\ KPF2} + \omega_{Quality\ KPF3}) \qquad \text{(Eqn.6.11)}$$

$$\sum_{j=1}^{7} \omega_{TimeKPFj} + \sum_{j=1}^{2} \omega_{CostKPFj} + \sum_{j=1}^{3} \omega_{QualityKPFj} = 1$$

(Eqn.6.12)

Where:

ω = weighting

Therefore, the final equation form used within the PERFORMO Tangible model is presented within Equation 6.13, with Figure 6-4 illustrating the overall model operation.

$$TP = \sum_{j=1}^{7} \omega_{TimeKPFj} \cdot Time_j + \sum_{j=1}^{2} \omega_{CostKPFj} \cdot Cost_j + \sum_{j=1}^{3} \omega_{QualityKPFj} \cdot Quality_j$$

(Eqn.6.13)

Where:

TP = tangible performance

$\omega_{TimeKPFj}$ = time key performance factor weightings

$\omega_{CostKPFj}$ = cost key performance factor weightings

$\omega_{QualityKPFj}$ = quality key performance factor weightings

$Time_j$ = represent the time key performance factors described in Section 6.5. Each key performance factor is forecast from a baseline using either Equation 6.1 or 6.4.

$Cost_j$ = represent the cost key performance factors described in Section 6.5. Each key performance factor is forecast from a baseline using Equation 6.2.

$Quality_j$ = represent the quality key performance factors described in Section 6.5. Each key performance factor is forecast from a baseline using Equation 6.3 or 6.5.

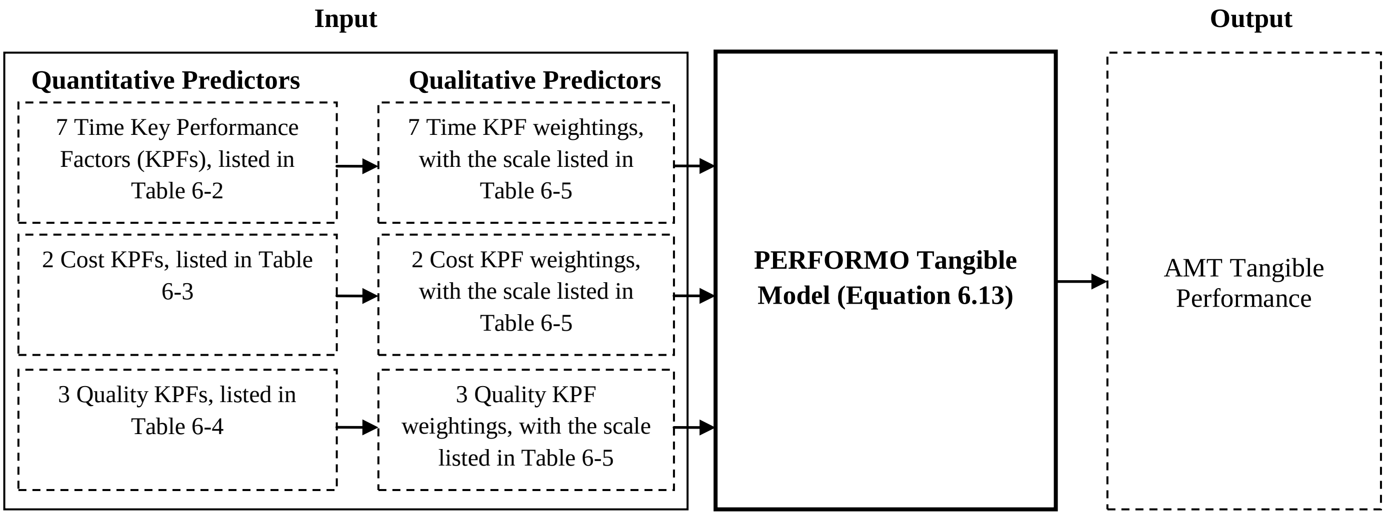

Figure 6-4 PERFORMO Tangible Model Operation

6.4.2 PERFORMO Intangible Derivation

The final PERFORMO Intangible model form was developed in collaboration with the performance forecasting and decision making experts listed in Appendix A.7, Table A7-2. Following the Intangible model discussed previously, the model forecasts performance to TRL7-9. The PERFORMO Intangible model equation form consists of five qualitative performance metrics: health and safety, flexibility, managerial/operations, risk and strategic objectives. Each metric is broken down into KPFs. The health and safety metric is broken down into three KPFs, flexibility two KPFs, managerial three KPFs, risk and strategic objectives each having two KPFs, all listed and described in detail within Section 6.6.

Once each KPF was placed into the themes, rating scales were applied based on expert opinion using the 9 AMT development experts and 2 decision making experts, forming Stage 3 of the workshops within the detailed research methodology, illustrated in Figure 6-2. The rating scales were: Very Low, Low, Nominal, High and Very High and range from -3 to 3, shown in Table 6-1. Full description of each KPF and its qualitative description for each rating are presented in Section 6.6.

Table 6-1 Rating Scale for PERFORMO Intangible Model Key Performance Factors

Extra Low	Very Low	Low	Nominal	High	Very High	Extra High
-3	-2	-1	0	1	2	3

This scale is then multiplied by the weighting of each KPF defined by the model user, presented in Equations 6.14 - 6.18. This defines the importance of each KPF for the AMT assessed.

$$\omega_{Health\,\&\,SafetyKPFj} = (\omega_{H\&S\ KPF1} + \omega_{H\&S\ KPF2} + \omega_{H\&S\ KPF3}) \qquad \text{(Eqn.6.14)}$$

$$\omega_{FlexibilityKPFj} = (\omega_{Flexibility\ KPF1} + \omega_{Flexibility\ KPF2}) \qquad \text{(Eqn.6.15)}$$

$$\omega_{ManagerialKPFj} = (\omega_{Managerial\ KPF1} + \omega_{Managerial\ KPF2} + \omega_{Managerial\ KPF3}) \qquad \text{(Eqn.6.16)}$$

$$\omega_{RiskKPFj} = (\omega_{Risk\ KPF1} + \omega_{Risk\ KPF2}) \qquad \text{(Eqn.6.17)}$$

$$\omega_{StrategicKPFj} = (\omega_{Strategic\ KPF1} + \omega_{Strategic\ KPF2}) \qquad \text{(Eqn.6.18)}$$

Where:

ω= weighting

Equation 6.19 categorises how the total weightings are normalised at 1 for all the KPFs combined. This allows for comparison of a variety of AMTs.

$$\sum_{j=1}^{3}\omega_{Health\,\&\,SafetyKPFj} + \sum_{j=1}^{2}\omega_{FlexibilityKPFj} + \sum_{j=1}^{3}\omega_{ManagerialKPFj} + \sum_{j=1}^{2}\omega_{RiskKPFj} + \sum_{j=1}^{2}\omega_{StrategicKPFj} = 1$$

(Eqn.6.19)

Therefore, the final PERFORMO Intangible model equation form is presented in Equation 6.20, with the model operation illustrated in Figure 6-5.

$$IP = \sum_{j=1}^{3}\omega_{Health\,\&\,SafetyKPFj}\cdot Health\ and\ Safety_j + \sum_{j=1}^{2}\omega_{FlexibilityKPFj}\cdot Flexibility_j + \sum_{j=1}^{3}\omega_{ManagerialKPFj}\cdot Managerial_j + \sum_{j=1}^{2}\omega_{RiskKPFj}\cdot Risk_j + \sum_{j=1}^{2}\omega_{StrategicKPFj}\cdot Strategic_j$$

(Eqn.6.20)

Where:

IP = intangible performance

$\omega_{Health\ and\ SafetyKPFj}$ = health and safety key performance factor weightings

$\omega_{FlexibilityKPFj}$ = flexibility key performance factor weightings

$\omega_{ManagerialKPFj}$ = managerial key performance factor weightings

$\omega_{RiskKPFj}$ = risk key performance factor weightings

$\omega_{StategicKPFj}$ = strategic objective key performance factor weightings

$Health\ and\ Safety_j$, $Flexibility_j$, $Managerial_j$, $Risk_j$, $Strategic_j$ = represent the health and safety, flexibility, managerial, risk and strategic objective key performance factors, each described in detail in Section 6.6 with their rating scale and its corresponding value from Table 6-1.

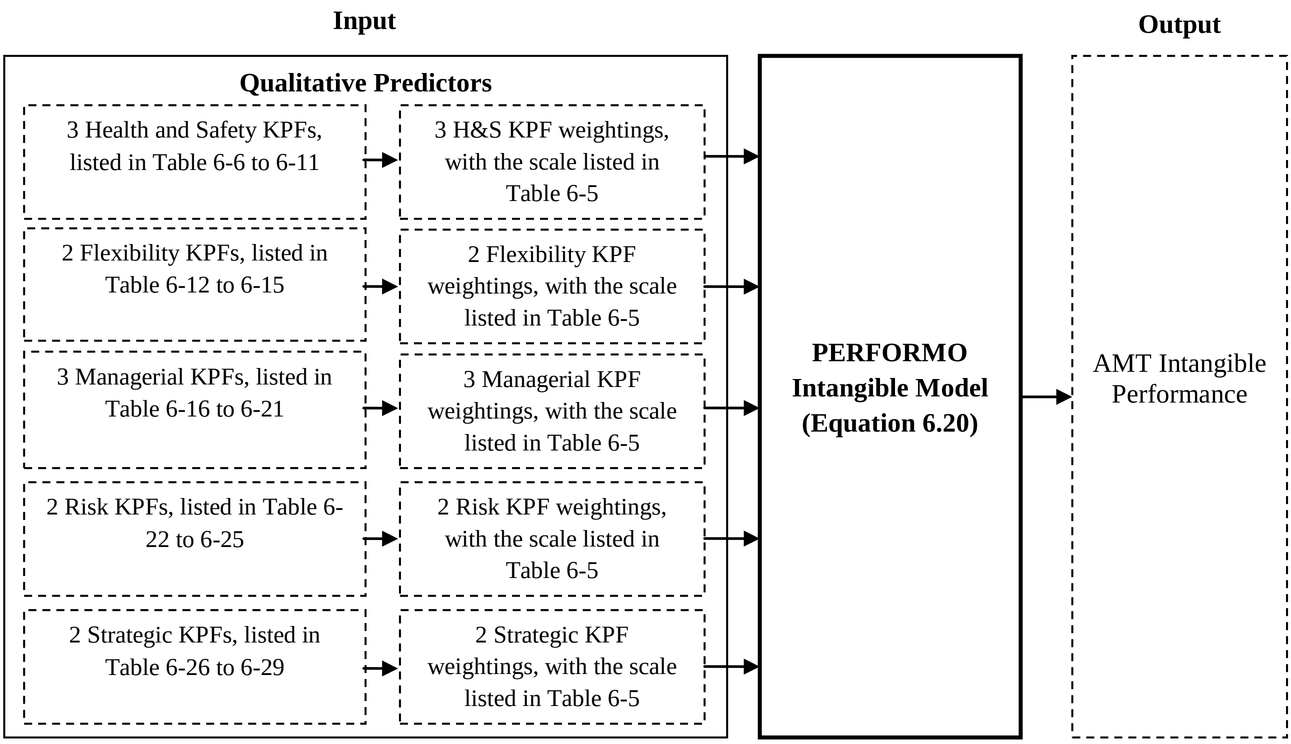

Figure 6-5 PERFORMO Intangible Model Operation

6.5 PERFORMO Tangible Key Performance Factor Study Results

The PERFORMO Tangible KPFs feed into the equation form presented in Equation 6.13. The proceeding Sub Sections are the final output from the followed detailed research methodology, illustrated earlier in Figure 6-2.

6.5.1 Tangible Model Key Performance Factors

The Tangible model KPFs are all compared to a datum baseline, presented mathematically within Equations 6.1-6.5. To help assist in defining the novel KPFs for forecasting performance of an aerospace AMT at the initial stages of development, each was placed into the following themes:

- Time. KPFs that predict the time impact of the AMT to a baseline operational hours.
- Cost. KPFs that capture the impact of the AMT to a baseline cost.
- Quality. KPFs that capture the quality enhancement or degradation of the AMT for its specific application, when compared to a baseline.

6.5.1.1 Time Key Performance Factors

The Time KPFs represent the forecast time of the new AMT development and its comparison to a datum AMT baseline. Typically, the datum baseline is the existing process the new AMT is replacing. When this data is not available, a nominal value of 1.0 is taken. The new AMT process is then compared to the nominal value as a predicted percentage change. For example, if a nominal baseline is set to 1.0 and the new AMT is forecast to increase performance by 5%, the data input for the aligned KPF would be 0.95. A higher performance output for 6 out of the 7 Time KPFs is scored, if the new AMT reduces time from the existing baseline. The ‘lifecycle time’ KPF equates to a performance enhancement if time is extended from the existing baseline.

Table 6-2 Time Key Performance Factors and Their Definitions

Time Key Performance Factor (KPF) Name	KPF Definition
Process TAKT Time	The desired time taken to make one unit of production output.
Process Waste	Total time of non-value added actions within the process.
Process Person-hours	Total person-hours utilised to perform the process within operations, the resources consumed.
Process up-time	The mean time between failures (unplanned shut down of the process).
Process Service Cycle Time	The total time required servicing the process when embedded within operations.
Process Lifecycle Time	Process time in service within operations before non-conformance to specification or becoming obsolete
Process Lag Time	Total non-productive time of the process prior to start up.

6.5.1.2 Cost Key Performance Factors

An AMT evaluation utilising these KPFs, scores a higher performance output the more an AMT can reduce cost, when compared to an existing baseline. Cost is typically a crucial driver for success to validate future investment, especially when a process is for consideration into a legacy product and requires a payback (return on investment) of two years. There are two cost factors.

Table 6-3 Cost Key Performance Factors and Their Definitions

Cost Key Performance Factor (KPF) Name	KPF Definition
Recurring Cost	Total recurring cost of the process for its direct application; typically the programme or manufacturing operations.
Non Recurring Cost	Total non-recurring cost of the process, the cost of the process when implemented into the programme or operations.

6.5.1.3 Quality Key Performance Factors

AMTs evaluated utilising these factors scores a higher performance output the more an AMT can enhance quality, when compared to an existing baseline. Within the aerospace manufacturing industry, quality is crucial to the success of a legacy or future product. If a process fails to meet the quality specification for its direct application, the development or implementation cannot commence. There are three quality factors.

Table 6-4 Quality Key Performance Factors and Their Definitions

Quality Key Performance Factor (KPF) Name	KPF Definition
Rework in Manufacture	The number of concessions for the process direct application.
Process Capability	Process capability performance (Cpk) for the direct application.
Number of Inspections	The number of inspections the process requires to conform to specification.

6.5.2 Key Performance Factor Intensity of Importance Weighting

Within the model operation, each of the KPFs listed previously are weighted by the model user with a KPF intensity of importance. The mathematical notation of the KPF intensity of importance was provided in Equations 6.9 - 6.11. The final KPF intensity of importance definitions were identified using the semi-structured interviews and workshops, listed in Table 6-5.

Table 6-5 KPF Intensity of Importance

KPF Intensity of Importance	Definition (Judgement)
1	Low Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Extreme Importance

The weighting of each KPF is converted by the final algorithm to a normalised output of 1.0, presented earlier in Equation 6.12. Experts agreed that the model should have the facilty of turning off a KPF by inputting a value of 0. This allowed performance forecasting comparison of diverse AMTs with a range of KPFs driving the development, permitting an apples to pears evaluation. This is crucial as many existing decision making and performance forecasting models evaluate multiple technology solutions for one application. PERFORMO provides the capability to evaluate a portfolio of diverse AMTs with varied applications.

6.6 PERFORMO Intangible Key Performance Factor Study Results

The PERFORMO Intangible KPFs feed into the final equation form presented earlier in Equation 6.20. The proceeding Sub Sections are the final outputs from the detailed research methodology (Figure 6-2) followed to define the KPFs for the Intangible model.

6.6.1 Intangible Key Performance Factors

Due to the qualitative nature of the intangible KPFs, a rating scale was required. This rating scale was not as easy to define as the KPFs within the Tangible model. To help assist with the novel KPFs for intangible AMT performance forecasting, each was placed into the following themes:

- Health and Safety. KPFs that predict the health and safety performance of implementing the AMT.
- Flexibility. KPFs that predict the flexibility performance of the AMT.
- Managerial/Operations. KPFs that predict the managerial and operational performance of the AMT.
- Risk. KPFs that quantify the risk for the AMT development and implementation.
- Strategic. KPFs that quantify the strategic performance of an AMT development.

Once each KPF was placed into the themes, rating scales were applied based on expert opinion. This formed Stage 3 of the KPF study within the detailed research methodology, illustrated in Figure 6-2. The rating scale defined by experts were presented earlier in Table 6-1 and included: Very Low, Low, Nominal, High and Very High. These linguistic ratings were similar to those used for each COTECHMO model, presented in Chapter 5. However, this scale has a nominal value of 0, not the logarithmic scale followed within COTECHMO. These were assigned qualitative ratings for each KPF, presented in the proceeding Sub Sections.

6.6.1.1 Health and Safety Key Performance Factors

The health and safety KPFs represent the impact of the AMT to the health and safety requirements. These subjective requirements can typically form fundamental drivers for many new AMT developments from changes in legislation. A typical example is the application of sealant within a fuel tank, involving an operator to climb in and manually apply sealant. A change in legislation could no longer allow the operator to climb within the fuel tank, generating a driver for the development of an automated approach. When evaluating as a Capital Expenditure (CapEX) business case, other projects would appear more financially viable. This identifies the importance of quantifying the health and safety factors for future business case analysis. For each of the health and safety KPFs, a higher rating equates to an increase in performance. There are three health and safety KPFs.

Table 6-6 Process Legislation Performance Definition

Process Legislation Performance Performance of process to meet legislation requirement (s) e.g. automated sealant to remove manual wing box entry.

Table 6-7 Process Legislation Performance Rating Scale

Extra Low	**Very Low**	**Low**	**Nominal**	**High**	**Very High**	**Extra High**
-3	**-2**	**-1**	**0**	**1**	**2**	**3**
Process highly disrupts existing legislation from extremely low legislation performance.	Process slightly disrupts existing from a lower than existing legislation performance	Process has lower than existing legislation performance.	Process replicates existing legislation performance	Process slightly exceeds existing legislation performance .	Process enhances existing operation but does not completely restructure.	Process restructures operation for advanced enhancement of existing legislation.

Table 6-8 Employee Relations Definition

Employee Relations Performance Performance of process learning, safety hazards or labour productivity.

Table 6-9 Improved Employee Relations Rating Scale

Extra Low	Very Low	Low	Nominal	High	Very High	Extra High
-3	**-2**	**-1**	**0**	**1**	**2**	**3**
≥3 performance degradation of the following: process learning, safety hazards and labour productivity.	≥2 performance degradation of the following: process learning, safety hazards and labour productivity.	≥1 performance degradation of the following: process learning, safety hazards and labour productivity.	Employee relations replicate existing operation.	≤ 1 performance enhancement of the following: process learning, safety hazards and labour productivity.	≤ 2 performance enhancement of the following: process learning, safety hazards and labour productivity.	≤ 3 performance enhancement of the following: process learning, safety hazards and labour productivity.

Table 6-10 Ergonomics Performance Definition

Ergonomics Performance
Process performance enhancement or degradation on ergonomics for its direct manufacturing application.

Table 6-11 Ergonomics Performance Rating Scale

Extra Low	Very Low	Low	Nominal	High	Very High	Extra High
-3	**-2**	**-1**	**0**	**1**	**2**	**3**
Process-human interaction is extremely complex with very low performance - significant further development.	Process-human interaction has medium complexity and very low performance - some further development	Process-human interaction has low complexity and low performance - minimal further development.	Ergonomics of the process replicate existing operation.	Process-human interaction with high performance.	Process-human interaction with very high performance	Streamlined process-human interaction.

6.6.1.2 Flexibility Key Performance Factors

The flexibility KPFs represent the impact the AMT has on the process and product flexibility. Following the health and safety forecasting factors discussed previously, flexibility can generate a subjective business driver for future product development. For both of the flexibility KPFs, a higher rating creates an increase in performance. There are two flexibility performance forecasting factors.

Table 6-12 Process Flexibility Definition

Process Flexibility
Capability of the process to increase the flexibility for its direct application e.g. decreased waiting time for parts, decreased work in progress.

Table 6-13 Process Flexibility Rating Scale

Extra Low	Very Low	Low	Nominal	High	Very High	Extra High
-3	**-2**	**-1**	**0**	**1**	**2**	**3**
Flexibility reduces > 50% of the existing operation.	Flexibility reduces > 20% of the existing operation.	Flexibility reduces > 10% of the existing operation.	Flexibility replicates existing operation.	Flexibility exceeds > 10% of the existing operation.	Flexibility exceeds >20% of the existing operation.	Flexibility exceeds >50% the existing operation.

Table 6-14 Product Flexibility Definition

Product Flexibility Capability of the process to enhance the product flexibility e.g. shorter cycle times and setups.

Table 6-15 Product Flexibility Rating Scale

Extra Low	Very Low	Low	Nominal	High	Very High	Extra High
-3	**-2**	**-1**	**0**	**1**	**2**	**3**
Product flexibility is reduced > 30%.	Product flexibility is reduced > 20%.	Product flexibility is reduced > 10%.	Product flexibility replicates existing.	Product flexibility increases > 10%.	Product flexibility increases > 20%.	Product flexibility increases > 30%.

6.6.1.3 Managerial/Operations Key Performance Factors

The managerial/operations KPFs represent the compatibility of the process with existing operations. This evaluates the complexity of implementing with the existing operation configuration and the learning advancement from a business perspective. Following the two previous intangible factor themes, a higher rating equates to an increased performance.

Table 6-16 Process Compatibility with Existing Operations Configuration Definition

Process Compatibility with Existing Operations Configuration Process compatibility with desired operational configuration. Higher risks are created from the development of non-legacy products/processes.

Table 6-17 Process Compatibility with Existing Operations Configuration Rating Scale

Extra Low	Very Low	Low	Nominal	High	Very High	Extra High
-3	**-2**	**-1**	**0**	**1**	**2**	**3**
Process incompatible with operations configuration. .	Process operations platform not defined; compatibility unknown.	Process operations platform part defined, low compatibility.	Existing operation with proven process compatibility (low novelty).	Process predicted compatible for part defined operation.	Process predicted compatible for fully defined operation.	Process fully compatible for seamless (planned) integration with fully defined operation.

Table 6-18 Technology Expansion Definition

Technology Expansion Learning advancement, further use, increased product/process innovations.

Table 6-19 Technology Expansion Rating Scale

Extra Low	Very Low	Low	Nominal	High	Very High	Extra High
-3	**-2**	**-1**	**0**	**1**	**2**	**3**
Extremely low process development novelty, only suited for specific application – no expansion.	Process development novelty very low, limited suitability for other applications.	Process development novelty low, limited suitability for other applications.	Moderate process development novelty, suited to an existing operation.	Process development novelty high, suited for one other product & process application.	Process development novelty high, suited to 2> future product & process developments.	Process development novelty extremely high, suited to 3> future product & process developments.

Table 6-20 Installation Complexity Definition

Installation Complexity Complexity of implementing the process within the assigned manufacturing application. A highly complex process would consist of many automation equipment installations.

Table 6-21 Installation Complexity Rating Scale

Extra High	Very High	High	Nominal	Low	Very Low	Extra Low
-3	**-2**	**-1**	**0**	**1**	**2**	**3**
Complexity installation procedure completely unknown.	Extremely complex: installation procedure exceeds existing process installation and similar developments.	Very complex: installation procedure exceeds existing process.	Moderately complex: installation procedure similar to existing process to replace.	Complexity slightly lower than exiting process installation procedure.	Complexity of very low levels: lower than existing process implementation and existing developments.	Complexity of extremely low levels: much lower than existing process implementation and existing developments.

6.6.1.4 Risk Key Performance Factors

The risk KPFs forms a crucial analysis for the development of a new AMT. The first risk KPF captures the development risk with the second KPF capturing the implementation risk. If the risk is too high, many AMTs are not selected for development. In reverse to the previous factor themes, a lower rating generates a performance enhancement.

Table 6-22 Development Risk Definition

Development Risk Risk of developing the process – higher risk if the process is completely novel.

Table 6-23 Development Risk Rating Scale

Extra High	Very High	High	Nominal	Low	Very Low	Extra Low
-3	**-2**	**-1**	**0**	**1**	**2**	**3**
Process not proven or developed in any domain, completely novel.	Process developed to low level (TRL3-6) in 1> non-aerospace domain.	Process developed to high level (TRL6-9) in 1> non-aerospace domain.	Process developed, implemented and proven in 1> non-aerospace domain e.g. automotive manufacture.	Process developed, implemented and proven within 3> non-aerospace domains.	Process developed, implemented and proven within 1> coherent aerospace domain.	Process developed, implemented and proven throughout the aerospace industry.

Table 6-24 Implementation Risk Definition

Implementation Risk Risk of the manufacturing process disrupting or impacting the new or existing manufacturing operational infrastructure.

Table 6-25 Implementation Risk Rating Scale

Extra High	Very High	High	Nominal	Low	Very Low	Extra Low
-3	**-2**	**-1**	**0**	**1**	**2**	**3**
Extreme operational disruption predicted; many unknowns.	Very high operational disruption predicted; many unknowns.	High operational disruption predicted; many unknowns.	High operational disruption predicted, partly documented implementation procedure.	Low operational disruption predicted, partly documented implementation procedure.	Low operational disruption predicted, fully documented implementation procedure.	No operational disruption, fully documented implementation procedure.

6.6.1.5 Strategic Key Performance Factors

The strategic KPFs predict the suitability and alignment of the AMT with future strategic plans. These KPFs are crucial for the future financial and technical success of the business. With large product and operational lifecycles, the aerospace manufacturing domain requires careful planning and documentation of future product manufacturing vision and requirements. There are two strategic factors, with a higher rating generating an increase in strategic performance.

Table 6-26 Manufacturing Vision Definition

Manufacturing Vision Vision and alignment of the process with future manufacturing strategies.

Table 6-27 Manufacturing Vision Rating Scale

Extra Low	Very Low	Low	Nominal	High	Very High	Extra High
-3	**-2**	**-1**	**0**	**1**	**2**	**3**
Process has no scope for inclusion with any future manufacturing strategy.	Process has limited scope for inclusion with future manufacturing strategy.	Process planned for inclusion within future manufacturing strategy for >5 years.	Process planned for inclusion within future manufacturing strategy for >10 years.	Process planned for inclusion within future manufacturing strategy for >15 years.	Process planned for inclusion within future manufacturing strategy for >20 years.	Process planned for inclusion within future manufacturing strategy for >25 years.

Table 6-28 Future Product Vision Definition

Future Product Vision Requirements of the manufacturing process for the manufacture of future products e.g. future aircraft programme composite assembly.

Table 6-29 Future Product Vision Rating Scale

Extra Low	Very Low	Low	Nominal	High	Very High	Extra High
-3	**-2**	**-1**	**0**	**1**	**2**	**3**
Process not part of any future product manufacturing requirement.	Process has potential for low levels of inclusion for future manufacturing requirement.	Process has documentation for low levels of inclusion for future manufacturing requirement.	Process required to manufacture 1> partially documented future product.	Process required to manufacture 1> fully documented future product.	Process required to manufacture 2> fully documented future products.	Process required to manufacture 3> fully documented future products.

6.6.2 Key Performance Factor Intensity of Importance Weighting

Within the model operation, each of the intangible KPFs listed previously are weighted by the model user with a KPF intensity of importance. The mathematical notation of the KPF intensity of importance was provided in Equations 6.14 - 6.18. The final KPF intensity of importance definitions were clarified using the semi-structured interviews and workshops, the same as those used within the Tangible model, listed earlier in Table 6-5. The weighting of each KPF is converted by the final algorithm to a normalised output value of 1.0, defined earlier in Equation 6.19. Following the format of the Tangible model, experts agreed that it should have the facilty of turning a KPF off by inputting a 0 into the KPF intensity of importance. This allowed performance forecasting comparison of diverse AMTs with varied applications and a range of KPFs driving the development.

6.7 PERFORMO Model Development

Using the detailed research methodology presented in Figure 6-3, prototype PERFORMO Tangible and Intangible forecasting models were developed in MS Excel. This formed Phase 2 of the detailed research methodology and involved initial qualitative validation with industry experts and enhancing from feedback where applicable. The first stage of this task included presenting the prototype models to the AMT development experts listed in Appendix A7, Table A7-1. Their feedback was recorded and implemented accordingly. Key feedback notes included:

- Use of a colour system to define a performance enhancement or degradation e.g. a performance enhancement colour coded green, with a degradation red.
- Identify the clustering of the KPFs within the models.

The models were then edited and refined using the constructive feedback and presented to the same AMT experts. Each of the experts agreed the models fulfilled the initial requirements specified in Section 6.3 and were suitable for use within R&T of the aerospace manufacturing industry. To further validate the refined models, they were presented at the Low Cost Manufacturing and Assembly of Composite and Hybrid Structures (LOCOMACHS) launch meeting, with excellent feedback from each of the 21 industrial partners. This initial model validation formed a suitable platform to test each model for assessment of 15 novel AMTs within the aerospace manufacturing industry, providing verification and validation. Further verification and validation was provided by testing each model for evaluation of 8 AMTs with known conclusions. Each is detailed and discussed within Chapter 8.

The final developed MS Excel PERFORMO Tangible model user interface is shown in Chapter 7, Figure 7-9. This interface forms part of the Cost-Benefit Forecasting Framework, with the operation presented in Chapter 7, Sub Section 7.4.5, Step 4A.

The MS Excel PERFORMO Intangible model user interface is shown in Chapter 7, Figure 7-11. This interface also forms part of the Cost-Benefit Forecasting Framework, with the operation described in Chapter 7, Sub Section 7.4.6, Step 4B.

6.8 Chapter Summary and Key Observations

This Chapter has presented the detailed development of two performance forecasting models. The first model is for forecasting the tangible performance of an AMT at the initial development stages. The second is for forecasting the intangible performance, also at the early development stages.

Section 6.2 presented the detailed research methodology followed for the development of each model. In Section 6.3 the model requirements from the aerospace manufacturing industry were detailed. In Section 6.4 the chosen model forms were presented and broken down into Tangible and Intangible performance models, detailing the full mathematical notation. Section 6.5 presented the results from the Tangible model KPF study, finalising the KPFs used within the model. Section 6.6 performed a similar study for the intangible KPFs, although this included qualitative ratings for each KPF, aligned with a numerical weighting scale. In Section 6.7 the models development in MS Excel was described, identifying minor reiterations made to each model specified from industry feedback. To verify and validate each PERFORMO model, a detailed industrial case study is performed in Chapter 8.

Each PERFORMO model presented within this Chapter is for quantifying the ‘y-axis’ of Figure 5-8, presented at the end of Chapter 5. Each COTECHMO model presented in Chapter 5 was for quantifying the ‘x-axis.’ To meet the industrial requirements specified in Chapter 4 and operate each model with a systematic user guide, a Cost-Benefit Forecasting Framework is presented in the following Chapter.

CHAPTER 7

A COST-BENEFIT FORECASTING FRAMEWORK FOR ASSESSMENT OF ADVANCED MANUFACTURING TECHNOLOGY

7.1 Introduction

Chapter 4 defined the requirements for an enhanced management of Advanced Manufacturing Technology (AMT) development process map, to justify and allocate Research and Technology (R&T) investment. The first requirement determined a need for an improved AMT development cost estimation technique, with Chapter 5 responding with the development of two parametric COTECHMO models. The second requirement defined a need for two models capable of forecasting AMT performance at the initial stages of development. The developed (PERFORMO) models fulfilled this requirement, with each detailed and presented in Chapter 6.

To operate each COTECHMO and PERFORMO model within an industrial setting and provide development value, a novel framework is required. The framework is desired to guide the user to plot outputs from each of the COTECHMO and PERFORMO models into Development Value Advice (DEVAL) graphs, with an example illustrated in Chapter 5, Figure 5-6. These outputs are used for the assessment of a portfolio of AMTs for forecasting value at the initial development stages. This detailed assessment provides the Cost-Benefit Framework user with the information to define which AMTs provide the business with the best R&T investment value. This Chapter presents a novel Cost-Benefit Forecasting Framework and is organised in the following structure. In Section 7.2, the detailed research methodology used for the development of the Cost-Benefit Forecasting Framework is described. Section 7.3 presents and explains the detailed framework requirements. Section 7.4 describes the developed Cost-Benefit Forecasting Framework, detailing each of the individual stages, including the operation of COTECHMO, PERFORMO and their application into DEVAL. The Chapter concludes in Section 7.5 with the summary and key observations.

7.2 Detailed Research Methodology

Figure 7-1 presents an overview of the research methodology used for the development of the Cost-Benefit Forecasting Framework. This feeds into Phase 4 of the overall research methodology presented in Chapter 3, Figure 3-2.

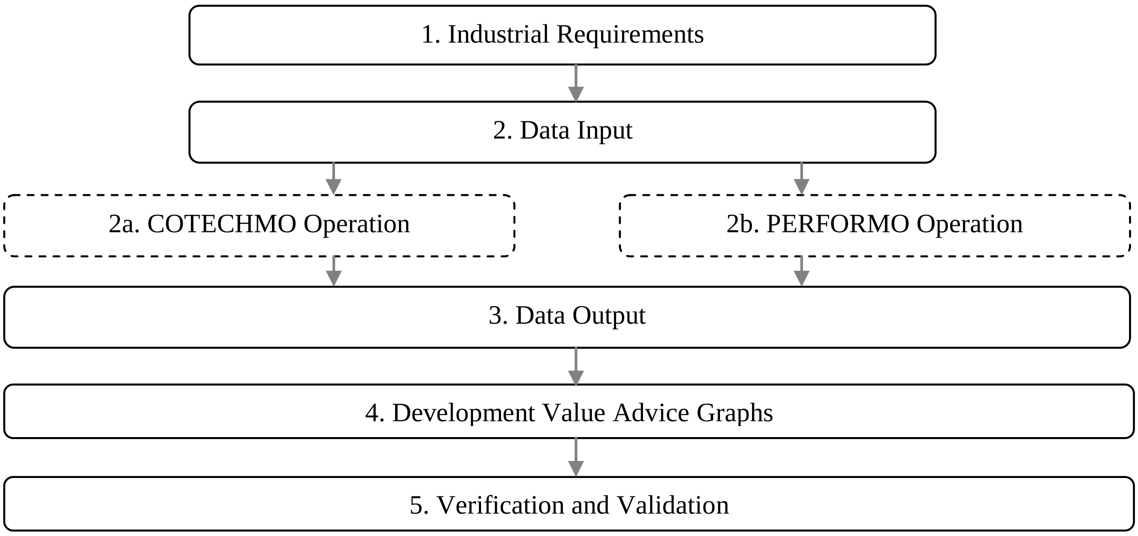

Figure 7-1 Research Methodology for the Cost-Benefit Framework Development, Verification and Validation

Step 1 involved defining the detailed industrial requirements, illustrated as an overview in Chapter 4, Figure 4-6. The primary focus was the operation of each COTECHMO and PERFORMO model. This involved studying the data input requirements for each model, forming Step 2 of the detailed research methodology. The data output from each model was the next Step, with identification crucial for the correct formation of the development value graphs in Step 4. Step 5 involves the detailed verification and validation of the Cost-Benefit Forecasting Framework within an industrial setting. This is presented and discussed in detail within Chapter 8.

7.3 Cost-Benefit Forecasting Framework Requirement Results

Chapter 4 defined an overview of the Cost-Benefit Forecasting Framework requirements. Within this detailed analysis, experts stated the framework needs to systematically operate the COTECHMO and PERFORMO MS models and feed the outputs into Development Value Advice (DEVAL) graphs. Following the development of COTECHMO and PERFORMO, the final DEVAL outputs were required in MS Excel. This modular approach allowed the operation of all the models within the framework.

Additionally, the framework must act as a central storage system for all AMTs evaluated within the business, allowing full traceability of all AMTs selected for development. The following are a detailed list of further industrial requirements:

- Usability

The framework should provide a data input flow from a detailed user interface and operate each of the COTECHMO and PERFORMO models. This must provide the data outputs for each of the DEVAL graphs. The framework must be suitable for the initial stages of AMT development and provide a robust forecasting process within an R&T function.

- Accuracy

The overall framework must be verified using at least 10 diverse AMT cases within the aerospace manufacturing industry. The DEVAL output must be validated within the business, using expert feedback for the development value advice of the AMTs under evaluation.

- Flexibility

The framework should be capable of forecasting cost-benefit for a diverse range of AMTs with vaired applications within the aerospace manufacturing industry.

- Data capture

The MS Excel based framework must be capable of storing all AMTs assessed within a central database. This enables future referencing of AMT development data.

7.4 Cost-Benefit Forecasting Framework

Figure 7-2 outlines the final developed Cost-Benefit Forecasting Framework. The following Sub Sections detail each of the individual Stages.

7.4.1 Stage 1 - User Information

Stage 1 of the framework involves inputting the user name and date of the AMT evaluation. This records their details and location within the business, allowing full traceability of decisions made at the initial stages of development.

7.4.2 Stage 2 - AMT Identification

This Stage involves identifying AMTs selected within the business for assessment. For each of the selected AMTs, the most recent TRL reviews are captured, along with the identification of the expert(s) involved with the specific development. This ensures that the development information is completely up to date and compiled ready for forecasting in the proceeding Stages of the framework.

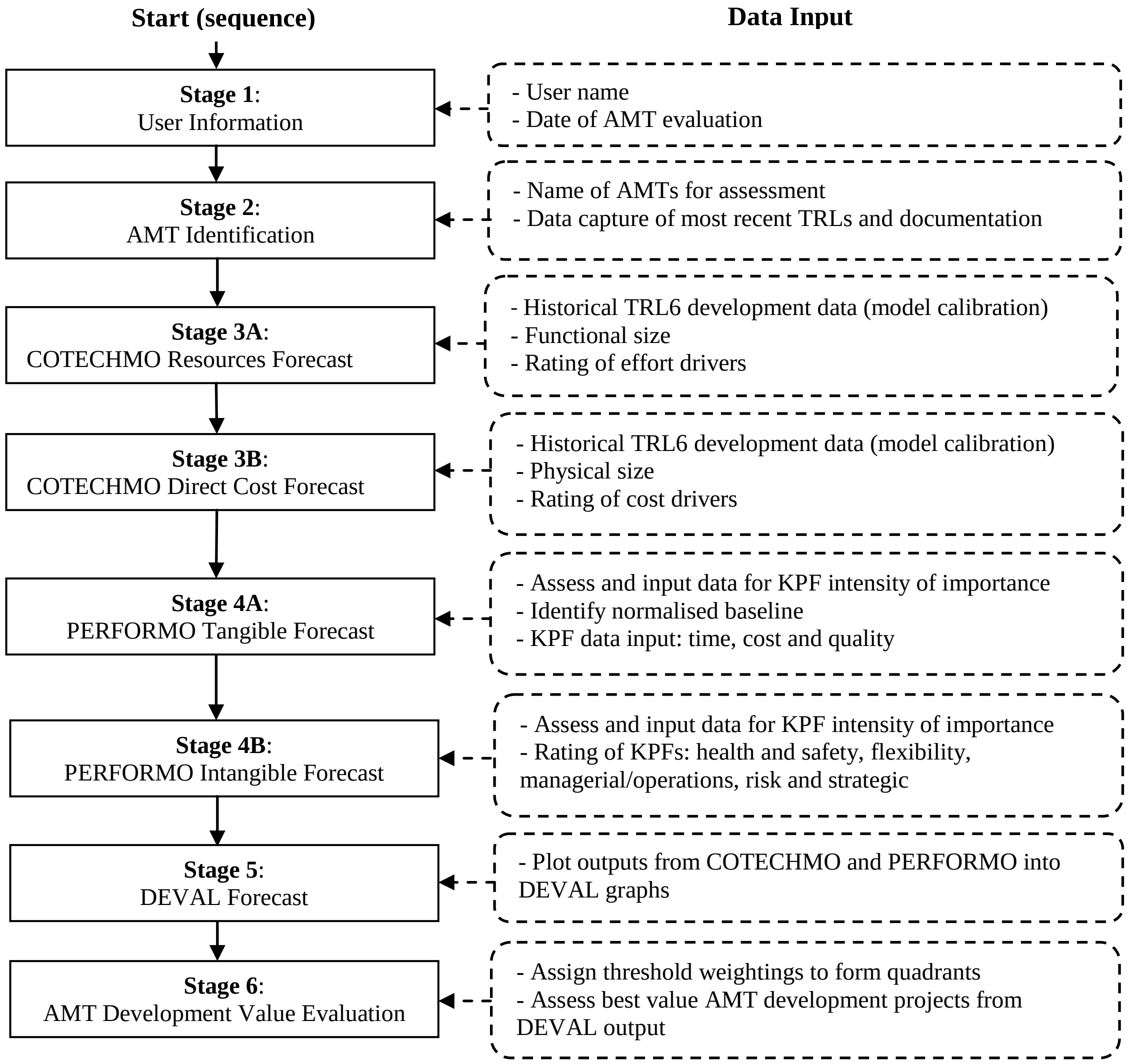

Figure 7-2 Developed Cost-Benefit Forecasting Framework for AMT Evaluation

7.4.3 Stage 3A - COTECHMO Resources (person-hours) Forecast

The first forecasting assessment involves utilising the COTECHMO Resources (person-hours) model, derived and discussed within Chapter 5, Section 5.4.1. The first step of performing a COTECHMO Resources forecast involves capturing data from historical AMT developments to TRL6. At TRL6 the AMT is developed to full scale for its direct application and ready for delivery into manufacturing operations. The toolset for historical

TRL person-hours data capture is shown in Table 7-1. Only data from AMTs fully developed to TRL6 is suitable for the model calibration. Unsuccessful projects are not suitable for the model calibration.

Table 7-1 Historical Technology Readiness Level Person-hours Data Collection Toolset

TRL1	TRL2	TRL 3	TRL4	TRL 5	TRL 6	Total Development Person-hours
0	0	0	0	0	0	0

The TRL historical data is input into the total effort table within the framework, with example data listed in Table 7-2. The mean is taken of the person-hours TRL development data, for the example shown 3,468 person-hours.

Table 7-2 Historical Technology Readiness Level Person-hours Data Collection Toolset

AMT Number	Total Person-hours
1	2,000
2	2,205
3	1,620
4	10,000
5	11,000
6	1,200
7	440
8	9,500
9	1,560
10	1,200
11	700
12	6,000
13	1,400
14	1,300
15	1,900
Mean	**3,468**

The next stage involves calibrating the model size driver by calculating the mean functional size for the AMTs listed in Table 7-2. The total functional size for these AMTs was 1000, thus 1000 divided by 15 is 66.66. Therefore, to equate the mean output of 3,468 person-hours with nominal complexity, the calibration constant is 52.15. This forms the final calibration factor (*A*) presented in Chapter 5, Equation 5.2. Figure 7-3 illustrates the summary of this data calibration exercise. This diagram is for illustration purposes only and is not to scale.

Now the model has been calibrated, the next step of the framework involves using the MS Excel COTECHMO Resources model to forecast development person-hours for the selected AMTs. The model user interface is shown in Figure 7-4.

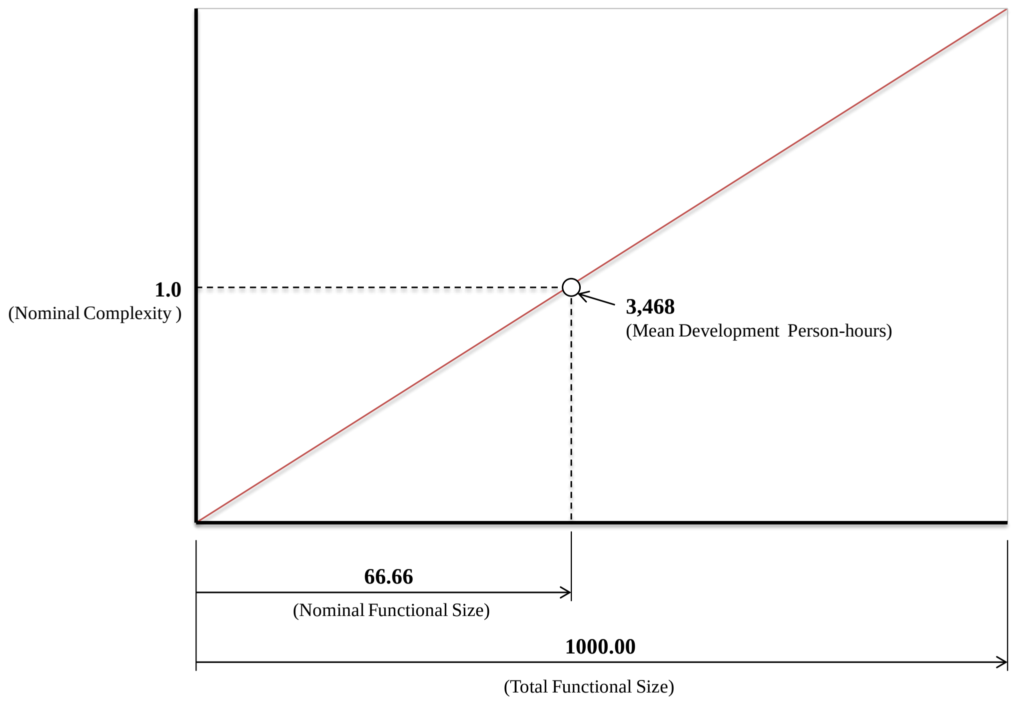

Figure 7-3 Example COTECHMO Resources Calibration

The application functional size requirements are illustrated at the top of the model interface. These are counted from the AMT documentation, quantitative information that should be available at TRL1-2. When this level of detail is not available, surrogate sources must be captured. These would typically include data from similar AMT developments. The elaborations of each size driver and its descriptive rating scale were listed in Chapter 5, Sub Section 5.5.1. Defining the quantity and complexity of each size driver is crucial to the model forecasting accuracy. Therefore, the model user must refer to the exact description of each size driver and its relative weighting.

	Complexity of Requirement			
Functional Size	**Easy**	**Nominal**	**Difficult**	
# Geometric Requirements	0	0	0	
# Process Steps	0	0	0	
# Test Pieces	0	0	0	
Effort Drivers				
Development Team Factors	**Rating**			
TRL Pack Experience	**N**	1.00		
Product Application Experience	**N**	1.00		
Process Experience	**N**	1.00		
Requirements Understanding	**N**	1.00		
Supplier Network Availability and Capability	**N**	1.00		
Demonstration & Application Factors	**Rating**			
Datum Complexity	**N**	1.00		
Test Piece Material Complexity	**N**	1.00		
Installation Complexity	**N**	1.00		
Degree of Process Novelty	**N**	1.00		
Project Factors	**Rating**			
Required Development Schedule	**N**	1.00		
Manufacturing Documentation of Requirements	**N**	1.00		
Location Variation of Trials and Tests	**N**	1.00		
Product Rate Factor	**Rating**			
Production Rate Requirements	**N**	1.00		
		1.00	Composite Effort Multiplier	
	AMT Development Person-hours	**0**		

Figure 7-4 COTECHMO Resources MS Excel Model Interface

The next step involves rating the cost drivers. Due to the qualitative nature of these drivers, the rating is more subjective than the functional size drivers discussed previously. To keep rating subjectivity to a minimum, full descriptions of each driver have been utilised from expert opinion and historical AMT development data, for the rating scale used: Very Low, Low, Nominal, High and Very High. The model user must reference these detailed rating descriptions when conducting the forecast. The full descriptions for each effort driver were listed in Chapter 5, Sub Section 5.5.2. A colour scheme is utilised within the model, with red identifying an increase in development effort for that specific cost driver, green a reduction and neutral having no impact. An example forecast using the COTECHMO Resources model is shown in Figure 7-5.

	Complexity of Requirement		
Functional Size	**Easy**	**Nominal**	**Difficult**
# Geometric Requirements	20	0	5
# Process Steps	30	0	0
# Test Pieces	0	30	0

Effort Drivers		
Development Team Factors	**Rating**	
TRL Pack Experience	**L**	1.22
Product Application Experience	**H**	0.77
Process Experience	**N**	1.00
Requirements Understanding	**L**	1.22
Supplier Network Availability and Capability	**H**	0.85
Demonstration & Application Factors	**Rating**	
Datum Complexity	**VH**	1.28
Test Piece Material Complexity	**H**	1.22
Installation Complexity	**L**	0.87
Degree of Process Novelty	**L**	0.79
Project Factors	**Rating**	
Required Development Schedule	**N**	1.00
Manufacturing Documentation of Requirements	**L**	1.22
Location Variation of Trials and Tests	**N**	1.00
Product Rate Factor	**Rating**	
Production Rate Requirements	**H**	1.37
		1.76 Composite Effort Multiplier

AMT Development Person-hours **7,793**

Figure 7-5 COTECHMO Resources MS Excel Model Example Estimate

7.4.4 Stage 3B - COTECHMO Direct Cost Forecast

The second forecasting assessment involves utilising the COTECHMO Direct Cost model, derived and detailed within Chapter 5, Section 5.4.2. Following the format of the previous COTECHMO forecast, the first step of performing a COTECHMO Direct Cost estimate involves capturing historical development data, for successful AMT developments to TRL6. Unsuccessful development projects are not suitable for the model calibration. The toolset for historical TRL direct cost data capture is shown in Table 7-3.

Table 7-3 Historical Technology Readiness Level Direct Cost Data Collection Toolset

TRL1	TRL2	TRL 3	TRL4	TRL 5	TRL 6	Total TRL Development Direct Cost
0	0	0	0	0	0	0

The output of the data capture toolset for each historical AMT development is then input into the total direct cost data capture table. The data input for this example is listed in Table 7-4. Following the form of the

COTECHMO Resources model, the mean is taken of all input historical development data, in this instance €881,933.

Table 7-4 Historical Technology Readiness Level Direct Cost Data Collection Toolset

AMT Number	Direct Cost (€)
1	1,000,000
2	500,000
3	140,000
4	235,000
5	1,000,000
6	2,000,000
7	650,000
8	2,200,000
9	1,920,000
10	900,000
11	874,000
12	205,000
13	160,000
14	550,000
15	895,000
Mean	**881,933**

The next step involves calibrating the model size driver, by calculating the mean physical size for the example AMTs listed in Table 7-4. The total physical size for these AMTs was 2,000m^3, thus 2,000m^3 divided by 15 is 133.33m^3. Therefore, to equate the mean output of €881,933 with nominal complexity, the calibration constant is 6,630. This forms the final calibration factor (*A*) presented in Chapter 5, Equation 5.4. Figure 7-6 illustrates the summary of this data calibration exercise. This diagram is for illustration purposes only and is not to scale.

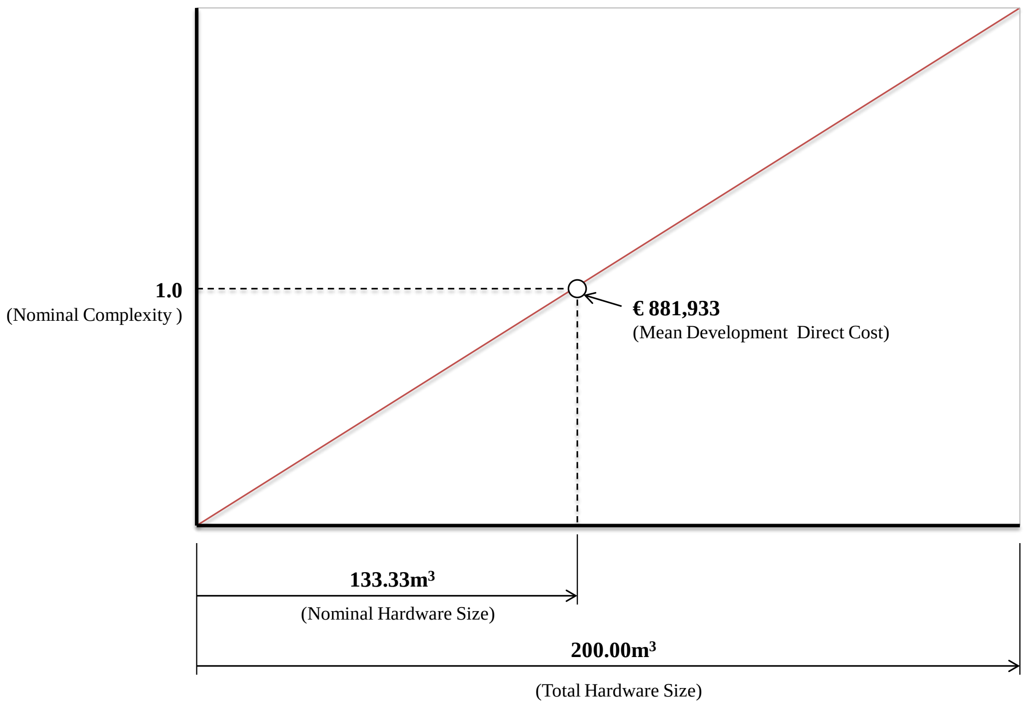

Figure 7-6 Example COTECHMO Direct Cost Calibration

Now the model has been calibrated, the next step of the framework involves using the MS Excel COTECHMO Direct Cost model to forecast development direct cost for the selected AMTs. The model user interface is shown in Figure 7-7.

The COTECHMO Direct Cost model uses physical volume of the AMT, illustrated at the top of the interface. The physical size of the AMT should be available at the initial development stages, TRL1-2. As advised previously for the operation of the Resources model, if exact measurements are not available, then surrogate sources of data must be input into the model. Typical surrogate sources could include quantifying the size of a similar AMT development.

Required Size of AMT Process	Width	Height	Length
Process Hardware Size (Meters)	0	0	0

Cost Drivers			
Primary Process Factors	**Rating**		
# Geometric Accuracy Requirements	**N**	1.00	
# Process Steps	**N**	1.00	
Process Capability Requirements	**N**	1.00	
Degree of Process Novelty	**N**	1.00	
Installation Complexity	**N**	1.00	
Secondary Process Factors	**Rating**		
Manufacturing Environment Requirements	**N**	1.00	
Automation Level Requirements	**N**	1.00	
Test Piece Material Complexity	**N**	1.00	
Process Test and Verification Requirements	**N**	1.00	
External Process Factors	**Rating**		
Metrology Requirements	**N**	1.00	
Human Factors Requirements	**N**	1.00	
Tooling Requirements	**N**	1.00	
Product Rate Factor	**Rating**		
Production Rate Requirements	**N**	1.00	
		1.00	Composite Cost Multiplier
	AMT Development Direct Cost	**€ 0**	

Figure 7-7 COTECHMO Direct Cost MS Excel Model Interface

The next step of conducting a Direct Cost forecast includes rating each cost driver. Due to the qualitative form of these drivers, the rating is far more subjective than quantifying the physical volume of the AMT process. The rating of each driver follows the form used within the Resources model: Very Low, Low, Nominal, High and Very High. Full descriptions of the ratings must be followed when operating the model for an AMT assessment. The descriptions for each cost driver are listed in detail within Chapter 5, Sub Section 5.6.2. Following the format of the previous Resources model, a colour scheme is utilised, with red indicating an increase in development direct cost for that specific cost driver, green a reduction and neutral having no impact. An example forecast using the COTECHMO Direct Cost model is shown in Figure 7-8.

Required Size of AMT Process	Width	Height	Length
Process Hardware Size (Meters)	10	6	4

Cost Drivers		
Primary Process Factors	**Rating**	
# Geometric Accuracy Requirements	L	0.60
# Process Steps	H	1.48
Process Capability Requirements	H	1.48
Degree of Process Novelty	H	1.49
Installation Complexity	L	0.90
Secondary Process Factors	**Rating**	
Manufacturing Environment Requirements	L	0.90
Automation Level Requirements	N	1.00
Test Piece Material Complexity	L	0.72
Process Test and Verification Requirements	L	0.90
External Process Factors	**Rating**	
Metrology Requirements	N	1.00
Human Factors Requirements	N	1.00
Tooling Requirements	N	1.00
Product Rate Factor	**Rating**	
Production Rate Requirements	N	1.00
	Composite Cost Multiplier	1.03
	AMT Development Direct Cost	**€ 1,635,482**

Figure 7-8 COTECHMO Direct Cost MS Excel Model Example Estimate

7.4.5 Stage 4A - PERFORMO Tangible Forecast

On completion of each COTECHMO forecast for the selected AMTs, the PERFORMO forecasting assessments are performed. The first PERFORMO model captures the tangible Key Performance Factors (KPFs), in the form of time, cost and quality, derived and discussed in Chapter 6, Sub Section 6.4.1. To conduct a PERFORMO Tangible assessment, the developed MS Excel model is utilised, with the user interface illustrated in Figure 7-9.

The first step of operating the model involves the user rating each of the 12 KPF, performed using the definition (judgement) scale, illustrated on the bottom left of the user interface. This scale ranges from low importance (1) to extreme importance (9). When a KPF falls between the definitions, intensities of 2, 4, 6, and 8 can be used to express intermediate values.

AMT Tangible Performance Forecast									
Metric Name	**Key Performance Factor (KPF)**	**Datum Baseline**	**Min Change**	**Most Likely Change**	**Max Change**	**Mean Change**	**KPF Intensity of Importance**	**Weighting**	**Estimate**
Time (Hours)	Process TAKT Time	1.00	1.00	1.00	1.00	1.00	1.00	0.08	1.00
	Process Waste	1.00	1.00	1.00	1.00	1.00	1.00	0.08	1.00
	Process Person-hours	1.00	1.00	1.00	1.00	1.00	1.00	0.08	1.00
	Process Up Time	1.00	1.00	1.00	1.00	1.00	1.00	0.08	1.00
	Service Cycle Time	1.00	1.00	1.00	1.00	1.00	1.00	0.08	1.00
	Process Lifecycle Time	1.00	1.00	1.00	1.00	1.00	1.00	0.08	1.00
	Process Lag Time	1.00	1.00	1.00	1.00	1.00	1.00	0.08	1.00
Cost (Euros)	Recurring Cost	1.00	1.00	1.00	1.00	1.00	1.00	0.08	1.00
	Non Recurring Cost	1.00	1.00	1.00	1.00	1.00	1.00	0.08	1.00
Quality	Rework in Manufacture	1.00	1.00	1.00	1.00	1.00	1.00	0.08	1.00
	Process Capability	1.00	1.00	1.00	1.00	1.00	1.00	0.08	1.00
	# Inspections	1.00	1.00	1.00	1.00	1.00	1.00	0.08	1.00

KPF Intensity of Importance	**Definition (Judgement)**
1	Low Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Extreme Importance

Tangible Performance	**1.00**

Figure 7-9 PERFORMO Tangible MS Excel Model Interface

Weightings for each KPF is then converted by the model into a normalised weighting, with the option to turn a KPF off by inputting a value of 0. The normalised weight totals 1.0, even when a metric is turned off, allowing evaultion of diverse AMTs. The mathematical notation was derived and discussed in Chapter 6, Sub Section 6.4.1.

The next step involves the identification of a datum baseline for comparison. When a baseline for comparison is available, data is entered into the minimum change, most likely change and maximum change cells, shown within the user interface. If baseline data is not available, the baseline is taken at a value of 1.0, with the minimum, most likely and maximum change derived as a percentage from the baseline. For example, if an AMT baseline is taken at a value of 1.0, the expert forecasts the minimum reduction from this baseline at 5% (entering 0.95), most likely reduction at 10% (entering 0.90) and maximum reduction from the baseline at 15% (entering 0.85). To help guide the user and evaluate individual KPF performance, a colour scheme is used with a performance degradation identified in red, performance enhancement as green and a neutral impact in white. An example tangible performance forecast is shown in Figure 7-10.

AMT Tangible Performance Forecast									
Metric Name	**Key Performance Factor (KPF)**	**Datum Baseline**	**Min Change**	**Most Likely Change**	**Max Change**	**Mean Change**	**KPF Intensity of Importance**	**Weighting**	**Estimate**
Time (Hours)	Process TAKT Time	107.00	53.00	50.50	48.00	50.50	4.00	0.09	2.12
	Process Waste	26.00	2.00	1.00	1.00	1.17	3.00	0.07	22.29
	Process Person-hours	258.00	140.00	133.00	127.00	133.17	6.00	0.14	1.94
	Process Up Time	1.00	1.00	1.00	1.00	1.00	4.00	0.09	1.00
	Service Cycle Time	4.00	4.00	3.00	2.00	3.00	8.00	0.18	1.33
	Process Lifecycle Time	3,220	11,500	12,000	12,880	12,063	1.00	0.02	3.75
	Process Lag Time	110.00	37.00	35.50	34.00	35.50	2.00	0.05	3.10
Cost (Euros)	Recurring Cost	45,000	40,000	38,000	36,000	38,000	9.00	0.20	1.18
	Non Recurring Cost	60,000	110,000	105,000	100,000	105,000	2.00	0.05	0.57
Quality	Rework in Manufacture	10.00	4.00	3.00	2.00	3.00	0.00	0.00	3.33
	Process Capability	48.00	4.00	2.00	1.00	2.17	0.00	0.00	0.05
	# Inspections	1.00	1.00	1.00	1.00	1.00	5.00	0.11	1.00

KPF Intensity of Importance	**Definition (Judgement)**
1	Low Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Extreme Importance

Tangible Performance	**2.92**

Figure 7-10 PERFORMO Tangible MS Excel Model Example Forecast

7.4.6 Stage 4B - PERFORMO Intangible Forecast

The second performance forecasting assessment of the AMTs selected involves utilising the PERFORMO Intangible model, derived and discussed within Chapter 6, Sub Section 6.4.2. To conduct an Intangible PERFORMO assessment, the developed MS Excel model is utilised, with the user interface illustrated in Figure 7-11.

Following the format of the previous PERFORMO forecast, the first Stage of operating the Intangible model involves rating the KPF intensity of importance, for each KPF, within the MS Excel Intangible model. This scale ranges from low importance (1) to extreme importance (9) and when a KPF falls between the definitions, intensities of 2, 4, 6, and 8 can be used to express intermediate values. Each KPF weighting is converted by the model into a normalised output and has the option to turn a KPF off, inserting a value of 0. The normalised weight totals 1.0, even when a metric is turned off, with the mathematical notation derived and discussed in Chapter 6, Sub Section 6.4.2.

AMT Intangible Performance Forecast					
Metric Name	**Key Performance Factor (KPF)**	**Performance Rating**		**KPF Intensity of Importance**	**Weighting**
H&S Advancement	Process Legislation Performance	**N**	0	1.00	0.08
	Employee Relations Performance	**N**	0	1.00	0.08
	Ergonomics Performance	**N**	0	1.00	0.08
Increased Flexibility	Process Flexibility	**N**	0	1.00	0.08
	Product Flexibility	**N**	0	1.00	0.08
Managerial/Operations	Process Compatibility	**N**	0	1.00	0.08
	Technology Expansion	**N**	0	1.00	0.08
	Installation Complexity	**N**	0	1.00	0.08
Risk	Development Risk	**N**	0	1.00	0.08
	Implementation Risk	**N**	0	1.00	0.08
Strategic Objectives	Manufacturing Vision	**N**	0	1.00	0.08
	Future Product Vision	**N**	0	1.00	0.08
				12.00	1.00

KPF Intensity of Importance	**Definition (Judgement)**
1	Low Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Extreme Importance

Intangible Performance	**0.00**

Figure 7-11 PERFORMO Intangible MS Excel Model Interface

The next step of utilising the Intangible model involves rating each of the KPFs. Due to their qualitative nature, the rating is more subjective than the tangible KPFs discussed previously. To keep rating subjectivity to a minimum, full descriptions of each KPF have been utilised from expert opinion, for each rating scale used: Extra Low, Very Low, Low, Nominal, High, Very High and Extra High. Rating descriptions for each KPF must be referenced by the model operator when conducting an assessment. Full descriptions for each KPF rating were listed in Chapter 6, Sub Section 6.6.1. The colour scheme utilised for each KPF follows the Tangible model, with a performance enhancement in green, degradation in red and neutral in white. A typical forecasting example is illustrated in Figure 7-12.

AMT Intangible Performance Forecast					
Metric Name	**Key Performance Factor (KPF)**	**Performance Rating**		**KPF Intensity of Importance**	**Weighting**
H&S Advancement	Process Legislation Performance	**EH**	3	9.00	0.12
	Employee Relations Performance	**N**	0	1.00	0.08
	Ergonomics Performance	**H**	1	1.00	0.07
Increased Flexibility	Process Flexibility	**L**	-1	1.00	0.01
	Product Flexibility	**N**	0	1.00	0.01
Managerial/Operations	Process Compatibility	**N**	0	1.00	0.11
	Technology Expansion	**VH**	2	1.00	0.11
	Installation Complexity	**H**	-1	1.00	0.09
Risk	Development Risk	**H**	-1	1.00	0.09
	Implementation Risk	**H**	-1	1.00	0.09
Strategic Objectives	Manufacturing Vision	**EH**	3	1.00	0.11
	Future Product Vision	**EH**	3	1.00	0.09
				12.00	1.00

KPF Intensity of Importance	**Definition (Judgement)**
1	Low Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Extreme Importance

Intangible Performance **0.96**

Figure 7-12 PERFORMO Intangible MS Excel Model Example Forecast

7.4.7 Stage 5 - DEVAL Forecast

Stage 5 of the Cost-Benefit Forecasting Framework involves capturing data outputs from each COTECHMO and PERFORMO model and plotting into Development Value Advice (DEVAL) graphs. This operation and output provides the R&T portfolio assessor with data to illustrate the development value of each selected AMT. AMT evaluation is presented by quantifying the 'x-axis,' utilising each COTECHMO model (Stage 3A and 3B of the framework) and the 'y-axis' with each PERFORMO model (Stage 4A and 4B of the framework). The data is plotted within each DEVAL graph using the following equation forms:

$$Development\ Value\ 1 = \frac{COTECHMO\ Resources\ (person{-}hours)}{PERFORMO\ (Tangible)} \quad \text{(Eqn. 7.1)}$$

$$Development\ Value\ 2 = \frac{COTECHMO\ Direct\ Cost\ (€)}{PERFORMO\ (Tangible)} \quad \text{(Eqn. 7.2)}$$

$$Development\ Value\ 3 = \frac{COTECHMO\ Resources\ (person{-}hours)}{PERFORMO\ (Intangible)} \quad \text{(Eqn. 7.3)}$$

$$Development\ Value\ 4 = \frac{COTECHMO\ Direct\ Cost\ (€)}{PERFORMO\ (Intangible)} \quad \text{(Eqn. 7.4)}$$

To capture the data and feed into the development value equations, a DEVAL data capture toolset is utilised in MS Excel. Example DEVAL data within the toolset is shown in Table 7-5.

Table 7-5 Example Forecast Outputs from COTECHMO and PERFORMO in MS Excel

	PERFORMO OUTPUT		**COTECHMO OUTPUT**	
AMT Number	**Tangible**	**Intangible**	**Resources (person-hours)**	**Direct Cost**
1	2.00	1.00	2,000	1,000,000
2	1.00	0.50	2,205	500,000
3	1.50	0.35	1,620	140,000
4	4.00	3.00	10,000	235,000
5	3.00	1.50	11,000	1,000,000
6	2.25	2.00	1,200	2,000,000
7	1.50	0.50	440	650,000
8	5.00	2.50	9,500	2,200,000
9	5.00	2.00	1,560	1,920,000
10	1.00	0.00	1,200	900,000
11	1.00	0.00	700	874,000
12	1.00	0.68	6,000	205,000
13	0.50	-0.48	1,400	160,000
14	0.70	-0.36	1,300	550,000
15	0.60	-0.30	1,900	895,000

This data is then plotted into a DEVAL graphical output, with an example shown in Figure 7-13. Within this example, the COTECHMO Resources output is compared with the PERFORMO Tangible output, using Equation 7.1.

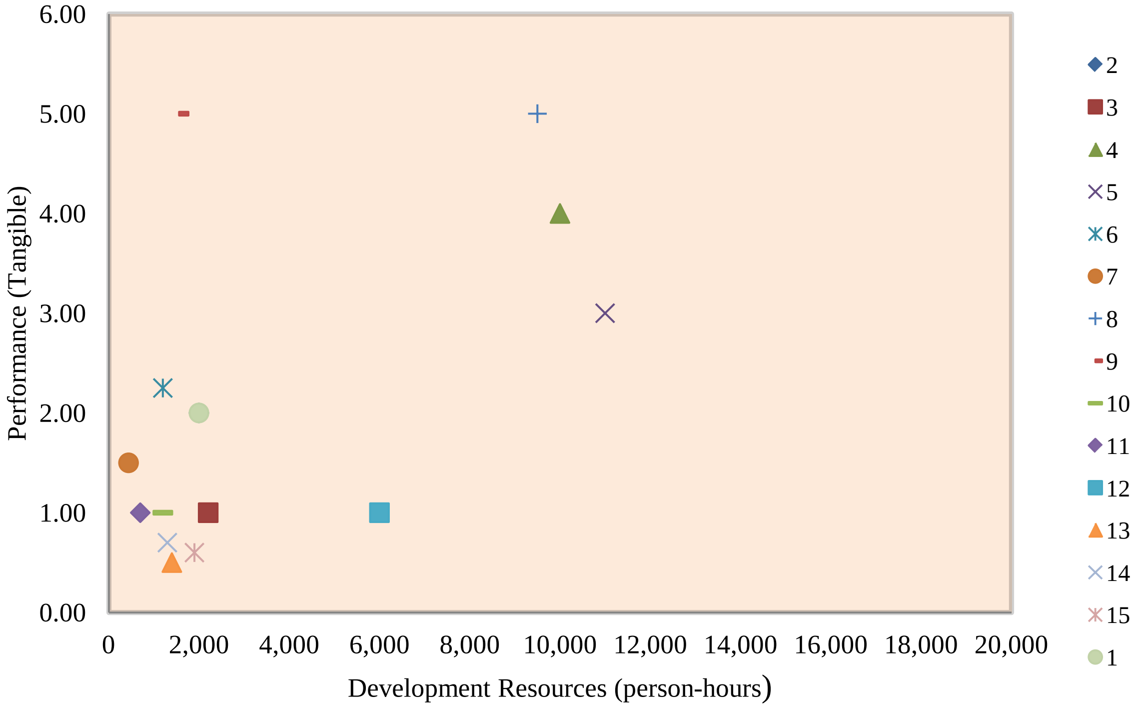

Figure 7-13 Example Outputs from COTECHMO Resources (person-hours) and PERFORMO Tangible Model Plotted within DEVAL

7.4.8 Stage 6 - AMT Development Value Evaluation

Within the final Stage of the Cost-Benefit Forecasting Framework, the output from DEVAL is assigned development effort and performance thresholds. These are usually assigned with a manager overseeing the overall resources and costs, typically within the R&T programme. Thresholds assist by graphically illustrating AMTs within the portfolio that provide the best development value. For the purpose of this example illustrated in Figure 7-14, quadrants are formed for the development resources (person-hours) and the tangible performance. The most desirable AMTs feed into the 'max-min quadrant,' making AMT number 9 the best value for development.

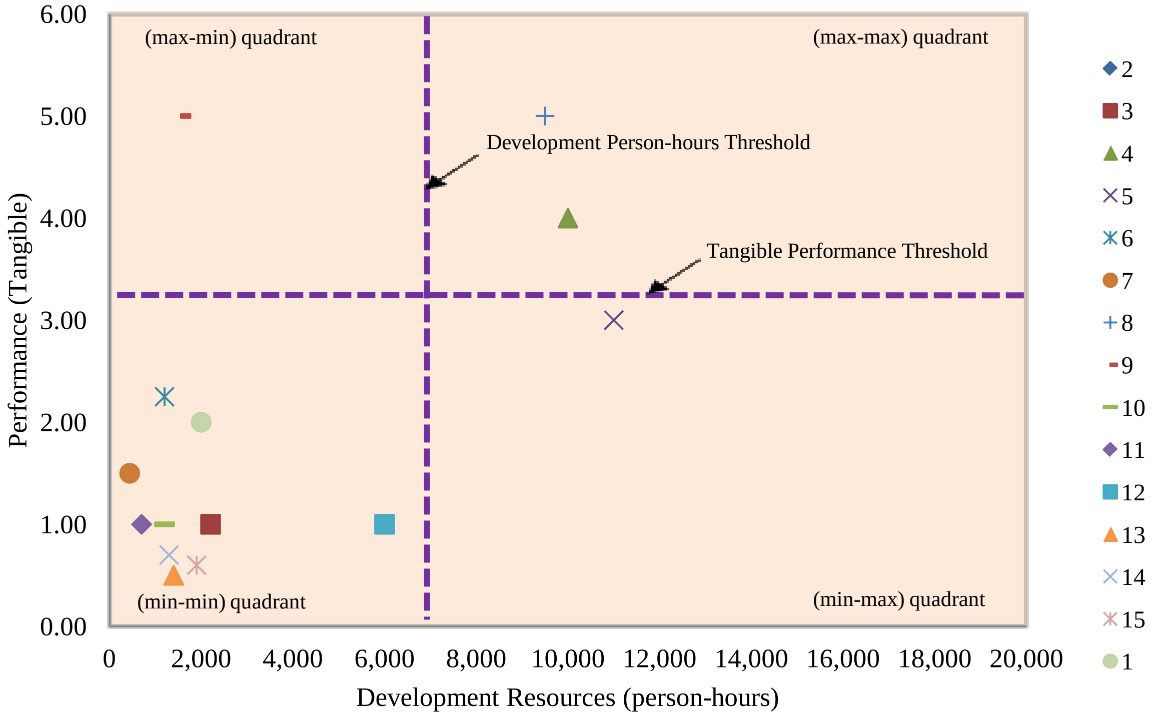

Figure 7-14 Example Outputs from COTECHMO Resources (person-hours) and PERFORMO Tangible Model Plotted within DEVAL with Assigned Thresholds

A detailed empirical case study for evaluation of 15 AMTs utilising each of the discussed framework Stages is presented in Chapter 8. This Chapter also presents a detailed verification and validation analysis of each model and the final framework.

7.5 Chapter Summary

This Chapter has presented a novel Cost-Benefit Forecasting Framework for assessment of aerospace AMTs at the initial stages of development. The framework is capable of operating each COTECHMO and PERFORMO model, plotting the outputs into DEVAL graphs within an industrial setting. This meets the detailed requirements formed from the enhanced management of AMT development process, presented in Chapter 4, Section 4.6 and represented in Figure 4-6.

The detailed research methodology followed for development of the Cost-Benefit Forecasting Framework was presented in Section 7.2. The primary aspect involved a study of the data input and output from each COTECHMO and PERFORMO model. In Section 7.3, the framework aerospace industry requirements were presented with a focus on R&T. Section 7.4 presented the developed Cost-Benefit Forecasting Framework and detailed each of the individual stages the users need to follow. This provides the platform to verify and validate the framework within an industrial setting, detailed and analysed within the case study in the following Chapter.

CHAPTER 8

COST-BENEFIT FORECASTING FRAMEWORK INDUSTRIAL VERIFICATION AND VALIDATION

8.1 Introduction

Chapter 5 developed and presented novel parametric Constructive Technology Development Cost Models (COTECHMO). Chapter 6 followed with the development of Performance Forecasting Models (PERFORMO). The systematic Cost-Benefit Forecasting Framework derived and developed in Chapter 7 then guides the user to operate COTECHMO and PERFORMO and feed the final outputs into Development Value Advice (DEVAL) graphs. Within DEVAL the quantified output from COTECHMO feeds into the 'x-axis' and PERFORMO the 'y-axis,' with an example illustrated in Chapter 7, Figure 7-14.

This Chapter performs a detailed industrial verification and validation of COTECHMO presented in Chapter 5, PERFORMO presented in Chapter 6 and the Cost-Benefit Forecasting Framework detailed in Chapter 7. The Chapter is organised in the following structure. In Section 8.2 a detailed research methodology is presented to perform the industrial verification and validation of each model and the overall framework. In Section 8.3 an empirical study is carried out within an aerospace manufacturing organisation for the evaluation of 15 novel AMTs, utilising the developed Cost-Benefit Forecasting Framework. In Section 8.4 a detailed verification is performed on the COTECHMO models, including statistical tests utilising the data from the 15 empirical AMTs. In Section 8.5 a validation process is carried out for each COTECHMO model, based on the responses of selected experts. In Section 8.6 a detailed verification process is presented for the developed PERFORMO models using eight AMTs with known outcomes, separate from those used within the empirical study. In Section 8.7 a validation process is performed on the PERFORMO models using the responses from selected experts. Section 8.8 details the validation process for the evaluation of the final output from the Cost-Benefit Forecasting Framework and the overall operation within the industrial setting. Section 8.9 concludes with the chapter summary and key observations.

8.2 Detailed Research Methodology for Industrial Verification and Validation

Figure 8-1 presents an overview of the research methodology used for the industrial verification and validation of the developed Cost-Benefit Forecasting Framework. Each step is described in the proceeding Sub Sections. This feeds into Phase 5 of the overall research methodology presented in Chapter 3, Figure 3-2.

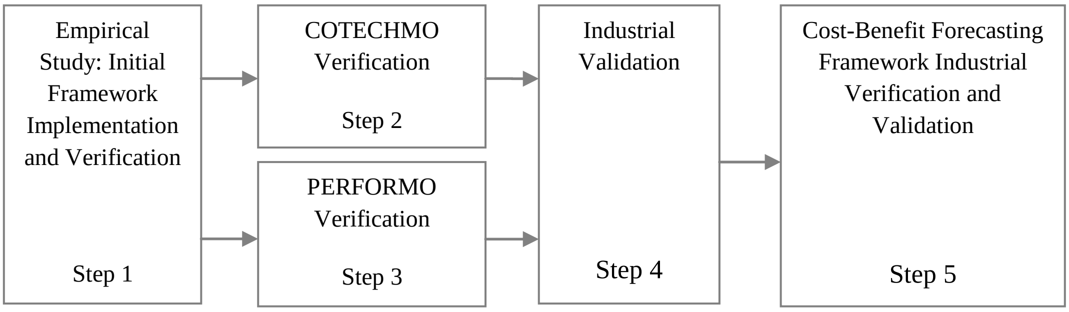

Figure 8-1 Detailed Research Methodology for Verification and Validation of the Cost-Benefit Forecasting Framework

8.2.1 Detailed Research Methodology for Empirical Study: Initial Framework Implementation and Verification

Step 1 of the detailed research methodology involved performing an evaluation of 15 AMTs within a large aerospace manufacturer's Research and Technology (R&T) division. This was performed using 10 experts; each involved with the AMT developments and listed in Table 8-1. Each expert operated the Cost-Benefit Forecasting Framework developed and detailed within Chapter 7.

Table 8-1 Experts used for Verification and Validation of the Cost-Benefit Forecasting Framework

AMT Number	Expert Number	Role	Years of AMT Development Experience
5	1	Automation Research Engineer	20
11	2	Manufacturing and Materials Advanced Research Engineer	25
14			
9	3	Research Portfolio Manager	15
4	4	Automation Specialist	4
2	5	Metrology/Manufacturing Research Engineer	6
10	6	Manufacturing Project Manager	5
12			
13			
15	7	Manufacturing Research Engineer	15
3			
7	8	Manufacturing Project Leader	10
8	9	Manufacturing Research Engineer	15
6	10	Machining Research Specialist	11
1			

8.2.2 Detailed Research Methodology for COTECHMO Verification

Step 2 of the detailed research methodology involved performing a detailed verification of the two COTECHMO models developed within Chapter 5. The detailed verification process included a statistical analysis for each of the 15 AMTs listed within Table 8-1. From the limited number of cases, each COTECHMO model was statically tested in reduced forms. The results are presented in Section 8.4.

8.2.3 Detailed Research Methodology for PERFORMO Verification

Step 3 of the detailed research methodology involved performing a detailed verification of the two PERFORMO models developed within Chapter 6. The detailed verification process followed for PERFORMO was different to COTECHMO. COTECHMO was verified using data from the 15 AMTs within the empirical study. The 15 AMTs listed in Table 8-1 had not been fully implemented and developed with known outcomes. To fully verify PERFORMO, evaluation of AMTs with known outcomes was required. To respond, five aerospace AMTs that had been successfully implemented within the aerospace manufacturing industry were selected. A further three AMTs that were determined as unsuccessful were also selected. Each PERFORMO model was used in conjunction with an aerospace manufacturing engineer with 13 years' experience, systematically evaluating the performance of each AMT. The model outputs were compared to the actual data from manufacturing operations, with the results presented in Section 8.6.

8.2.4 Detailed Research Methodology for COTECHMO Industrial Validation

The performance of each COTECHMO model for the industrial application was crucial to validate each model and identify they fulfilled the requirements specified by the aerospace manufacturing industry in Chapter 5, Section 5.3. To further validate within the industrial setting, a questionnaire was developed. The questionnaire used three applicability criteria proposed by Platts, Walter and Gregory (1990). This was successfully utilised by Evans, Lohse and Summers (2013) within the manufacturing domain including: feasibility, usability and utility. Feasibility defines if users can follow the methodology, usability determines if it's easily followed and utility studies the output. The final questionnaire contained 13 questions segmented into each of the applicability criteria. The questions were rated using a 5-point 'likert' scale and were completed by each of the 10 experts listed in Table 8-1. The responses were analysed and the results are presented in Section 8.5.

8.2.5 Detailed Research Methodology for PERFORMO Industrial Validation

Following the COTECHMO validation discussed previously, each PERFORMO model must meet the industrial requirements detailed by the aerospace manufacturing industry in Chapter 6, Section 6.3. The questionnaire developed for the PERFORMO industrial validation used the same three applicability criteria proposed by Platts et al. (1990) including: feasibility, usability and utility. The final questionnaire contained 13 questions with the 10 AMT development experts asked to rate each. The responses were analysed, with the results presented in Section 8.7.

8.2.6 Detailed Research Methodology for Cost-Benefit Forecasting Framework Industrial Validation

To ensure the Cost-Benefit Forecasting Framework developed in Chapter 7 fulfilled its industrial requirements detailed within Chapter 4, a questionnaire was developed. The framework used the same applicability criteria used for the validation of COTECHMO and PERFORMO including: feasibility, usability and utility. The questions under each criterion were tailored for a framework application. The questionnaire was completed by each of the 10 AMT development experts listed in Table 8-1, after using the framework and the responses were analysed, with the results presented in Section 8.8. This included the final evaluation of the recommended AMTs selected for development from the empirical study final output.

8.3 Empirical Study: Initial Framework Implementation and Verification Results

To verify and validate outputs from COTECHMO, PERFORMO and the Cost-Benefit Forecasting Framework, an industrial empirical verification study was followed using the 15 AMTs listed in Table 8-1.

This formed step 1 of the detailed research methodology discussed in the previous Section. Each of the selected AMTs was picked based on their technological and application diversity, vigorously testing each stage of the forecasting procedure. For the purpose of the empirical study, each of the 15 selected AMTs were run through the Cost-Benefit Framework, with each stage described in Chapter 7, Section 7.4. This acts as the initial verification for implementing the Cost-Benefit Forecasting Framework within industry, using actual case study data. The results are presented in the proceeding Sub Sections.

8.3.1 Stage 1 - User Information

Stage 1 of the framework involved the user inputting their name and the date of the AMT evaluation. This recorded their details and location within the business, providing full traceability of decisions made at the initial stages of development. The users of the framework, including their role and AMT development experience, were listed earlier in Table 8-1.

8.3.2 Stage 2 - AMT Identification

The 15 AMTs selected for evaluation within a large aerospace manufacturing R&T division are listed in Table 8-1. Care was taken to ensure the most recent TRL reviews were captured and compiled for each case. This ensured that the development information was fully up to date, certifying that each forecast stage utilised all available technical information. Each selected AMT was run through the Cost-Benefit Forecasting Framework, described in the proceeding Sub Sections.

8.3.3 Stage 3A - COTECHMO Resources (person-hours) Forecast

The first forecasting assessment utilised the COTECHMO Resources (person-hours) model, derived and discussed within Chapter 5. Detailed operation of the model was described in Chapter 7, Sub Section 7.4.3, with the MS Excel interface illustrated in Figure 7-4.

The first stage of performing a COTECHMO Resources (person-hours) forecast, involved capturing data from historical AMT developments to TRL6. The mean TRL6 development data for the 15 AMTs equalled 5,374 person-hours. The next stage involved calibrating the model size driver, by calculating the mean functional size for the 15 AMTs. The total functional size for the 15 AMTs was 972.5, thus 972.5 divided by 15 equals 64.83. Therefore, to equate the mean output of 5,374 person-hours with nominal complexity, the calibration constant is 82.93. This forms the final calibration factor (A) detailed in Chapter 5, Equation 5.2. Figure 8-2 illustrates the summary of this data calibration exercise. This diagram is for illustration purposes only and is not to scale.

Now the model has been calibrated, the next step of the framework involved using the MS Excel COTECHMO Resources model, with the operation discussed in Chapter 7, Sub Section 7.4.3 and the MS interface illustrated in Figure 7-4. The first step of operating the Resources model involved capturing the application functional size requirements for each case, with full definitions listed in Chapter 5, Sub Section 5.5.1.

The next step involved the user rating the effort drivers for each case, with the detailed definitions listed within Chapter 5, Sub Section 5.5.2. For the intention of this empirical study, the model was utilised for forecasting development person-hours for each AMT listed in Table 8-1, with the assigned experts. The final outputs are presented in Table 8-4 and illustrated graphically in Sub Section 8.3.8.

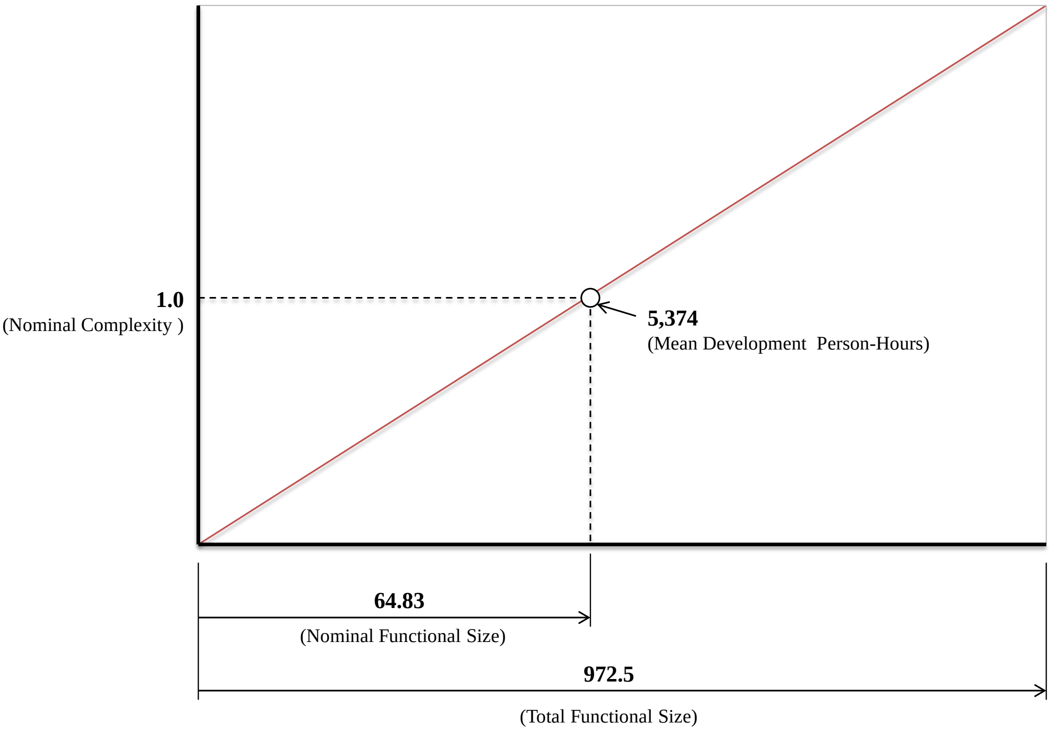

Figure 8-2 COTECHMO Resources Calibration

Table 8-2 AMT Function Size Requirements

	# Geometric Requirements			# Process Steps			# Test Pieces		
AMT Number	**Easy**	**Nominal**	**Difficult**	**Easy**	**Nominal**	**Difficult**	**Easy**	**Nominal**	**Difficult**
1.		3			1	1		6	
2.	3			3			1		1
3.		6		2	4		10	40	
4.		1	2	4	4	3		5	2
5.		10		8					1
6.		14	1					2	
7.		25	1		15	1			1
8.		4			5				2
9.	2			27				30	
10.		1	2		3				5
11.	5	5			5			3	
12.		1	1		2		4	2	
13.			1		3	1	4	2	
14.	10	5	2		6		100	100	
15.			100	50	9	2		20	20

8.3.4 Stage 3B - Direct Cost Forecast

The second forecasting assessment involved utilising the COTECHMO Direct Cost model, derived and discussed within Chapter 5. The operation of the developed model was described in Chapter 7, Sub Section 7.4.4, with the MS Excel interface illustrated in Figure 7-7. Following the Resources model discussed previously, the first stage of performing a COTECHMO Direct (Hardware) Cost forecast involved capturing data from AMT developments to TRL6. The mean TRL6 development data for the 15 AMTs listed in Table 8-1 equalled 979,942 Euros. The next stage involved calibrating the model size driver by calculating the mean physical size of the AMT hardware for the 15 AMTs. The total hardware size for the 15 AMT historical cases was 5,498.8m^3, thus 5,498.8m^3 divided by 15 equals 366.6m^3. Therefore, to equate the mean output of 979,942 Euros with nominal complexity, the calibration constant is 2,673.4. This forms the final calibration factor (A) presented in Chapter 5, Equation 5.4. Figure 8-3 illustrates the summary of this data calibration exercise. This diagram is for illustration purposes only and is not to scale.

The next step of the framework involved using the MS Excel COTECHMO Direct Cost model, with the operation discussed in Chapter 7, Sub Section 7.4.4 and the MS Interface illustrated in Figure 7-7. The first step of operating the Direct Cost model involved predicting the physical size of each AMT listed in Table 8-1. A summary of the AMT size requirements for each case is listed in Table 8-3.

The next step of utilising the Direct Cost model involved the user rating the cost drivers for each case, with the detailed definitions listed within Chapter 5, Sub Section 5.6.2. For the intention of this empirical study, the model was utilised for forecasting development direct cost for each AMT listed in Table 8-1, using the assigned expert. The final outputs are presented in Table 8-4 and illustrated graphically in Sub Section 8.3.8.

8.3.5 Stage 4A - PERFORMO Tangible Forecast

On completion of each COTECHMO forecast, the PERFORMO forecasting assessments were performed with the assigned expert for the AMTs listed in Table 8-1. The first PERFORMO forecasting assessment involved utilising the PERFORMO Tangible model, derived and discussed in Chapter 6. The operation of the developed model was described within Chapter 7, Sub Section 7.4.5, with the MS Excel interface illustrated in Figure 7-9.

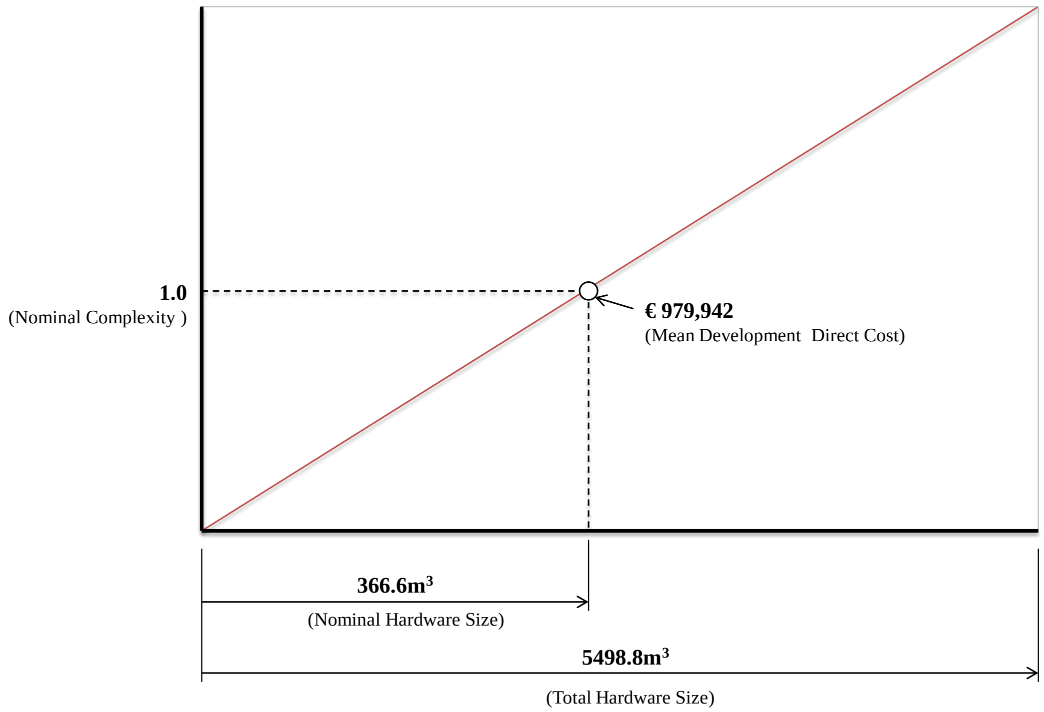

Figure 8-3 COTECHMO Direct Cost Calibration

Table 8-3 AMT Process Hardware Volume Requirements

AMT Number	Hardware Volume (m^3)
1.	500.00
2.	14.00
3.	6.25
4.	1,260.00
5.	100.00
6.	75.00
7.	550.00
8.	17.50
9.	525.00
10.	320.00
11.	2,000.00
12.	3.00
13.	60.00
14.	32.00
15.	16.00

The first step of conducting a PERFORMO Tangible forecast involved the users weighting each of the 12 Key Performance Factors (KPFs) using the definition (judgement) scale. The weighting of each KPF varied significantly for each of the 15 cases ranging from 0, with the KPF turned off, to 9, extreme importance. The

KPF weighted the highest out of the 15 cases was ‘Recurring Cost Per Aircraft,’ with an average weighting of 7.2 and equates to a very strong importance within the definition (judgement) scale. The KPF with the lowest intensity of importance was ‘Process Service Cycle Time,’ with a mean output of 2.0. Chapter 7, Sub Section 7.4.5 discussed how the KPF intensity of importance rating is then translated into a weighting percentage and is normalised at 1.0. This allows for comparison of the diverse AMTs, with the mathematical notation derived and discussed in Chapter 6, Sub Section 6.4.1.

The next step of conducting a Tangible performance forecast involved identifying the datum baseline for each AMT being assessed. For 3 of the 15 cases, baseline data was not available. When baseline data is not available, the baseline is taken at a value of 1.0, with the minimum, most likely and maximum change derived as a percentage from this baseline. These 3 outputs were checked for validity, when compared against input data with a known baseline for comparison. For the intention of this empirical study, the model was utilised for forecasting tangible performance of each AMT listed in Table 8-1, with the assigned expert. The final outputs are presented in Table 8-4 and illustrated graphically in Section 8.3.8.

8.3.6 Stage 4B - PERFORMO Intangible Forecast

The second PERFORMO forecasting assessment involved utilising the PERFORMO Intangible model, derived and discussed in Chapter 6. The operation of this model is described within Chapter 7, Sub Section 7.4.6, with the MS Excel Interface illustrated in Figure 7-11.

Following the Tangible forecast, the first step of performing an Intangible forecast involved the user weighting each of the 12 KPFs using the definition (judgement) scale. For each of the cases, the weighting of each KPF varied significantly ranging from 0, with the KPF turned off, to 9, extreme importance. The KPF weighted the highest out of the 15 cases was ‘Future Product Vision,’ with an average weighting of 6.0. This equated to an intermediate value between ‘Strong Importance’ and ‘Very Strong Importance’ within the definition (judgement scale). The lowest KPF average for each of the cases evaluated was ‘Employee Relations Performance,’ with an average value of 2.4, equating to an intermediate definition value between ‘Low Importance’ and ‘Moderate Importance.’ Following the format of the Tangible model, the KPF intensity of importance rating is then translated into a weighting percentage and is normalised at 1.0. This allows an apple to pears comparison, with the mathematical notation derived and discussed in Chapter 6, Sub Section 6.4.2. For the intention of this empirical study, the model was utilised with the assigned expert for forecasting Intangible performance for each AMT listed in Table 8-1. The final outputs are presented in Table 8-4 and illustrated graphically in Sub Section 8.3.8.

8.3.7 Stage 5 - DEVAL Forecast

On completion of the COTECHMO and PERFORMO forecasting assessment, the data from each was plotted into the DEVAL graphs for each AMT listed in Table 8-1. This involved utilising the DEVAL MS Excel data capture toolset. The final DEVAL output for each of the selected AMTs in Table 8-1 are listed in Table 8-4. PERFORMO feeds into a 'y-axis,' with the COTECHMO output feeding into the 'x-axis.' The equation form and operation were discussed in detail in Chapter 7, Sub Section 7.4.7.

The graphical DEVAL outputs are part of this stage, although to avoid repetition, are presented in the following stage with the inclusion of performance and development effort thresholds.

Table 8-4 COTECHMO and PERFORMO Outputs Plotted within DEVAL for the 15 AMTs

	PERFORMO OUTPUT		**COTECHMO OUTPUT**	
AMT Number	**Tangible**	**Intangible**	**Resources (Person-hours)**	**Direct Cost €**
1.	1.46	0.62	2,348	305,729
2.	1.10	0.58	2,559	629,074
3.	1.24	0.35	1,725	319,065
4.	4.53	0.96	7,872	1,276,060
5.	2.08	0.21	2,497	2,571,462
6.	1.68	0.23	4,791	396,427
7.	1.43	0.98	5,921	619,845
8.	2.93	0.02	3,326	468,751
9.	1.15	0.56	19,332	1,072,707
10.	2.50	0.36	3,598	695,545
11.	2.11	-0.11	7,262	2,661,120
12.	1.68	0.68	1,747	591,738
13.	1.45	-0.48	1,273	678,017
14.	1.24	0.36	18,317	2,076,878
15.	1.40	0.34	2,571	610,420

8.3.8 Stage 6 - AMT Development Value Evaluation

The final stage of the Cost-Benefit Forecasting Framework involved assigning development effort and performance thresholds for the DEVAL outputs in MS Excel. Thresholds were assigned with a research manager involved in the overall R&T portfolio evaluation. As part of the AMT evaluation process, the research manager evaluated the results from the AMTs listed in Table 8-4. The thresholds defined are listed in Table 8-5, based on the R&T available resources, budget and performance requirements. The final DEVAL graphical outputs are illustrated in Figures 8-4 to 8-7.

Table 8-5 Development Forecast Thresholds

Thresholds			
Person-hours	**Direct Cost**	**Tangible Performance**	**Intangible Performance**
8,000	1,300,000	2.25	0.30

These DEVAL outputs were evaluated in detail to select AMTs providing the business with the best value, creating the following results. ‘AMT 4’ was the first recommended for development, despite falling within the upper boundaries of the person-hours and direct cost limits. This AMT was selected based on its outstanding tangible and intangible performance forecasts. The second AMT recommended for development was ‘AMT 10.’ This AMT was selected based on its low forecast development person-hours and direct cost, compiled with tangible and intangible performance forecasts that both fulfilled the threshold requirements. ‘AMT 7’ was considered from the excellent intangible forecast performance; although from not meeting the tangible performance threshold this AMT was eliminated. To assess these development recommendations, a detailed verification and validation is performed on each model and the overall Cost-Benefit Forecasting Framework operation, discussed in the proceeding Sections.

8.4 COTECHMO Verification Results

The empirical case study presented previously provided the data to perform a detailed verification of the COTECHMO Resources and Direct Cost model. Each model was statistically verified using multiple regression diagnostic tests with the results presented in the following Sub Sections.

8.4.1 Resources Model Verification

The COTECHMO Resources model is defined using a multiple regression model. The model output is development person-hours, with the 16 drivers forming the predictors that have an impact on aerospace AMT development effort, with the overall operation illustrated in Figure 8-8.

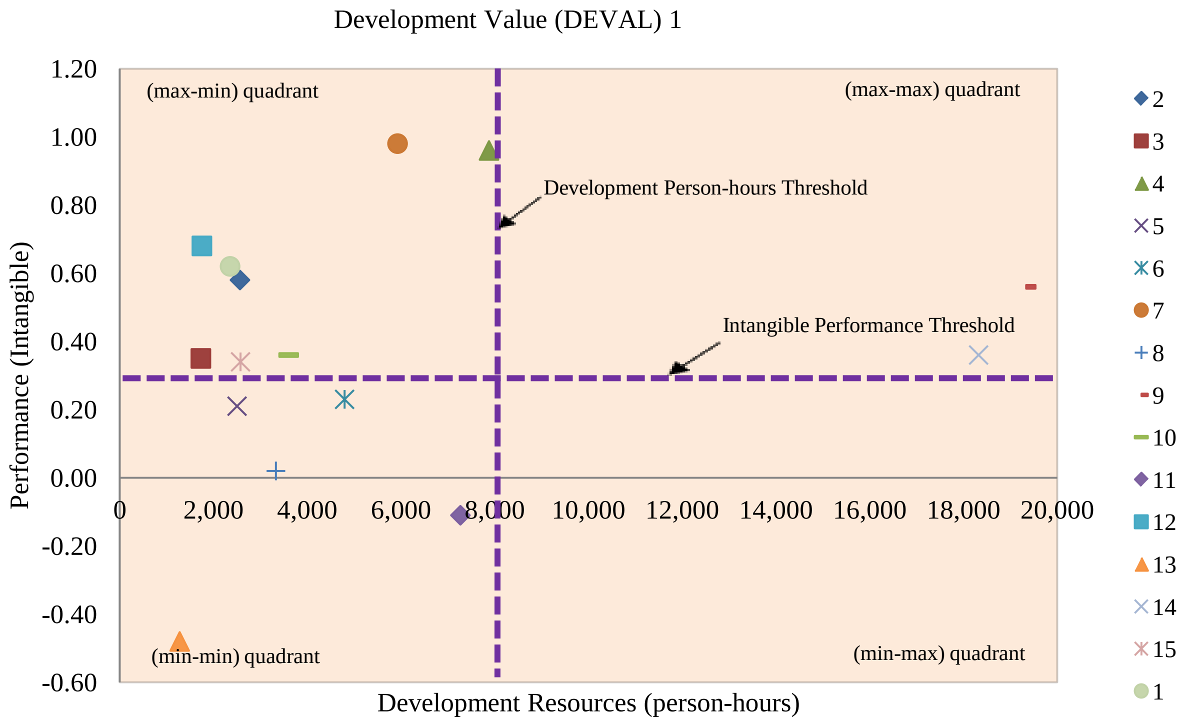

Figure 8-4 Outputs from COTECHMO Resources and PERFORMO Intangible Models Plotted within DEVAL with the Assigned Thresholds

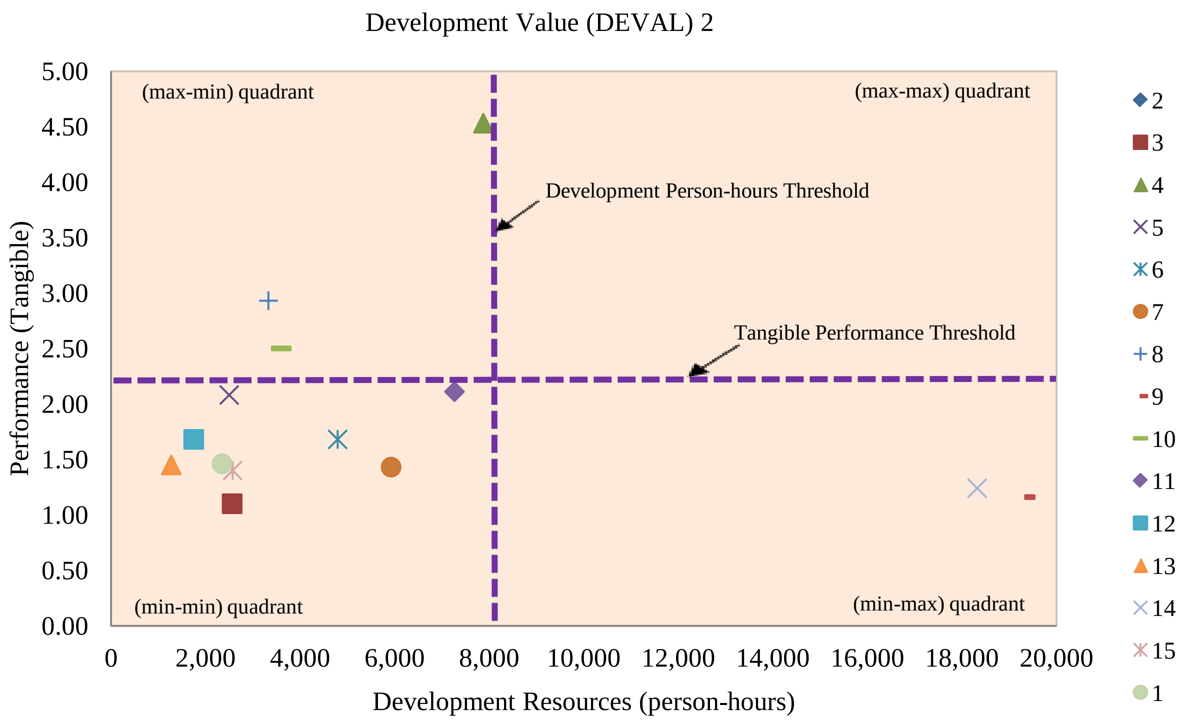

Figure 8-5 Outputs from COTECHMO Resources and PERFORMO Tangible Models plotted within DEVAL with the Assigned Thresholds

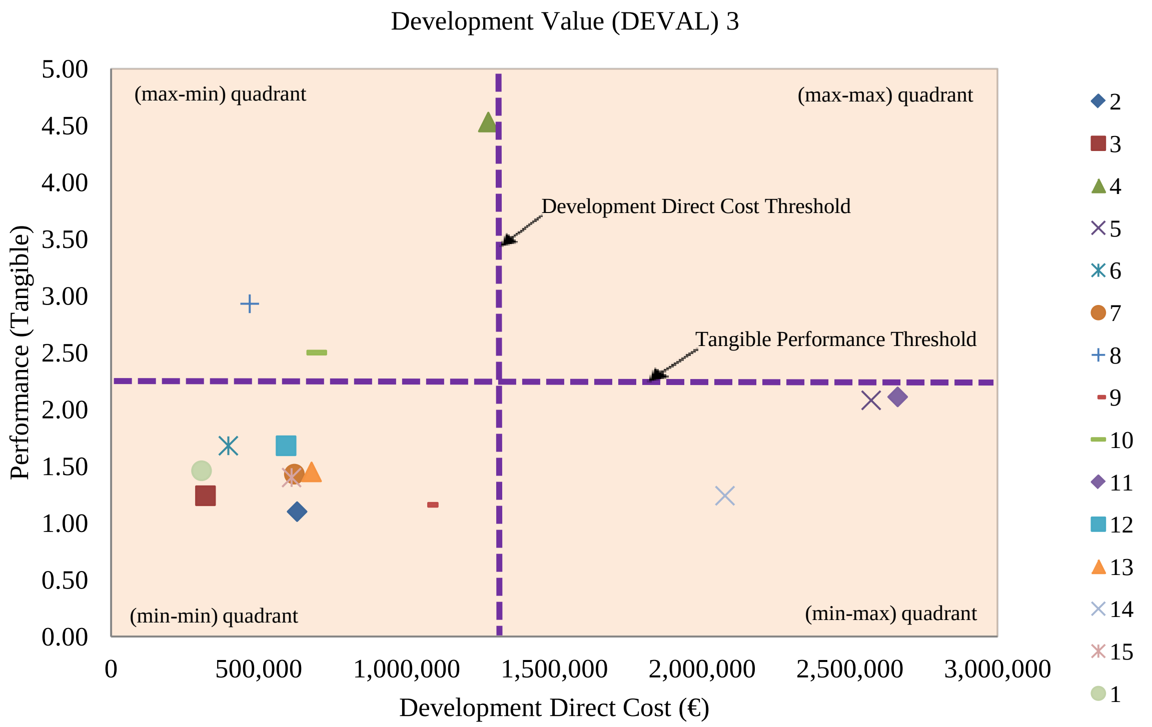

Figure 8-6 Outputs from COTECHMO Direct Cost and PERFORMO Tangible Models plotted within DEVAL with the Assigned Thresholds

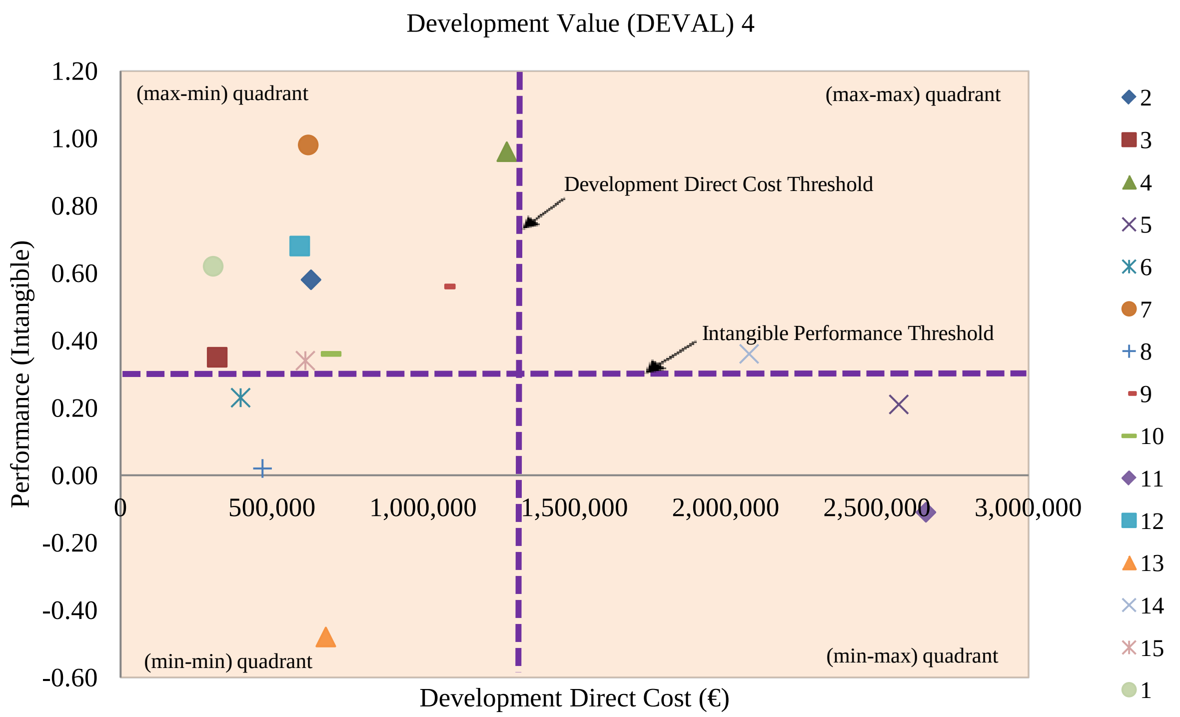

Figure 8-7 Outputs from COTECHMO Direct Cost and PERFORMO Intangible Models Plotted within DEVAL with the Assigned Thresholds

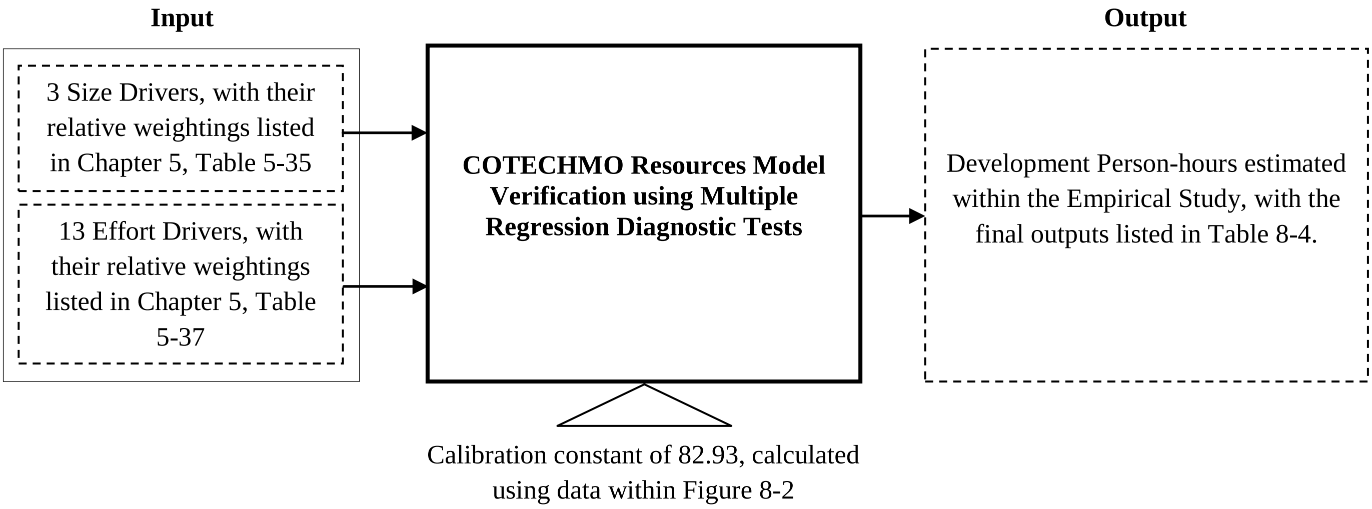

Figure 8-8 Resources Model Verification

There was an estimation of a linear application utilising the Ordinary Least Squares (OLS) criterion. This aims to characterise a straightforward linear regression and determine the correlation to the 16 AMT development drivers (independent variables), with the AMT development person-hours (dependent variable). The equation is in the following format:

$$\gamma_t = \beta_0 + \beta_1 x_{t1} + \ldots + \beta_k x_{tk} + \varepsilon_t \qquad \text{(Eqn. 8.1)}$$

Where $x_{t1} \ldots x_{tk}$ represent the values of the predictor variables for the t_{th} observation, $\beta_0 \ldots \beta_k$ are coefficients estimated via OLS regression, ε_t is the error term and γ_t is the response variable for the t_{th} observation. This technique makes the assumption that there is a lot of historical data, an assumption not fulfilled from the available 15 AMT historical cases (Griffiths et al., 1993). This number of historical cases is not sufficient to perform multiple regression on the full model containing 16 AMT drivers. Therefore, the model was tested and verified in a reduced form. To reduce the final Resources model, each of the drivers was clustered into the common themes, detailed within Chapter 5, Section 5.5. These included: Development Team Factors, Demonstration and Application Factors, Project Factors and a Product Rate Factor. The three size drivers were combined to form an overall size predictor and were compiled with the drivers clustered into the four themes. The reduced model one size and four effort predictors are listed in Table 8-6, showing a logarithmic scale and summary description.

In order to express the required linear relationships, logarithmic transforms were taken for the dependant independent variables of the reduced model form to produce Equation 8.2.

Table 8-6 Reduced Resources Model Predictor Descriptions

Predictor	Term	Description
S_1	Log (SIZE)	Functional Size Factors. Drivers that capture the functional size of the AMT.
EM_1	Log (TEAM)	Development Team Factors. Drivers that capture the skill set and comprehension of the development team.
EM_2	Log (DEM)	Demonstration and Application Factors. Drivers that capture the complexity of the process and its target application.
EM_3	Log (PROJECT)	Project Factors. Drivers that capture the project requirements.
EM_4	Log (PRODUCT)	Product Rate Factor. The driver that captures the required production rate of the assigned product.

$$\text{In(DEVELOPMENT\_PERSONHOURS)} = \beta_0 + \beta_1 \cdot \text{In}(S_1) + ... + \beta_5 \cdot \text{In}(\text{EM}_4)$$

(Eqn. 8.2)

The reduced model five parameters are presented in Equation 8.3.

$$\text{log(DEVELOPMENT\_PERSONHOURS)} = \text{log(SIZE)} + \text{log(TEAM)} + \text{log(DEM)} + \text{log(PROJECT)} + \text{log (PRODUCT)}$$

(Eqn. 8.3)

Reduction of the model predictors granted the following multiple regression diagnostic tests to validate the significance of the reduced model hypothesis and provide statistical validation of each driver:

- Model significance/*F*-test

An *F*-test was performed on the Resources model to validate the significance of the reduced model hypothesis. The final *F*-value for the reduced Resources model is listed in Table 8-7 and illustrated in Figure 8-9, identifying exceptional statistical significance of the hypothesis.

- Sensitivity Analysis

Identification of the relevance of predictor data points within the reduced Resources model was performed and tested for statistical significance. *T*-values and *p*-values were used to determine the impact of the predictors, with each illustrated for the reduced model using the data from the empirical study within Figure 8-9. "A *t*-value is the ratio between the estimate and its corresponding standard error, where standard error is the square root of variance" (Valerdi, 2005). Generally speaking, an increase in a *t*-value generates an enhanced statistical significance. The reduced model *t*-values had exceptional statistical significance for each of the model predictors listed in Table 8-6. The 'Production Rate' predictor did not have a high statistical significance. A *p*-value refers to the probability of observing a value, with outputs falling below 0.05 indicating high predictive influence on the mean function. Figure 8-9 lists the final reduced model predictor *p*-values, with each meeting the specified value of 0.05, excluding the 'Production Rate' predictor. Enhancement of the 'Production Rate' predictor *t*-value and *p*-value is discussed within Chapter 9, concluding with recommendations for future research. The reduced Resources model summary regression statistics for the 15 cases are listed in Table 8-7; identifying an exceptional R-squared value and an outstanding *F*-Value, validating the model hypothesis.

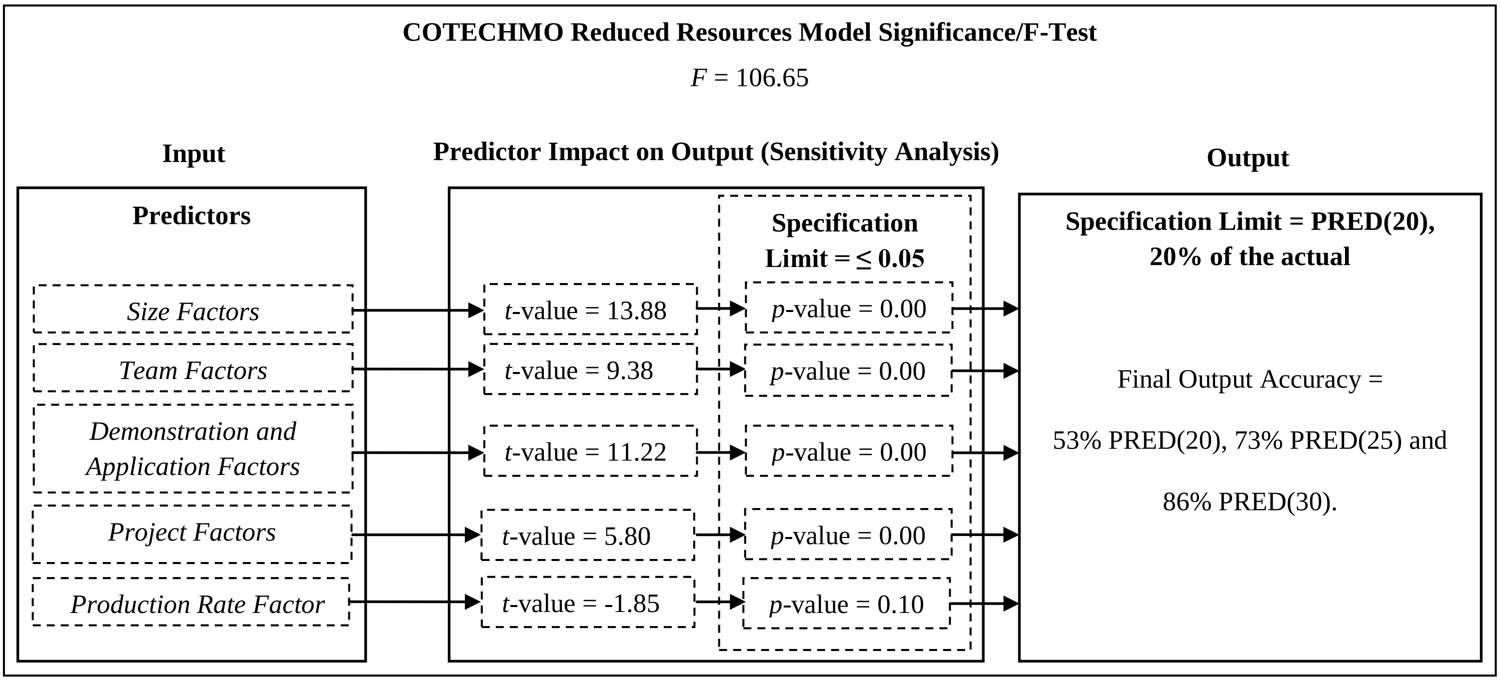

Figure 8-9 Reduced Resources Model Verification and Sensitivity Analysis

Table 8-7 Reduced Resources Model Performance

Model Name	Predictors	R-Squared	Observations	*F*-Value
COTECHMO Resources	5	0.98	15	106.65

Further to the multiple regression analysis, experts specified that each COTECHMO Cost Estimation Relationship (CER) form must be further verified using PRED (Prediction Level) values. For example, a PRED(20) value requires the forecast data to be within 20% of the actual historical value for the 15 AMT cases (Conte et al., 1986). To calculate the PRED value for this application, the number of forecast cases falling within 20% of the actual data is divided by the total number of cases. For this case study, 8 of the 15 AMTs fell within 20% of the actual data, thus 8 is divided by the total of 15, equating a value of 53%. Therefore, 53% of the data fell within PRED(20), 73% of the data fell within PRED(25) and 86% within PRED(30).

8.4.2 Direct Cost Model Verification

The COTECHMO Direct Cost model is defined using a multiple regression model. The model output is development direct cost, with the 14 drivers forming the predictors that have an impact on aerospace AMT development cost, illustrated in Figure 8-10.

Following the format of the Resource model statistical verification discussed previously, the estimation of a linear application is predicted using the OLS approach. The multiple regression model is written in the form introduced earlier in the Equation 8.1. Following the Resources model verification, the 15 AMT historical cases were not sufficient to perform multiple regression on the full model, including the 14 AMT development drivers. Therefore, the Direct Cost model was also tested and verified in a reduced form. To reduce the Direct Cost model, drivers were clustered into the common themes detailed within Chapter 5, Section 5.6. These included: AMT Process Primary Factors, AMT Process Secondary Factors, AMT Process External Factors and a Product Rate Factor. Each theme was compiled with the size driver and listed in Table 8-8, with logarithmic scale and a summary description.

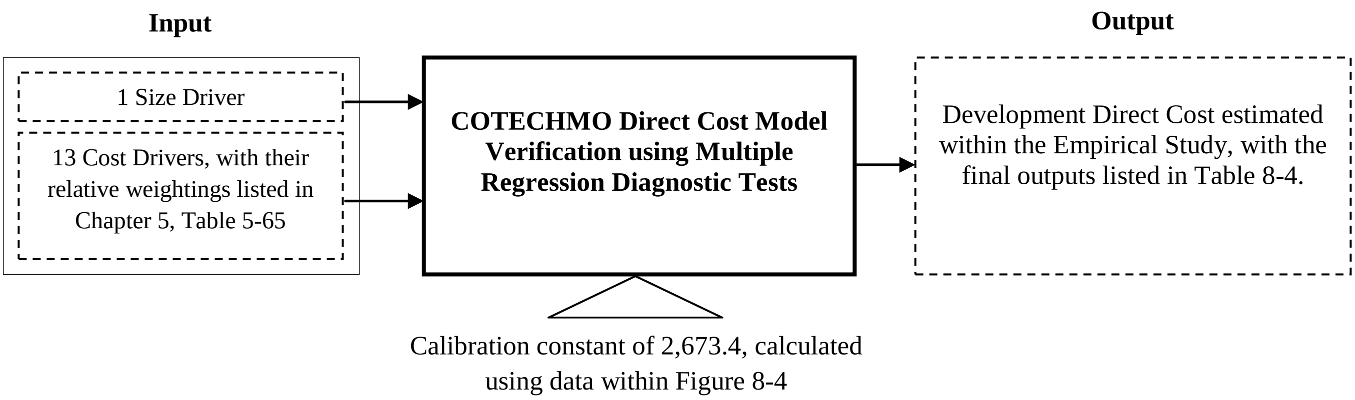

Figure 8-10 Direct Cost Model Verification

In order to express the required linear relationships, logarithmic transforms were applied to the dependant and independent variables, presented in Equation 8.4.

In(DEVELOPMENT_DIRECT COST) = β_0 + β_1 · In(S_1) +...+ β_5 · In(EM$_4$)

(Eqn. 8.4)

The Direct Cost model in its reduced form is presented in Equation 8.5.

log(DEVELOPMENT_DIRECT COST) = log(SIZE) + log(PRIMARY) +log(SECONDARY) + log(EXTERNAL)+log(PRODUCT) .

(Eqn. 8.5)

Table 8-8 Reduced Direct Cost Model Predictor Descriptions

Predictor	Term	Description
S_1	Log (SIZE)	AMT Size Factor. The Driver that captures the AMT process hardware size.
EM_1	Log (PRIMARY)	AMT Process Primary Factors. Drivers that capture primary process parameter requirements for the target application.
EM_2	Log (SECONDARY)	AMT Process Secondary Factors. Drivers that capture the secondary parameters of the process for the targeted application.
EM_3	Log (EXTERNAL)	AMT External Factors. Drivers that capture external AMT requirements for the target application.
EM_4	Log (PRODUCT)	Product Rate Factor. The driver that captures the required production rate of the assigned product.

Reduction of the Direct Cost model granted the following multiple regression diagnostics to validate the significance of the reduced model hypothesis and provide statistical validation of each driver:

- Model significance/*F*-test

An *F*-test was performed on the Direct Cost model to validate the significance of the reduced model hypothesis. The final *F*-value for the reduced Direct Cost model is listed in Table 8-9 and illustrated in Figure 8-11, clarifying statistical significance of the hypothesis.

- Sensitivity Analysis

Following the sensitivity analysis of the Resources model, identification of the relevance of predictor data points for the model were tested using *t*-values and *p*-values, with each illustrated for the reduced model using the data from the empirical study and presented within Figure 8-11. The Size, Primary and External predictors have outstanding *t*-values and *p*-values, both meeting the specified *p*-value of 0.05. Secondary and Production Rate predictors did not meet the specified *p*-value of 0.05, although each are discussed within Chapter 9, concluding with recommendations for future research. The summary regression statistics for the 15 cases are listed in Table

8-9; identifying a reasonable R-squared value and a significant *F*-Value, validating the reduced model hypothesis.

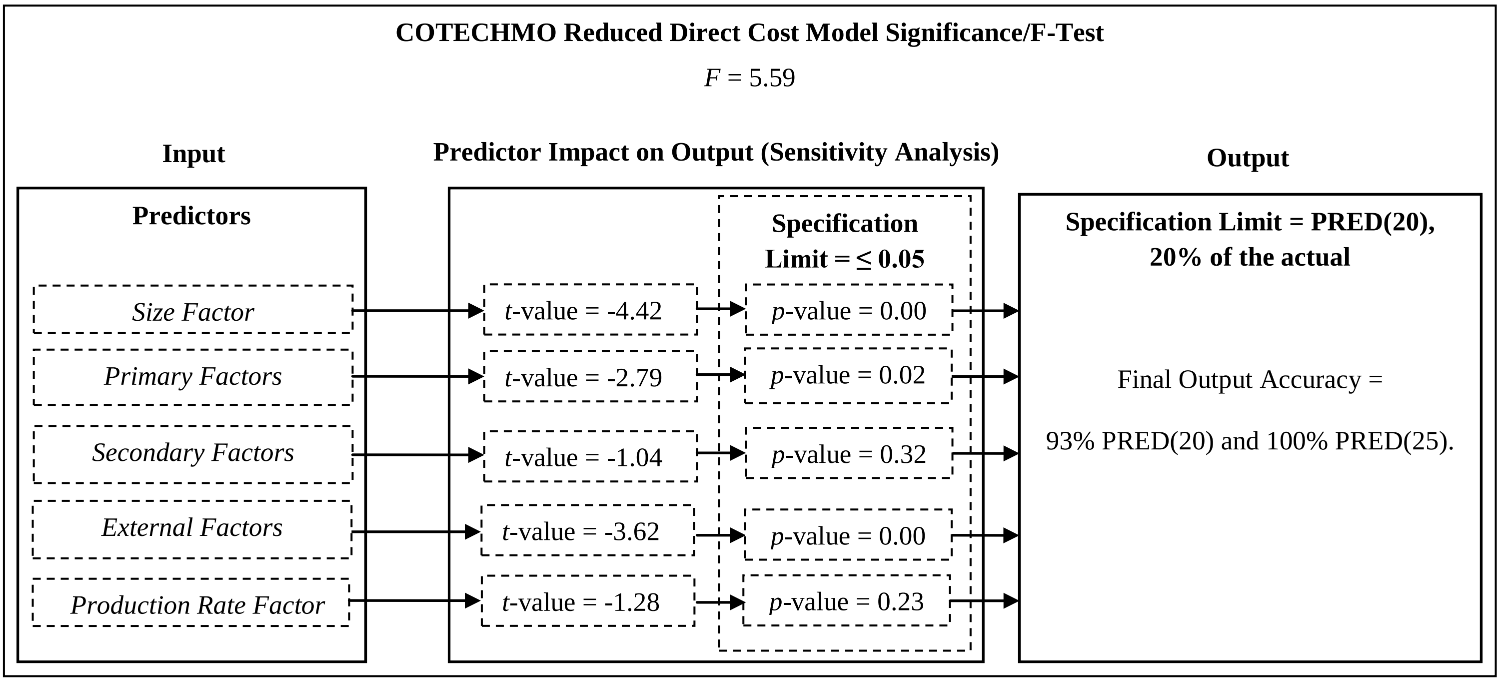

Figure 8-11 Reduced Direct Cost Model Verification and Sensitivity Analysis

Table 8-9 Reduced Direct Cost Model Performance

Model Name	Predictors	R-Squared	Observations	*F*-Value
COTECHMO Direct Cost	5	0.76	15	5.59

Following the Resources model, experts specified that the CER form must be further verified using PRED values. The Direct Cost model forecasting accuracy achieved 93% of the forecast data within PRED(20) and 100% within PRED(25).

8.5 COTECHMO Validation Results

The statistical analysis discussed previously is a quantitative form of validation. Nevertheless, as AMT development experts, project, portfolio and research managers aim to use each COTECHMO forecasting model within an industrial practical environment, an expert driven validation process was followed, detailed within the research methodology in Sub Section 8.2.4. The results are presented in the proceeding Sub Sections. Any model criticisms are referenced and discussed in the recommendations for future work within Chapter 9.

8.5.1 Resources Model Validation Results

The final questionnaire used for the validation of the COTECHMO Resources model is listed in Table 8-10. The AMT development experts were asked to rate each of the questions after they performed a COTECHMO Resources (person-hours) forecast for their AMT(s).

The results of the questionnaire are presented graphically in Figure 8-12, with the question numbers on the ‘x-axis’ and the average rating from each of the 10 users on the ‘y-axis.’ The questionnaire was completed by each expert, rating the specific question using the scale provided ranging from 1, strongly disagree to 5, strongly agree. To complete the Resource model validation, each expert involved with completing the questionnaire was asked to define strengths and weaknesses of the model, with all conversations recorded.

The feasibility, usability and utility responses provided by each of the 10 AMT development experts are now discussed in detail.

- Feasibility

To evaluate the feasibility of the Resources model four questions were asked. These related to the structure of the information input into the model and how capable the model was within its practical application. The rating of each question ranged between ‘neutral’ to ‘strongly agree,’ with an average of 4.28. The lowest average rating was question 1.2, with an average of 3.9. The experts who rated the question neutral defined that the level of information at the initial development stages was limited, especially when developing a completely novel AMT. This was resolved when surrogate sources of data were explained. Each expert was impressed with the time taken to use the software, with an average rating of 4.1. The question with the highest average rating involved evaluating whether the model enhances any existing AMT development person-hours forecasting processes, with an average value of 4.8.

- Usability

To determine the usability of the model, five questions were asked to define how easy the model was to use within its industrial application. The average rating for the five usability questions from the 10 AMT development experts was lower than the feasibility discussed previously, with a value of 3.84. On detailed analysis, question 2.5 was rated the lowest with an average value of 3.1. Question 2.1 and 2.4 had the next lowest average score of 3.7 and 3.9. Question 2.2 and 2.3 scored average outputs of 4.3 and 4.2 respectively, defining successful operation of the model interface and each of the forecasting stages.

Table 8-10 Resource Model Validation Questionnaire

Assessment Criteria	**1**	**2**	**3**	**4**	**5**
1. Feasibility					
1.1. The model is logical for forecasting AMT development person-hours?					
1.2. The model is suitable for forecasting at the initial development stages?					
1.3. The time taken to perform a forecast was appropriate?					
1.4. The model enhances existing AMT development person-hours forecasting techniques?					
2. Usability					
2.1. The objective and purpose of using the forecasting model was clearly defined?					
2.2. The model interface was easy to use?					
2.3. The stages of the model operation were easy to follow?					
2.4. The model software was intuitive?					
2.5. The model calibration can be performed easily?					
3. Utility					
3.1. The input parameters capture all of your AMT drivers impacting development person-hours?					
3.2. The effort drivers were clustered under the correct 'themes'?					
3.3. The TRL formed an appropriate data capture technique for AMT development person-hours?					
3.4. The model output was appropriate for its application?					
4. Suggestions					
4.1. Strengths of the model					
4.2. Weaknesses of the model					
4.3. Areas for improvement					

1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree

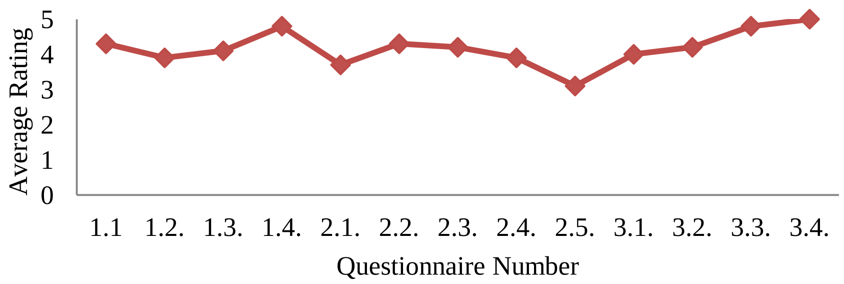

Figure 8-12 Average Resource Model Questionnaire Ratings from 10 Industrial AMT Development Experts

- Utility

To determine the utility of the model, four questions were asked to analyse the success of the model output. When combining the four questions to provide an average, the utility of the model was the highest of the three categories with a value of 4.5. Most of the 10 experts strongly agreed with the questions. Question 3.4 was regarded as crucial by defining whether the model output was appropriate for its application. This question scored the highest average with a value of 5, indicating that every one of the 10 AMT experts thought the output was suitable. Each of the other questions provided validation that the model evaluates using the correct parameters, organised in the correct themes using the most appropriate data collection platform.

- Strengths of the Model

There were many noted strengths of the model from each of the 10 AMT development experts. The reduced subjectivity of forecasting development person-hours at the initial stages of development was the first. This was an obvious strength as there is currently no existing AMT development cost estimation techniques and toolsets, defined within the industry analysis in Chapter 4. The enhancement clarified the model would improve future manufacturing R&T portfolio planning and project management and feeds into the cost estimation requirements from the new management of AMT development process map, detailed within Chapter 4, Section 4.6 and illustrated in Figure 4-6.

When operating the model, experts generally liked the visualisation of the impact of functional size on the development person-hours. Furthermore, with a systematic thought process performed by having to input data for their AMT(s) for each effort driver, consideration was then determined by revealing who will be developing the AMT. For example, could a development engineer with more experience be aligned to reduce development person-hours? Each of the experts was impressed by the capability of the model to further calibrate when more AMTs are developed within the business. Another strength raised identified the model could act as a central data storage system for all AMTs developed within R&T.

- Weaknesses of the Model

Many experts felt the model acted like a black box, a typical drawback of parametric cost modelling. Another weakness raised was the lack of TRL data for historical AMTs. This formed an area for discussion as the aerospace manufacturing organisation involved with this case study had only implemented the TRL in 2009; so many AMTs had been developed without the TRL platform. However, as the model is currently being implemented within this organisation, historically developed AMTs will continue to grow, generating a reiterative model.

- Areas of Improvement

Experts discussed how the elaborations for each input parameter would improve operational efficiency, by having a drop down within the MS Excel model interface and not having to revert to the MS Word file. A further suggestion included the alignment to the overall Project and Programme Management Software used within the aerospace manufacturing organisation that this case study was performed. This included the 'Unified Portfolio, Project and Programme Management' (UP-3P) Toolset for R&T. Many experts deliberated the model would enhance this existing planning software. Another area of improvement was inclusion of a reset button within the Model MS Excel interface, allowing the user to reset to the default values after performing a person-hours forecast.

8.5.2 Direct Cost Model Validation Results

The final questionnaire used for the validation of the COTECHMO Direct Cost model is listed in Table 8-11. The AMT development experts were asked to rate each of the questions after they performed a COTECHMO Direct Cost forecast for their AMT(s).

The results of the questionnaire are presented graphically in Figure 8-13, with the question numbers on the 'x-axis' and the average rating from each of the 10 users on the 'y-axis.' The questionnaire was filled in by each expert, rating the specific question using the scale provided, ranging from 1, strongly disagree, to 5, strongly agree. To complete the Direct Cost model validation each expert involved with completing the questionnaire was asked to define strengths and weaknesses of the model.

The feasibility, usability and utility responses provided by each of the 10 AMT development experts are now discussed in detail.

- Feasibility

Following the feasibility of the Resources model discussed previously, four questions were asked to define the input information and its capability within its practical application. The rating of each question ranged from 'neutral' to 'strongly agree,' with an average of 4.2. The lowest average rating was question 1.1, with an average of 3.9. This was based on the low availability of data at the initial development stages, although was resolved when surrogate sources of data were explained. Each expert was impressed with the time taken to use the software, with an average rating of 4.1. The question with the highest average rating was whether the model enhances the existing AMT development direct cost forecasting process, with an average value of 4.8.

Table 8-11 Direct Cost Model Validation Questionnaire

Assessment Criteria	**1**	**2**	**3**	**4**	**5**
1. Feasibility					
1.1. The model is logical for forecasting AMT development Direct (hardware) Cost?					
1.2. The model is suitable for forecasting at the initial development stages?					
1.3. The time taken to perform a forecast was appropriate?					
1.4. The model enhances existing AMT development Direct (hardware) Cost forecasting techniques?					
2. Usability					
2.1. The objective and purpose of using the forecasting model was clearly defined?					
2.2. The model interface was easy to use?					
2.3. The stages of the model operation were easy to follow?					
2.4. The model software was intuitive?					
2.5. The model calibration can be performed easily?					
3. Utility					
3.1. The input parameters capture all of your AMT drivers impacting development Direct (hardware) Cost?					
3.2. The cost drivers were clustered under the correct 'themes'?					
3.3. The TRL formed an appropriate data capture technique for AMT development Direct (hardware) Cost?					
3.4. The model output was appropriate for its application?					
4. Suggestions					
4.1. Strengths of the model					
4.2. Weaknesses of the model					
4.3. Areas for improvement					

1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree

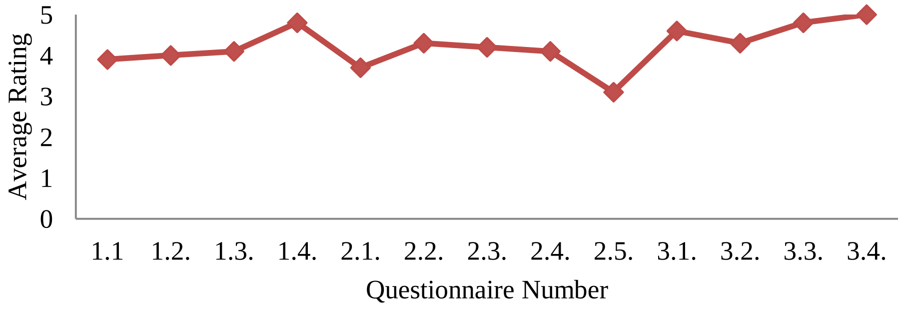

Figure 8-13 Average Direct Cost Model Validation Questionnaire Results from 10 Industrial AMT Development Experts

- Usability

Following the usability of the Resources model, five questions were asked to define how easy the model was to use within its industrial application. The average rating for the five usability questions evaluated by the 10 AMT development experts was slightly lower than the feasibility discussed previously, with a value of 3.9. On detailed analysis, question 2.5 was rated the lowest with an average value of 3.1. Question 2.1 and 2.4 had the next lowest average score of 3.7 and 4.1. Question 2.2 and 2.3 scored average outputs of 4.3 and 4.2 respectively, defining the successful operation of the model interface and each of the forecasting stages.

- Utility

Following the utility of the Resources model, four questions were asked to analyse the success of the model output. When combining the four questions to provide an average, the utility of the model had a value of 4.7. Question 3.4 was regarded as the most crucial question in defining whether the model output was appropriate for its application. This question scored the highest average with value of 5, defining that all 10 AMT experts thought the output was completely suitable. Each of the other questions provided validation that the model uses the correct parameters, organised in precise themes using the most appropriate data collection platform.

- Strengths of the Model

The strengths of the Direct Cost model noted were very similar to those noted for the Resources model. The first strength identified by experts was the reduced subjectivity of forecasting AMT development direct cost. Currently, there is no formal direct cost forecasting process, so experts defined that implementation of the model would significantly enhance future manufacturing R&T portfolio planning and project management. This cost estimation model feeds into the requirements defined within the new management of AMT development process map, detailed within Chapter 4, Section 4.6 and illustrated in Figure 4-6.

When operating the model, experts found it beneficial having to consider each of the cost drivers in detail for their AMT(s). Another strength identified was the capability to refine calibration as more AMTs are developed, theoretically refining the model accuracy. A further identified strength was the model capability to act as a central data storage system for all AMTs developed within R&T.

- Weaknesses of the Model

Experts noted that the model performed like a black box, although this is a typical parametric cost modelling drawback. Another weakness identified was the lack of existing TRL data from historically developed AMTs. However, the model is currently being implemented within a large aerospace manufacturing organisation, so historical AMTs within R&T will continue to grow.

- Areas of Improvement

The areas of improvement for the Direct Cost model were very similar to those identified for the Resources model. Each expert discussed how the elaborations for each input parameter would improve operational efficiency, by having a drop down within the MS Excel model interface. Alignment to the overall Project and Programme Management Software used within the aerospace manufacturing organisation R&T division this case study is based was another suggestion. Many experts deliberated the model would enhance this existing planning software. Another area of improvement was inclusion of a reset button within the Model MS Excel interface, allowing the user to reset to the default values after performing a Direct Cost forecast.

8.6 PERFORMO Verification Results

Chapter 6 discussed the development of the two PERFORMO forecasting models. To verify each model, AMTs with known conclusions were selected. These were not included within the empirical study presented in Section 8.3 and were selected based on their known conclusion within the aerospace manufacturing industry. Each PERFORMO model was statistically verified using ranking tests with the known conclusions of the AMTs listed in Table 8-12, with the results presented within the following Sub Sections.

Table 8-12 AMTs Utilised for PERFORMO Industrial Verification and their Success within an Aerospace Manufacturing Organisation

AMT Number	Status within the Manufacturing Organisation
16.	In Operation
17.	In Operation
18.	In Operation
19.	In Operation
20.	Unsuccessful
21.	Unsuccessful
22.	In Operation
23.	Unsuccessful

8.6.1 Tangible Model Verification Results

The PERFORMO Tangible model was defined using Equation 6.13, presented earlier within Chapter 6. The time, cost and quality Key Performance Factors (KPFs) form the input predictors that have an impact on the AMT tangible performance, illustrated in Figure 8-14.

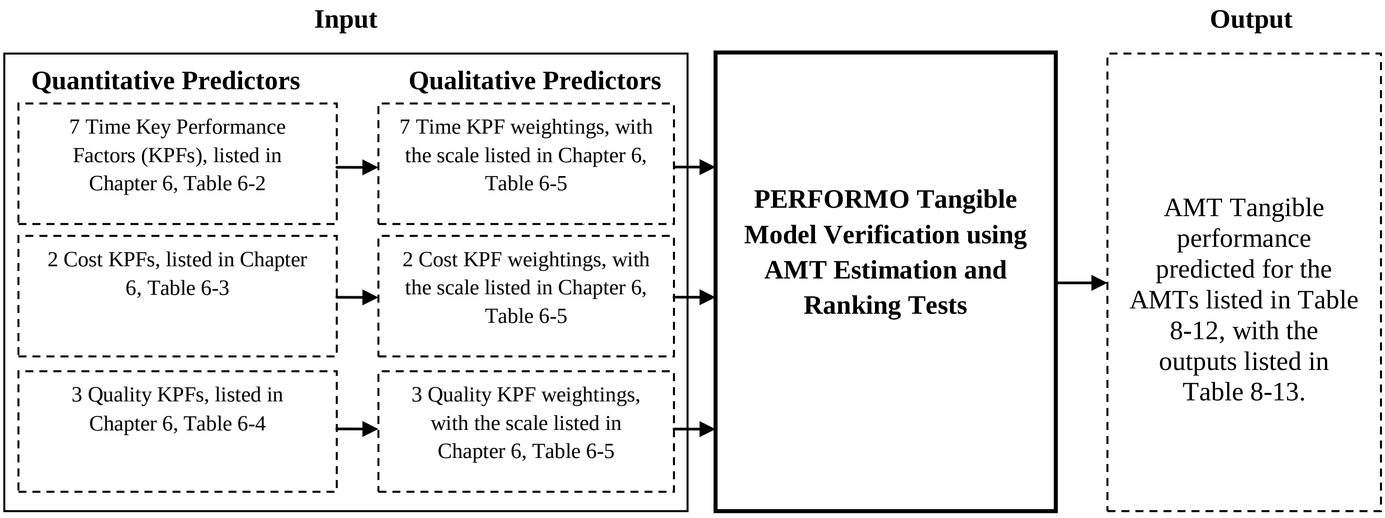

Figure 8-14 Tangible Model Verification

The first step of evaluating the performance of the AMTs listed in Table 8-12 involved utilising the PERFORMO MS Excel Tangible model, with the operation described in Chapter 7, Sub Section 7.4.5. The final outputs are listed in Table 8-13. Outputs with a value higher than 1.0 represent performance enhancement, with values below 1.0 indicating a performance degradation. Within the Table, performance outputs highlighted green represent successful accuracy, with red indicating unsuccessful accuracy. All of the 8 AMTs selected for evaluation were correctly forecast by the model, equating to an accuracy of 100%, initially verifying the model hypothesis.

Table 8-13 PERFORMO Tangible Performance Output for 8 AMTs

AMT Number	Tangible Performance
16.	2.11
17.	1.91
18.	2.22
19.	2.40
20.	0.55
21.	0.10
22.	3.55
23.	0.36

To further verify, the 5 successful AMTs were ranked on their actual data within operations. The forecast performance output from the model was checked for correlation with the ranking from the actual operations data. The output ranking was coherent for 4 of the 5 AMTs, indicating an accuracy of 80%. Chapter 9 discusses how to further enhance the model verification and eliminate the minor discrepancies in the accuracy, with recommendations for future work.

8.6.2 Intangible Model Verification Results

Equation 6.20 presented within Chapter 6 formed the final PERFORMO Intangible Equation. Figure 8-15 illustrates how the health and safety, flexibility, managerial, risk and strategic qualitative KPFs impact the intangible performance output.

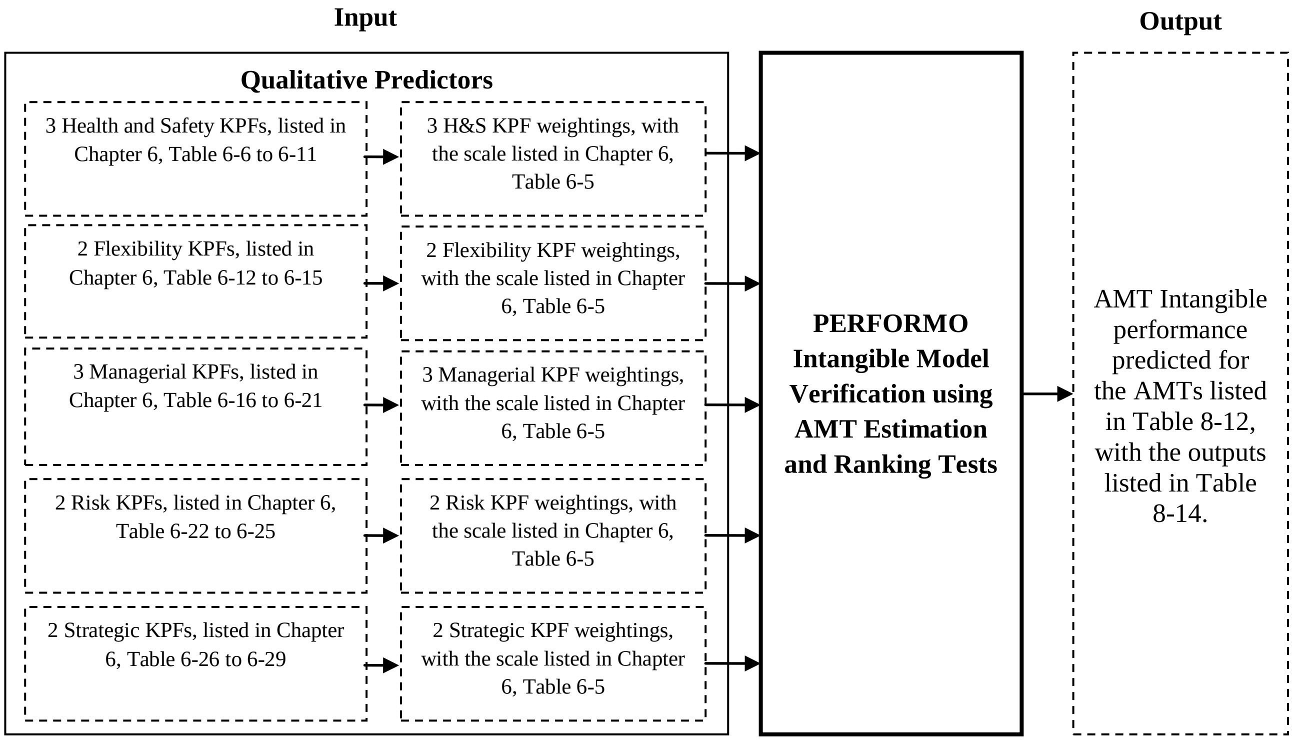

Figure 8-15 Intangible Model Verification

The second Step of evaluating the performance of the AMTs listed in Table 8-12, involved using the PERFORMO MS Excel Intangible model, with the operation detailed in Chapter 7, Sub Section 7.4.6. The final performance outputs are listed in Table 8-14. Outputs higher than 0.0 represent a performance enhancement and below 0.0 a performance degradation. Following the Tangible model, performance outputs highlighted green within the Table represent a successful accuracy and red an unsuccessful accuracy. All of the 8 AMTs selected for evaluation were correctly forecast by the model, equating to an accuracy of 100%, determining initial hypothesis verification.

Following the further verification of the Tangible model, the 5 successful AMTs were ranked on their actual data within operations. The output from the Intangible model was checked for correlation. The output ranking was coherent for 4 of the 5 AMTs, equating to an accuracy of 80%.

The minor discrepancies in the model verification are the subject of future work recommendations, discussed within Chapter 9.

Table 8-14 PERFORMO Intangible Performance Output for 8 AMTs

AMT Number	Intangible Performance
16.	0.02
17.	0.59
18.	0.66
19.	0.61
20.	-0.13
21.	-0.49
22.	0.98
23.	-0.11

8.7 PERFORMO Validation Results

The evaluation of the 8 AMTs within the aerospace manufacturing industry is a quantitative form of validation. AMT development experts, project, portfolio and research managers aim to use each PERFORMO forecasting model within an industrial practical environment, thus, an expert driven validation process was followed. This used the detailed research methodology described in Sub Section 8.2.5 and the results are presented in the following Sub Sections. Any model criticisms are referenced and discussed in the recommendations for future work within Chapter 9.

8.7.1 Tangible Model Validation Results

The final questionnaire used for the validation of the PERFORMO Tangible model is listed in Table 8-15. The 10 AMT development experts were asked to rate each of the questions, after they performed a PERFORMO Tangible forecast for their specific AMT(s) used within the empirical study, discussed earlier in Section 8.3.

The results of the questionnaire are presented graphically in Figure 8-16, with the question numbers on the 'x-axis' and the average rating from each of the 10 users on the 'y-axis.' The questionnaire was filled in by each expert rating the specific question using the scale provided ranging from 1, strongly disagree, to 5, strongly agree. Each expert involved with completing the questionnaire was asked to define strengths and weaknesses of the model.

Table 8-15 Tangible Model Validation Questionnaire

Assessment Criteria	**1**	**2**	**3**	**4**	**5**
1. Feasibility					
1.1. The model is logical for forecasting AMT Tangible performance?					
1.2. The model is suitable for forecasting Tangible performance at the initial development stages?					
1.3. The time taken to perform a forecast was appropriate?					
1.4. The model enhances existing AMT performance forecasting techniques?					
2. Usability					
2.1. The objective and purpose of using the forecasting model was clearly defined?					
2.2. The model interface was easy to use?					
2.3. The stages of the model operation were easy to follow?					
2.4. The model software was intuitive?					
2.5. The data input can be performed easily?					
3. Utility					
3.1. The Key Performance Factors captured all 'Tangible' performance parameters for your AMT(s)?					
3.2. The Key Performance Factors were clustered under the correct 'themes'?					
3.3. The weighting of each Key Performance Factor was suitable for the application?					
3.4. The model final output was appropriate for its application?					
4. Suggestions					
4.1. Strengths of the model					
4.2. Weaknesses of the model					
4.3. Areas for improvement					

1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree

The feasibility, usability and utility responses provided by each of the 10 AMT development experts are now presented in detail.

- Feasibility

To evaluate the feasibility of the Tangible model, four questions were asked to define the input information and the model capability within its practical application. The rating of each question ranged between ‘neutral’ to ‘strongly agree,’ with an average of 4.28. The lowest average rating was question 1.1 and 1.3, with an average of 4. The question with the highest average rating involved evaluating whether the model enhances the existing AMT Tangible forecasting process with an average value of 4.8.

- Usability

To determine the usability of the model, five questions were asked to define how easy the model was used within its industrial application. The average rating for the five usability questions was slightly lower than the feasibility discussed previously, with a value of 4.1. On detailed analysis, question 2.4 was rated the lowest with an average value of 3.8. Question 2.1 and 2.3 were the next lowest with each having an average score of 4. Question 2.2 and 2.5 scored average outputs of 4.4 and 4.2 respectively, defining successful operation of the model interface and the input parameters.

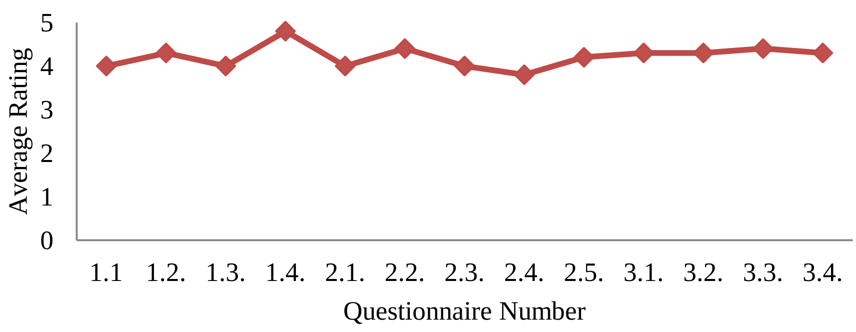

Figure 8-16 Average Tangible Model Validation Questionnaire Results from 10 Industrial AMT Development Experts

- Utility

To determine the utility of the model, four questions were asked to analyse the success of the model output. When combining the four questions to provide an average, the utility of the model was slightly higher than the feasibility with a value of 4.3. Most of the 10 experts strongly agreed with the questions. Question 3.4 was regarded as the most crucial question in defining whether the model output was appropriate for its application. This question scored an average value of 4.3 defining a successful tangible performance output. Each of the other questions provided validation that the model evaluates using the correct KPFs organised in the correct themes.

- Strengths of the Model

The first strength included reducing existing subjectivity when forecasting AMT tangible performance at the initial stages of development. Currently there is no constructive performance forecasting process within industry, so experts defined that implementation of the model would significantly enhance future manufacturing R&T portfolio planning and project management. This feeds into the performance forecasting requirements of the new management of AMT development process map, detailed within Chapter 4, Section 4.6 and illustrated in Figure 4-6.

Experts were impressed by the model ability to capture uncertainly at the initial development stages as a 3 point estimate. Another benefit raised included the ability of the model to eliminate KPFs not applicable to an AMT selected for evaluation. This allowed an apple to pears comparison for a wide range of AMTs with varied applications and experts further clarified there is currently no model with such capability. Another strength identified was justifying new AMT investments at the initial development stages by quantification of performance. Each expert stated the model would help validate and select the most suitable AMT for development. Furthermore, each expert discussed how the model forms a central storage system for all AMTs within the R&T portfolio; acting as a reiterative process the more AMTs are developed.

- Weaknesses of the Model

Experts identified that although the model provided an automated output from the data input; this generated some sceptical views for confidence in the final output.

- Areas of Improvement

Each expert discussed that having elaborations for each KPF parameter would improve operational efficiency by having a drop down tab within the MS Excel model interface and not having to revert to the MS Word file. Alignment to the overall Project and Programme Management Software used within the aerospace manufacturer R&T division was a further suggestion. Another area of improvement was inclusion of a reset button within the interface, allowing the user to reset to the default values after performing a tangible performance forecast.

8.7.2 Intangible Model Validation Results

The final questionnaire used for the validation of the PERFORMO Intangible model is listed in Table 8-16. The 10 AMT development experts were asked to rate each of the questions after they performed a PERFORMO Intangible forecast for their specific AMT within the empirical study, discussed within Section 8.3.

The results of the questionnaire are presented graphically in Figure 8-17, with the question numbers on the ‘x-axis’ and the average rating from the 10 users on the ‘y-axis.’

The feasibility, usability and utility responses provided by each of the 10 AMT development experts are now discussed in detail.

- Feasibility

Following the feasibility of the Tangible model discussed previously, four questions were asked. The rating of each question ranged between ‘agree’ to ‘strongly agree,’ with an average of 4.5. The lowest average rating was question 1.1, with an average of 4.1. The question with the highest average rating involved evaluating whether the model enhances existing AMT intangible forecasting processes, with an average value of 4.8.

Table 8-16 Intangible Model Validation Questionnaire

Assessment Criteria	**1**	**2**	**3**	**4**	**5**
1. Feasibility					
1.1. The model is logical for forecasting AMT Intangible performance?					
1.2. The model is suitable for forecasting at the initial development stages?					
1.3. The time taken to perform a forecast was appropriate?					
1.4. The model enhances existing AMT performance forecasting techniques?					
2. Usability					
2.1. The objective and purpose of using the forecasting model was clearly defined?					
2.2. The model interface was easy to use?					
2.3. The stages of the model operation were easy to follow?					
2.4. The model software was intuitive?					
2.5. The data input can be performed easily?					
3. Utility					
3.1. The Key Performance Factors captured all 'Intangible' performance parameters for your AMT(s)?					
3.2. The Key Performance Factors were clustered under the correct 'themes'?					
3.3. The weighting of each Key Performance Factor was suitable for the application?					
3.4. The model final output was appropriate for its application?					
4. Suggestions					
4.1. Strengths of the model					
4.2. Weaknesses of the model					
4.3. Areas for improvement					

1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree

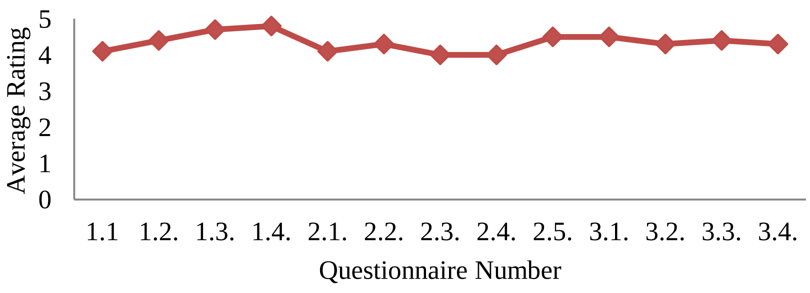

Figure 8-17 Average Intangible Model Validation Questionnaire Results from 10 Industrial AMT Development Experts

- Usability

Five questions were asked to define how easy the model was to use within its industrial application. The average rating for the five usability questions was slightly lower than the feasibility discussed previously, with a value of 4.2. Questions 2.3 and 2.4 were the lowest average rating, each having average values of 4.0. Question 2.2 and 2.5 scored average outputs of 4.3 and 4.5 respectively, defining successful operation of the model interface and input parameters.

- Utility

Following the utility evaluation of the Tangible model, four questions were asked to analyse the success of the Intangible model output. The overall average for each of the utility questions was slightly below that recorded for feasibility with a value of 4.4. Question 3.4 was regarded as the most crucial and defined whether the model output was appropriate for its application. This question scored an average value of 4.3 defining a successful intangible performance output. Each of the other questions provided validation that the model evaluates using the correct KPFs, which are organised in suitable themes.

- Strengths of the Model

The first strength identified was the model capability to reduce high levels of subjectivity when evaluating the intangible performance of novel AMTs. Experts were impressed by the capability to transfer the typically qualitative parameters into a quantitative output. Experts identified that there is currently no intangible performance forecasting process, so implementation of the model would definitely enhance future R&T planning and project management. This feeds into the intangible performance requirements from the new management of AMT development process map, detailed within Chapter 4, Section 4.6 and illustrated in Figure 4-6.

Another benefit raised included the ability of the model to eliminate KPFs not applicable to the AMT selected for evaluation. This allowed an apple to pears comparison, for a wide range of AMTs with varied applications. Furthermore, each expert discussed how the model forms a central storage system for all AMTs within the R&T portfolio; acting as a reiterative process.

- Weaknesses of the Model

The weakness identified by experts was that although the model provided an automated output from the data input; this generated some sceptical views for confidence in the final output.

- Areas of Improvement

Following the improvement recommendations made for the Tangible model, having elaborations for each KPF parameter would improve operational efficiency by having a drop down tab within the model interface. Alignment to the overall Project and Programme Management Software used within the aerospace manufacturing organisation R&T department was another suggestion. Another area of improvement was inclusion of a reset button.

8.8 Cost-Benefit Forecasting Framework Validation Results

The Cost-Benefit Forecasting Framework validation used the same applicability criteria as the COTECHMO and PERFORMO models including: feasibility, usability and utility. For this application the questions under each criterion differed, tailoring for a framework, evaluating the operation and the final output. The final questionnaire used for validation of the Cost-Benefit Forecasting Framework is listed in Table 8-17. The AMT development experts were asked to rate each question after they performed a Cost-Benefit Forecast for their AMT(s). The results of the questionnaire are presented graphically in Figure 8-18. Framework criticisms are referenced and discussed in the recommendations for future work within Chapter 9.

The feasibility, usability and utility responses provided by each of the 10 AMT development experts are now discussed in detail.

- Feasibility

To evaluate the feasibility of the Cost-Benefit Forecasting Framework four questions were asked. The rating for each question ranged from ‘neutral’ to ‘strongly agree,’ with an average of 4.28. The lowest average rating was question 1.1 and 1.3 with an average of 4. Few experts thought the time taken to perform the forecast was slightly high. The next lowest average rating was question 1.2, with an average of 4.1. A small number of experts defined that the level of information at the initial development stages was limited, especially when developing a completely novel AMT. However, this was resolved when explaining how to analyse surrogate sources of data. The question with the highest average rating evaluated if the framework enhanced the existing AMT development cost-benefit forecasting process with an outstanding average value of 5.0.

- Usability

The average rating for the five usability questions was slightly lower than the feasibility discussed previously, with a value of 3.96. On detailed analysis, question 2.5 was rated the lowest with an average value of 3.5. Some experts felt that the data input required at the stages to sufficiently operate each model could potentially be challenging. Question 2.2 and 2.4 had an average score of 4.0, proving the interfaces were easy to use and the software is intuitive. Question 2.3 scored an average of 4.1; with experts defining the overall stages were followed suitably. Question 2.1 scored the highest, with experts defining the overall framework and objective was clearly defined.

Table 8-17 Cost-Benefit Framework Validation Questionnaire

Assessment Criteria	**1**	**2**	**3**	**4**	**5**
1. Feasibility					
1.1. The framework is logical for forecasting AMT development value?					
1.2. The framework is suitable for forecasting at the initial development stages?					
1.3. The time taken to perform a cost-benefit forecast was appropriate?					
1.4. The framework enhances existing AMT cost-benefit forecasting techniques?					
2. Usability					
2.1. The objective and purpose of using the framework was clearly defined?					
2.2. The framework interfaces were easy to use?					
2.3. The stages of the framework were easy to follow?					
2.4. The framework software was intuitive?					
2.5. The data input can be performed easily?					
3. Utility					
3.1. The framework cost-benefit analysis had the appropriate level of granularity?					
3.2. The framework stages were in the correct order?					
3.3. The final development value output was correct for your AMT(s)?					
3.4. The framework final output was appropriate for its application?					
4. Suggestions					
4.1. Strengths of the framework					
4.2. Weaknesses of the framework					
4.3. Areas for improvement					

1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree

- Utility

To determine the utility of the framework, four questions were asked to analyse the success of the cost-benefit output. When combining the four questions to provide an average, the utility of the model was the highest of the three categories with a value of 4.6. Question 3.3 and 3.4 were regarded as the most crucial and each scored an average of 4.5. This included assessment of the final outputs from the empirical study, illustrated in Figures 8-4 to 8-7, with the majority strongly agreeing on the final development value and the use of the thresholds. These defined the model output was appropriate for its application, crucial when selecting a novel AMT with the best development value, the primary focus of the framework. Each of the other questions provided exceptional validation, proving the framework performed the analysis with a precise level of granularity and in the correct order.

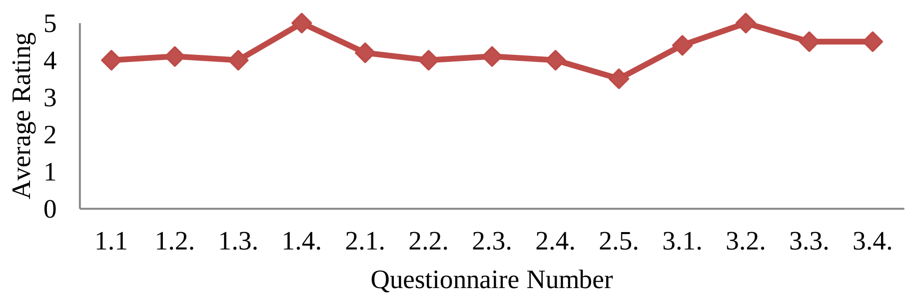

Figure 8-18 Average Cost-Benefit Forecasting Framework Validation Questionnaire Results from 10 Industrial AMT Development Experts

- Strengths of the Framework

There were many noted strengths of the model from each of the 10 AMT development experts. Each defined that performing a forecast for person-hours and the direct cost and plotting against the perceived tangible and intangible benefits, provides an excellent evaluation for an AMT assessment. This enhanced the R&T investment decision and AMT development management process, with the design of a modified management of AMT development process map presented in Chapter 4, Section 4.6 and illustrated in Figure 4-6. This analysis then supports allocation of the required R&T investment within the R&T programme and systematically guides the user through the assessment, forming development value. General consensus defined that implementation would significantly reduce the selection of incorrect AMTs at the initial development stages, the primary focus of the framework.

Experts also described the TRL as a suitable platform to perform the cost-benefit assessment. A further strength included the reduction of AMT development risk, by systematically evaluating at the initial development stages.

Furthermore, experts identified the framework could act as an excellent central storage system for all AMTs developed within R&T, creating a historical database.

- Weaknesses of the Framework

There were very limited negative comments from experts for the overall Cost-Benefit Framework. The main comments were captured in the weaknesses of the COTECHMO and PERFORMO models, discussed in detail within Section 8.5 and 8.7 respectively.

- Areas of Improvement

The first suggestion identified by experts involved seamlessly linking each of the stages and models within MS Excel using Visual Basic for Applications (VBA). This would enhance the operation of the models at each framework stage, logically guiding the user and the data required. Alignment to the overall Project and Programme Management Software used within the aerospace manufacturing organisation was another suggestion. Many experts identified the framework would significantly enhance existing planning software.

8.9 Chapter Summary

This Chapter presented the industrial verification and validation of the Cost-Benefit Forecasting Framework. In Section 8.2 the followed detailed research methodology was presented, including the list of AMTs and the experts involved. In Section 8.3 the initial verification of the framework was performed using 15 novel AMTs within a large aerospace manufacturing organisation. This included the information input into the framework through each stage and the development advice output in graphical form. In Section 8.4 a detailed verification of each COTECHMO model was completed using the data from the empirical study, verifying each model hypothesis. Section 8.5 presented a validation of each COTECHMO model using the excellent responses from 10 AMT development experts. Section 8.6 detailed the verification of each PERFORMO model. To successfully verify, 8 further AMTs within the aerospace manufacturing organisation were selected with known conclusions, separate to those assessed within the empirical study. Section 8.7 validated each PERFORMO model by analysis of 10 AMT expert responses.

Section 8.8 assessed the overall Cost-Benefit Forecasting Framework operation within its industrial application, also using the responses from the 10 AMT experts. This validated that the framework was suitable for use within the aerospace manufacturing organisation and meets the requirements formed within the industrial study, presented in Chapter 4.

The next Chapter presents the discussion and conclusion of this research, including recommendations of how to enhance each model, the framework and its impact outside the supporting organisation.

CHAPTER 9

DISCUSSION AND CONCLUSIONS

9.1 Introduction

This Chapter initially discusses the key research findings and identifies the primary knowledge contributions. A discussion is then presented of how the original research aim and objectives were successfully addressed. Research limitations are then evaluated and discussed, with future work recommendations suggested of how to enhance these minor limitations and the overall impact of the research. Final concluding remarks complete the Chapter and close the thesis.

9.2 Summary of Key Research Findings

This Section presents a summary of the key research findings and observations. To remain concise and coherent, this Section has been divided into Sub Sections that follow the structure of the thesis.

9.2.1 Literature Review

The literature review covered the three primary areas of this research: management of aerospace Advanced Manufacturing Technology (AMT) development, cost estimation and technology forecasting. The evaluation of the management of aerospace AMT development revealed that industry uses Technology Management (TM) techniques for the management of new technologies, through the manufacturing technology lifecycle. Despite availability of existing TM frameworks, the literature identified a clear lack of understanding how industry and research centres justify their Research and Technology (R&T) investment to develop novel AMTs. At this early stage of development, AMTs require large investments to develop within R&T, using the Technology Readiness Level (TRL) as a maturity platform. The literature revealed that there is a significant lack of understanding how industry and research institutions estimate AMT development resources and hardware costs. In response, the cost estimation domain was explored, revealing the availability of state-of-the-art models from universities and commercial cost estimation companies. Despite this availability, each was not aligned or applied to estimate AMT development resources and cost. The existing TM techniques available within the literature also revealed a lack of understating how industry and research institutions estimate the AMT performance at the early stages of development, prior to entering development research. This analysis revealed AMT evaluation techniques with inclusion of tangible and intangible performance, although each was not suited for the initial stage of development. These techniques were not suitable for diverse AMTs with varied applications. Subsequently, the technology forecasting domain was explored, identifying no existing techniques or state-of-the-art models and toolsets have been applied for forecasting AMT performance, at the initial development stages. At this stage, there are high levels of technological and development uncertainty.

9.2.2 Research Methodology

Chapter 3 described the development of a research methodology. To successfully achieve the aims and objectives, a qualitative and quantitative research design was required. This allowed for a flexible research approach, with the capability to verify and provide validity within an industrial setting. From the direct involvement to real life data with the collaborating manufacturing organisation, a case study research strategy was selected. The information formed the platform for the development of a final research design and consisted of 5 key Phases, effectively followed within this research.

9.2.3 A Study of the Management of Aerospace Advanced Manufacturing Technology Development

A review of the literature presented in Chapter 2 revealed a lack of understanding how industry manages AMT development and provides justification of the required R&T investment. Subsequently, Chapter 4 performed a detailed study of existing techniques used within the aerospace manufacturing industry. This revealed that industry allocate and justify the required R&T investment to develop novel AMTs using expert opinion, consisting of subjective and inconsistent outputs. Additionally, industry estimates the development cost and perceived performance of the AMT using expert opinion. The detailed analysis formed a new process map design, for the management of AMT development and formed the final research protocol, validated by an industrial partner. The first requirement of the new process map included the capability to estimate AMT development resources and hardware costs, within an R&T function. This formed the requirement for the development of the 'Constructive Technology Development Cost Models' (COTECHMO). The second requirement was the need for two AMT 'Performance Forecasting Models' (PERFORMO), capable of forecasting the tangible and intangible performance, at the early stage of development. Also revealed within the industry analysis was a lack of development value forecasting toolsets and techniques. This formed the requirement to plot outputs from COTECHMO and PERFORMO, generating development value. Therefore, a systematic framework was required to operate the developed models within an industrial setting, with Chapter 7 presenting the developed Cost-Benefit Forecasting Framework.

9.2.4 The Constructive Technology Development Cost Model (COTECHMO)

A detailed analysis of literature and industry defined a lack of cost estimation models, toolsets and processes, capable of estimating AMT development resources in person-hours and hardware cost. To address this problem, two parametric cost models were developed using the detailed research methodology.

An initial model form study was conducted with cost estimation experts, identifying a suitable parametric hypothesis. The size, effort and cost driver study followed, using industry experts. This revealed novel AMT development effort and cost drivers, with their qualitative descriptions. These were validated with experts from AMT development and cost estimation, forming the platform for the two stage Wideband Delphi study. This consisted of 21 and 20 experts, each successfully reaching consensus on the quantitative driver weightings. The parametric models were built in MS Excel, enhanced and initially validated using expert feedback. Model industrial verification and validation followed, proving their capability to solve the AMT development cost estimation problem.

9.2.5 The Performance Forecasting Model (PERFORMO)

The literature and industry analysis revealed a lack of performance forecasting models and toolsets, capable of estimating AMT tangible and intangible performance, at the early development stages. To address, two Performance Forecasting Models (PERFORMO) were developed using the detailed research methodology. The first step involved identification of two performance forecasting model hypothesis. This was performed in collaboration with various performance forecasting and decision making experts from diverse backgrounds. A Key Performance Factor (KPF) study followed, identifying novel AMT tangible and intangible KPFs using AMT development experts and was initially validated with decision making specialists. The models were then built in MS Excel, enhanced and initially validated using feedback from AMT development experts. These were ready to be tested within an industrial setting, using statistical verification and expert validation, identifying their capability to resolve the AMT performance forecasting problem.

9.2.6 Cost-Benefit Forecasting Framework

The detailed industrial study, performed in Chapter 4, formed a requirement for an enhanced process map for the management of AMT developments, for justification and allocation of R&T investment. To meet the cost estimation aspect, COTECHMO was developed in Chapter 5. Chapter 6 followed with the development of two

PERFORMO models to meet the AMT performance forecasting requirements. To operate each COTECHMO and PERFORMO model within an industrial setting and plot the outputs, forming development value, a novel Cost-Benefit Forecasting Framework was developed. The framework guided the user to plot outputs from each COTECHMO and PERFORMO model into Development Value Advice (DEVAL) graphs. This involved a detailed analysis of the data input for the operation of each COTECHMO and PERFORMO model. The outputs were evaluated to allow seamless data entry into the DEVAL graphs. The final DEVAL graphs provide the framework user with the information to define which AMTs provide the business with the best R&T investment value. This final Cost-Benefit Forecasting Framework was successfully verified and validated, a discussion point for the proceeding Sub Section.

9.2.7 Cost-Benefit Forecasting Framework Industrial Verification and Validation

To prove the Cost-Benefit Forecasting Framework capability within an aerospace manufacturing R&T division, a detailed industrial verification and validation was performed. The initial verification involved an empirical study using the Cost-Benefit Forecasting Framework within a large aerospace manufacturing organisation. There were 10 AMT experts involved in operating the framework, proving the capability to forecast within an R&T function, for assessment of diverse AMTs with varied manufacturing applications. This successfully plotted outputs from each COTECHMO and PERFORMO model, providing final DEVAL graphical outputs, effectively presenting the user with AMT development value advice.

The data from the 15 AMTs within the empirical case study was then used to verify each COTECHMO output. Multiple regression was performed on the Resources and Direct Cost model. From the limited number of historical AMTs within the empirical study, each model was tested in reduced forms, with the drivers clustered into common themes, allowing an F-test to be performed, determining model significance. The COTECHMO Resources model had an outstanding final F-value of 106.65, verifying model hypothesis significance. The final F-value for the COTECHMO Direct Cost model was lower at 5.59, although this was still sufficient to determine model hypothesis significance. To further verify, a sensitivity analysis was performed on the predictors of each reduced model, using t-values and p-values. Four of the five COTECHMO Resources model predictors were statically verified, using a specified p-value of 0.05. For the COTECHMO Direct Cost model three of the five predictors complied with the specified p-value of 0.05. On detailed evaluation with experts, the low predictor variation was estimated from having a small number of cases. To test each model Cost Estimation Relationship (CER) forecasting accuracy, PRED (Prediction Level) values were utilised. The industry specification required each model to fall within PRED(20), requiring the forecast outputs to be within 20% of the actual historical value. The Resources model complied with this PRED value for 8 of the 15 AMTs, although 11 of the 15 AMTs complied with PRED(25), identifying the model was only 5% from achieving the specified accuracy. The Direct Cost model had a higher accuracy with 93% of the forecast data falling within PRED(20), superseding the industrial requirements. In summary, each model parametric hypothesis has been proven for the AMT development application. To assess each COTECHMO model within an industrial setting, a validation was performed using the feedback from 10 AMT development experts. The responses clarified each model feasibility, usability and utility, identifying their excellent suitability for application within the assigned aerospace manufacturing organisation R&T division.

The COTECHMO statistical verification utilised data from the empirical study, successfully proving each hypothesis using multiple regression. However, these AMTs were still within an R&T function and not fully implemented within manufacturing. To verify each PERFORMO model, eight AMTs were selected from within an aerospace manufacturing organisation with known outcomes, with five determined successful and three unsuccessful. The PERFORMO models were used to forecast performance for each of the eight AMTs, identifying an outstanding 100% accuracy for each model, indicating hypothesis verification.

To determine the accuracy of the PERFORMO outputs, each model was tested for correlation with the ranking of five successful AMTs. This ranking was coherent for four of the five AMTs for each model, equating to a good accuracy of 80%. Following the COTECHMO validation, each PERFORMO model was evaluated using the responses from the 10 AMT development experts. These responses validated each model feasibility, usability and utility.

To provide applicability validation of the Cost-Benefit Forecasting Framework, including the final development value outputs from DEVAL, responses were also evaluated from the 10 AMT experts. These responses indicated validation of the framework, defining suitability for the application. The final outputs were also assessed, identifying correct development value advice for the assessed AMTs, resolving the R&T development value advice problem.

9.3 Key Research Contributions

This research feeds into existing aerospace manufacturing Technology Management (TM) and has specifically contributed to enhancement of the management of AMT development, including the allocation and justification of R&T investment. The key research contributions are summarised in the following:

Development of a parametric cost model capable of estimating aerospace AMT development effort in resources.

- The first reported use of a parametric cost model for successful estimation of aerospace AMT non-recurring development effort, in resources (person-hours), using the TRL for development.
- The model CER hypothesis is statistically verified from assessment of 15 novel AMTs.
- The cost model development identified 16 key size and effort drivers with their relative rating scales, using AMT development and cost experts. These novel predictors have been proven to form an operational model in conjunction with the CER.
- The model provides enhancement of the aerospace manufacturing industry existing planning of AMT non-recurring development resources in person-hours.
- Validation of the model in an industrial setting has been proven from the responses of AMT development experts.
- The model is suitable for alignment outside the aerospace manufacturing industry for application to AMT research centres and universities.

Development of a parametric cost model capable of estimating aerospace AMT development effort in hardware cost.

- The first reported use of a parametric cost model for successful estimation of aerospace AMT non-recurring development cost of hardware, using the TRL for development.
- The model CER hypothesis is statistically verified from assessment of 15 novel AMTs.
- Development of the cost model defined a key size driver and 13 cost drivers with rating scales, using AMT development and cost experts. Each has been proven to form an operational model with the CER.
- Provides enhancement of the aerospace manufacturing industry existing planning of AMT non-recurring development hardware cost.

- Fully validated within an industrial setting using the responses of 10 AMT development experts.
- Suitable for alignment with AMT research centres and universities.

Development of AMT performance forecasting models capable of assessing diverse aerospace AMTs with varied applications.

- Development of two novel models capable of forecasting by quantifying AMT tangible and intangible performance, for assessment at the early development stages.
- Each model hypothesis has been verified using 8 AMTs with known conclusions and validated with the responses from 10 AMT development experts.
- Identification of tangible and intangible novel Key Performance Factors (KPFs) in a detailed study, using AMT development and decision making experts.
- Provides enhancement of existing AMT performance forecasting, assisting with the justification of the required AMT development investment.

Development of a Cost-Benefit Forecasting Framework, providing AMT development value for justification and allocation of R&T investment.

- A novel Cost-Benefit Forecasting Framework was developed for systematic assessment of AMTs at the initial stages of development.
- The framework was successfully verified and validated within an aerospace industrial application, using data from a total of 23 diverse AMTs with varied applications and feedback from AMT development experts.
- The existing management of AMT development is enhanced by providing a constructive, accurate, seamless and rapid evaluation of development value, assisting with selection at the conceptual development stages.

9.4 Achievement of Research Aim and Objectives

The focus of this Section is to define the success of achieving the aim and objectives of this thesis. The research aim was defined in Chapter 1:

To develop, implement, verify and validate a cost-benefit forecasting framework capable of quantifying the AMT development effort, cost and perceived performance at the conceptual stages; providing development value advice."

The research aim has been successfully achieved within this research. Chapter 3 defined the research objectives and to evaluate the success of this research in further detail, assessment of how each objective has been achieved is discussed in the following.

The **first objective** was aimed at understanding current practice and state-of-the-art, in the management of aerospace AMT development and the methods used to estimate, justify and allocate development investment.

This objective was initially evaluated from the detailed evaluation of literature and state-of-the-art, performed in Chapter 2. A lack of understating how industry manages the R&T development investment of AMTs was defined within this Chapter.

Chapter 4 successfully addressed current practice, by studying large aerospace manufacturing organisations and state-of-the-art research centres, using a series of interviews and a review of internal documentation. This included evaluation of existing AMT development cost estimation, performance forecasting techniques and the selection process of AMTs for R&T investment. The analysis created a requirement for a new management of AMT development process map, designed and validated with industry, forming the platform for the proceeding objectives.

The **second objective** required a systematic approach capable of estimating novel AMT development resources and hardware cost, at the initial development stages. The 'Constructive Technology Development Cost Model' (COTECHMO), detailed within Chapter 5, fulfilled this objective with the development of two parametric cost models. Each model was statistically verified with 15 AMTs in Chapter 8, by performing multiple regression analysis. This successfully verified each model hypothesis and the novel size, effort and cost drivers. Evaluation of the operation of each model within the industrial setting was provided from the responses of 10 AMT development experts, validating suitability for the assigned application.

The **third objective** specified the need for a performance forecasting model capable of quantifying tangible and intangible performance for a diverse range of AMTs with varied applications, each at the early development stages. The Performance Forecasting Model (PERFORMO), presented in Chapter 6, successfully satisfied this objective with the development of two novel forecasting models. Each model was statistically verified using 8 AMTs with known conclusions. Validation for the application was provided from the responses of 10 AMT development experts after operating within an industrial setting. The verification and validation was presented in Chapter 8.

The **fourth objective** required a guide for users within an industrial R&T application, to align the cost-benefit forecasts and provide development value advice at the early stages of development, for a range of aerospace AMTs with diverse applications. Chapter 7 developed a novel Cost-Benefit Forecasting Framework capable of systematically guiding industrialists through the operation of COTECHMO and PERFORMO, plotting the outputs in DEVAL graphs. The operation of the framework was tested within a large aerospace manufacturing organisation R&T division, for assessment of 15 diverse AMTs with varied applications, using 10 AMT development experts, detailed within Chapter 8. Graphical outputs were successfully presented to the users, clearly defining AMT development value. Further to the successful statistical verification of each model within the framework, assessment of the overall framework operation and the final outputs was provided by the detailed responses from 10 AMT experts. These indicated the framework was suitable for the application and the final development value was correct for the 15 AMTs evaluated. This validated the final Cost-Benefit Forecasting Framework within its industrial application, successfully meeting the **fifth objective**.

9.5 Research Limitations

The developed Cost-Benefit Forecasting Framework successfully fulfilled and addressed the research aim and objectives. Nevertheless, from the generic nature of the models within the framework, each could become more accurate if they were aligned and calibrated more specifically with AMTs categorised within specific domains e.g. metrology. This would allow for a local calibration, forming a more robust solution. The aspects of each model and framework that are addressed as minor limitations are now discussed in the proceeding Sub Sections.

9.5.1 The Constructive Technology Development Cost Model (COTECHMO)

Chapter 8 involved an initial empirical study for assessment of 15 novel AMTs, using the entire Cost-Benefit Forecasting Framework within a large aerospace manufacturing organisation. The input and output from each COTECHMO model was a key aspect of the framework. To perform a detailed verification on each

COTECHMO model, the data from the empirical study was used to run multiple regression. This included the estimation of a linear application using Ordinary Least Squares (OLS) criterion. The technique assumes there is a large amount of data, an aspect not fulfilled from only having 15 AMTs available for assessment. This number of historical cases was not sufficient to perform multiple regression on each model containing 14 and 16 drivers. Therefore, the models were tested in reduced form, each consisting of 5 drivers clustered into common themes. When conducting sensitivity analysis on the reduced models, a *p*-value of 0.05 was specified to determine predictor statistical significance. Each of the COTECHMO Resources model predictors had exceptional statistical significance, listed in Chapter 8, Table 8-8. However, the 'Production Rate' predictor had a low *t*-value combined with a *p*-value of 0.10, not meeting the specification limit. Despite these values not fulfilling the requirements, on detailed evaluation with cost estimation and AMT development experts, each predicted that the low variation was formed by the limited number of cases. Subsequently, this predictor is recommended for additional evaluation in future research presented in Sub Section 9.6.1, using a selection of further AMTs. If this analysis indicated a high *p*-value outside the specified 0.05, the predictor should be removed from the model. Additionally, when performing a sensitivity analysis on predictor data points for the reduced Direct Cost model, listed in Chapter 8 Table 8-11, three of the five predictors fulfilled the required *p*-value of 0.05. However, 'Secondary' and 'Production Rate' predictors did not conform and produced values of 0.32 and 0.23, although these were estimated as low values from the limited number of cases. The 'Secondary' predictor consisted of four drivers clustered into one predictor. To evaluate this high *p*-value, each of the drivers would need to be dissected and analysed individually. This would require additional historical AMT cases, a subject of future research recommendations presented in Sub Section 9.6.1. Following the Resources model, evaluation of further AMTs would either validate or eliminate the 'Production Rate' predictor.

The 15 AMTs within the case study were used to calibrate each COTECHMO model, forming a local calibration. These AMTs were also used to estimate and perform multiple regression. In an ideal scenario, AMTs used for calibration would be separate from those used within the cost estimation case study. Additionally, each AMT within the case study was from one large aerospace manufacturing organisation. To enhance model verification, selection of further AMTs from varied aerospace manufacturing organisation sources is recommended. These could be used in the model calibration, with separate AMTs used for the case study to evaluate model performance, using the multiple regression techniques discussed in Chapter 8.

Further to the detailed statistical verification, the COTECHMO models were evaluated using the responses from 10 AMT development experts, for assessment within the industrial setting. This identified excellent validation, although there were some slight suggestions for future work, with each discussed in Sub Section 9.6.1.

9.5.2 The Performance Forecasting Model (PERFORMO)

Chapter 6 presented the development of two PERFORMO models, the first for assessment of tangible performance and the second intangible performance. Following the COTECHMO models, each PERFORMO model was initially verified within an empirical case study, detailed in Chapter 8. To further verify PERFORMO, AMTs with known outcomes were required. In response, 8 AMTs with known outcomes from a large aerospace manufacturing organisation were selected. Of the 8 AMTs, 5 were successfully implemented within the organisation and 3 were determined unsuccessful. This outcome was correctly forecast by each PERFORMO model, providing 100% accuracy. To provide additional verification, the 5 successful AMTs were ranked, based on their actual data. Each model predicted 4 of the 5 AMTs in the correct ranking order, equating to an accuracy of 80%. To refine this accuracy, further AMTs with known conclusions are suggested for assessment. Additional enhancement would involve evaluation of AMTs from supplementary organisations, a suggestion of future work, presented in Sub Section 9.6.2.

Following a similar format to the validation of COTECHMO, the PERFORMO models were successfully validated using the responses from 10 AMT experts, after utilising within an industrial setting. The experts suggested few minor enhancements; each is addressed in future work recommendations, presented in Section 9.6.2.

9.5.3 Cost-Benefit Forecasting Framework

Chapter 7 presented a novel Cost-Benefit Forecasting Framework for assessment of AMTs at the early development stages. To validate the operation of the framework and the final DEVAL outputs, 10 AMT development experts assessed and provided responses using a comprehensive validation process, detailed in Chapter 8. This presented an excellent result, identifying the framework significantly improves the existing AMT development R&T investment decision. Nevertheless, there were small suggestions of enhancement, each addressed with suggestions for future work in the following Section.

9.6 Future Work

To address the generic nature of the models within the framework, the first future work suggestion involves further refinement of each model using AMTs aligned to specific domains. Theoretically speaking, this should advance the model accuracies and create a more robust approach, therefore forming the first recommendation for future work. Furthermore, technologies readily available from external AMT vendors have not been included within the assessment of the framework. To further the research impact, future work could aim at utilising the framework for assessment of AMTs available from fully external AMT vendors. Additionally, a primary focus of enhancing the Cost-Benefit Forecasting Framework involves evaluating further AMTs from outside the large aerospace manufacturing organisation used for successful verification and validation. This research elaboration is discussed for each framework element in the following Sub Sections.

9.6.1 COTECHMO Future Work

Assessment of further AMTs with known conclusions from additional organisations and research centres would provide data to further test each COTECHMO model using multiple regression. The slight limitation of testing the models in reduced form was discussed in Sub Section 9.5.1. Utilising further AMTs would permit calibration to be performed with AMTs separate from those involved in the case study. This would grant further assessment of each predictor's statistical significance, not having to cluster in a reduced model form. Operating each model outside the large organisation used for each COTECHMO model verification and validation, would enhance the impact of the AMT cost research and assist with additional organisations R&T investment selections. Testing within state-of-the-art manufacturing research centres is another suggestion, providing further verification and validation and assisting with their management of AMT developments.

Further to additional testing of each model, there were minor enhancement recommendations, detailed in Chapter 8, Section 8.5. The first suggestion included adding a drop down box within the model for elaboration of each driver, enhancing operation efficiency. This would require programming within the MS Excel software. Each COTECHMO model was verified and validated within a large aerospace manufacturing organisation. This organisation operated an existing Project and Programme Management Software application. Alignment of each model would enhance this existing software application, forming the suggestion for future work. Another suggestion included the improvement of each model, with inclusion of a reset button within the Model MS Excel interface, allowing the user to reset to the default values after performing the forecast.

9.6.2 PERFORMO Future Work

The minor PERFORMO accuracy discrepancies were discussed in Sub Section 9.5.2. Assessment of further AMTs from within and outside the supporting aerospace manufacturing organisation would help clarify and refine model accuracy. Further verification using the additional data from AMTs with known conclusions is suggested. This would enhance the impact of each PERFORMO model and help assist with other organisations in their AMT development investment decision. Following the COTECHMO future work suggestions, testing each model within manufacturing research centres would provide additional verification and validation, advancing their AMT development decisions.

Experts involved in the model validation, presented in Chapter 8 Section 8.6, identified potential areas for future work. Each expert discussed that having elaborations for the KPF parameters would improve operational efficiency, by having a drop down tab within the MS Excel model interface and not having to revert to the MS Word file. Alignment to the overall Project and Programme Management Software used within the aerospace manufacturing R&T division was a further suggestion. Another slight element for future work was the inclusion of a reset button within the interface, allowing the user to reset to the default values after forecasting.

9.6.3 Cost-Benefit Forecasting Framework Future Work

Verification and validation of the framework was effectively performed in one large aerospace manufacturing organisation. To enhance the impact of this research, testing the framework in a further organisation would provide additional verification and validation. The framework could also be tested with AMT research centres and universities, providing advancements in their management of AMT developments.

9.7 Concluding Remarks

The research presented in this thesis has developed a novel solution to solve the existing problem for the management of AMT development. The overall Cost-Benefit Forecasting Framework has been successfully verified and validated within a large aerospace manufacturing organisation. This proved the framework excellent capability for enhancing the existing R&T investment justification and allocation for development of novel AMTs, at the conceptual stages of development.

In summary, the framework has successfully achieved the research aim and objectives. Implementing the Cost-Benefit Forecasting Framework within further aerospace manufacturing organisations and AMT research centres will enhance their selection of AMTs and extend the research impact outside the supporting organisation.

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APPENDIX A.1

Experts Used within the Study of the Management of AMT Development

Table A1-1 Experts used to Study the Management of Aerospace Advanced Manufacturing Technology Development

Organisation	Role	Years of Relevant Experience
A	Manufacturing Research Manager	15
A	Manufacturing Research Engineer	15
A	Manufacturing Project Manager	13
A	Automation Research Engineer	20
A	Manufacturing Metrology Research Engineer	13
A	Manufacturing Implementation Engineer	16
A	Manufacturing Research Manager	17
A	Manufacturing Implementation Engineer	12
A	Manufacturing Research Engineer	19
A	Technology Product Leader	9
A	Technology Development Specialist	22
A	Technology Product Leader	31
A	Manufacturing Engineering Technology Leader	13
B	Internal TRL Developer	18
B	Project Technology Coordinator	6
C	Managing Director	15
D	Manufacturing Commercial Director	8
E	Manufacturing Capability Manager	12
E	Manufacturing Technical Manager	10
F	Chief of Capability Acquisition	22
F	Capability Acquisition Strategy Manager	15
F	Manufacturing Quality	11
G	Professor of Aero-structure Design and Assembly	25

Table A1-2 Experts used to Study Development Cost Estimation of Advanced Manufacturing Technology

Organisation	Role	Years of Relevant Experience
A	Manufacturing Research Manager	15
A	Manufacturing Research Engineer	15
A	Manufacturing Project Manager	13
A	Automation Research Engineer	20
A	Manufacturing Metrology Research Engineer	13
A	Manufacturing Implementation Engineer	16
A	Manufacturing Implementation Engineer	12
A	Cost Engineer	16
A	Project Management Control	16
B	Project Technology Coordinator	6
D	Manufacturing Commercial Director	8
E	Cost Engineer	25
F	Manufacturing Capability Manager	12
F	Manufacturing Cost Modeller	8
F	Manufacturing Cost Engineer	20

Table A1-3 Experts used to Determine Current Practice in Commercial Cost Estimation of AMT Development

Organisation	Role	Years of Relevant Experience
G	Cost Engineering – commercial cost software interface	11
H	Cost Estimation Training and Support Manager	30
H	Cost Estimation Business Development Manager	20
I	Cost Director	15

Table A1-4 Experts used to Study Performance Forecasting of Advanced Manufacturing Technology at the Initial Stages of Development

Organisation	Role	Years of Relevant Experience
A	Manufacturing Research Manager	15
A	Manufacturing Research Engineer	15
A	Manufacturing Project Manager	13
A	Automation Research Engineer	20
A	Manufacturing Metrology Research Engineer	13
A	Manufacturing Implementation Engineer	16
A	Manufacturing Implementation Engineer	12
A	Project Management Control	16
A	Decision Making Specialist	19
A	Decision Making Specialist	11
A	Technology Value Analysis	13
A	Manufacturing Engineering Technology Leader	13
B	Project Technology Coordinator	6
D	Manufacturing Commercial Director	8
E	Manufacturing Capability Manager	12
E	Manufacturing Technical Manager	10
F	Chief of Capability Acquisition	22
F	Capability Acquisition Strategy Manager	15
F	Manufacturing Quality	11
G	Professor of Aero-structure Design and Assembly	25
J	Researcher in Manufacturing Decision Making	5

Table A1-5 Experts used to Validate the Enhanced AMT Development Process Map

Organisation	**Role**	**Years of Relevant Experience**
A	Manufacturing Research Manager	15
A	Manufacturing Research Engineer	15
A	Manufacturing Project Manager	13
A	Automation Research Engineer	20
A	Manufacturing Metrology Research Engineer	13
A	Manufacturing Implementation Engineer	16
A	Manufacturing Research Manager	17
A	Manufacturing Implementation Engineer	12
A	Technology Product Leader	9
A	Technology Development Specialist	22
A	Technology Product Leader	31
A	Manufacturing Engineering Technology Leader	13
B	Project Technology Coordinator	6
D	Manufacturing Commercial Director	8
E	Manufacturing Technical Manager	10
F	Chief of Capability Acquisition	22
G	Professor of Aero-structure Design and Assembly	25
G	Cost Engineering	11

APPENDIX A.2

Experts Used within the Development of COTECHMO

Table A2-1 AMT Development Experts used to Determine COTECHMO Model Requirements

Organisation	Role	Years of Relevant Experience
A	Manufacturing Research Manager	15
A	Manufacturing Research Engineer	15
A	Manufacturing Project Manager	13
A	Automation Research Engineer	20
A	Manufacturing Metrology Research Engineer	13
A	Manufacturing Implementation Engineer	16
A	Manufacturing Research Manager	17
A	Manufacturing Implementation Engineer	12
A	Manufacturing Research Engineer	19
A	Technology Product Leader	9
A	Technology Development Specialist	22
A	Technology Product Leader	31
A	Manufacturing Engineering Technology Leader	13
B	Internal TRL Developer	18
B	Project Technology Coordinator	6
C	Managing Director	15
D	Manufacturing Commercial Director	8
E	Manufacturing Capability Manager	12
E	Manufacturing Technical Manager	10
F	Manufacturing Quality	11
G	Professor of Aero-structure Design and Assembly	25

Table A2-2 Cost Estimation/Engineering Experts used to Determine COTECHMO Model Forms

Organisation	Role	Years of Relevant Experience
G	Cost Estimation Research Fellow	11
H	Cost Estimation Business Development Manager	20
H	Cost Estimation Training and Support Manager	30
I	Cost Director	15
K	Associate Professor (Cost Estimation)	10
L	Principle Consultant (Cost Estimation)	29
M	Software Development Company Owner	35

APPENDIX A.3

COTECHMO Resources (Person-hours) Model Driver Workshop

Name:

Company:

Department:

Years of Advanced Manufacturing Technology Development Experience:

Introduction

The purpose of this workshop is to define the qualitative rating scale for each Size and Effort Driver. We will systematically work through each, discussing in detail using your experience and knowledge of AMT development. Any historical data from AMT developments to support the ratings would be gratefully received. These will then be used in the Wideband Delphi Study to determine the quantitative weighting for each rating. The final model will estimate the development Resources (person-hours) to prove an aerospace AMT process at full scale, for the direct application (TRL6).

Size Drivers

The Size Drivers quantify the functional size of the AMT process for its direct manufacturing application. Each size driver represents an output created from an objective measure (i.e. physical size).

Table A3-1 Number of Geometric Requirements Definition

Number of Geometric Requirements The number of requirements taken from the AMT process customer specification. These can be quantified by counting the conceptual application documentation.

Do you agree with this size driver and its definition?
Input your descriptions for Number of Geometric Requirements Rating Scale?

Table A3-2 Number of Geometric Requirements Rating Scale

Easy	Nominal	Difficult

Table A3-3 Number of Process Steps Definition

Number of Process Steps The number of process steps counted from the customer application specification to prove the AMT process at full scale, TRL6.

Do you agree with this size driver and its definition?
Input your descriptions for Number of Process Steps into the Rating Scale?

Table A3-4 Number of Process Steps Rating Scale

Easy	Nominal	Difficult

Table A3-5 Number of Test Pieces Definition

Number of Test Pieces The number of process steps counted from the customer application specification to prove the AMT process at full scale, TRL6.

Do you agree with this size driver and its definition?
Input your descriptions for Number of Test Pieces into the Rating Scale?

Table A3-6 Number of Test Pieces Rating Scale

Easy	Nominal	Difficult

Effort Drivers

The Effort Drivers or Effort Multipliers impact the whole AMT development in a multiplicative configuration.

Table A3-7 TRL Pack Experience Definition

TRL Pack Experience The level of familiarity of the development team from compiling successful Technology Readiness Level development (TRL) documents.

Do you agree with this driver and its definition?
Input your descriptions for TRL Pack Experience into the Rating Scale?

Table A3-8 TRL Pack Experience Rating Scale

Very Low	Low	Nominal	High	Very High

Table A3-9 Product Application Experience Definition

Product Application Experience The level of product knowledge for the direct application e.g. understanding the existing aircraft manual sealant application to develop an automated manufacturing technology solution.

Do you agree with this driver and its definition?
Input your descriptions for Product Application Experience into the Rating Scale?

Table A3-10 Product Application Experience Rating Scale

Very Low	Low	Nominal	High	Very High

Table A3-11 Process Experience Definition

Process Experience The level of experience of the development team in the manufacturing process domain e.g. direct automation development experience.

Do you agree with this driver and its definition?
Input your descriptions for Process Experience into the Rating Scale?

Table A3-12 Process Experience Rating Scale

Very Low	Low	Nominal	High	Very High

Table A3-13 Requirements Understanding Definition

Requirements Understanding
The understanding of the requirements from the direct customer e.g. automated drilling hole requirements for their exact product.

Do you agree with this driver and its definition?
Input your descriptions for Requirements Understanding into the Rating Scale?

Table A3-14 Requirements Understanding Rating Scale

Very Low	Low	Nominal	High	Very High

Table A3-15 Supplier Network Availability and Capability Definition

Supplier Network Availability and Capability
Manufacturing process supplier availability and capability to develop the process.

Do you agree with this driver and its definition?
Input your descriptions for Supplier Network Availability and Capability into the Rating Scale?

Table A3-16 Supplier Network Availability and Capability Rating Scale

Very Low	Low	Nominal	High	Very High

Table A3-17 Datum Complexity Definition

Datum Complexity
Complexity of datum(s) for the manufacturing process application.

Do you agree with this driver and its definition?
Input your descriptions for Datum Complexity into the Rating Scale?

Table A3-18 Datum Complexity Rating Scale

Very Low	Low	Nominal	High	Very High

Table A3-19 Test Piece Material Complexity Definition

Test Piece Material Complexity
Complexity of the test piece material to prove the manufacturing process at full scale application.

Do you agree with this driver and its definition?
Input your descriptions for Test Piece Material Complexity into the Rating Scale?

Table A3-20 Test Piece Material Complexity Rating Scale

Very Low	Low	Nominal	High	Very High

Table A3-21 Installation Complexity Definition

Installation Complexity
Installation complexity of the manufacturing process to prove at full scale. A very complex process would consist of many automation equipment installations.

Do you agree with this driver and its definition?
Input your descriptions for Installation Complexity into the Rating Scale?

Table A3-22 Installation Complexity Rating Scale

Very Low	Low	Nominal	High	Very High

Table A3-23 Degree of Process Novelty Definition

Degree of Process Novelty
Manufacturing process novelty for the direct application, e.g. automated assembly process from an automotive plant, now developed using the TRL for the aerospace domain.

Do you agree with this driver and its definition?
Input your descriptions for Degree of Process Novelty into the Rating Scale?

Table A3-24 Degree of Process Novelty Rating Scale

Very Low	Low	Nominal	High	Very High

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Table A3-25 Required Development Schedule Definition

Required Development Schedule
Required delivery from the customer for the development and deployment of the manufacturing process, proven at full scale for the direct application (TRL6). Very low is an accelerated schedule (schedule compression) with very high having a development schedule slower than the nominal.

Do you agree with this driver and its definition?
Input your descriptions for Required Development Schedule into the Rating Scale?

Table A3-26 Required Development Schedule Rating Scale

Very Low	Low	Nominal	High	Very High

Table A3-27 Manufacturing Documentation of Requirements Definition

Manufacturing Documentation of Requirements
Specific documentation by Manufacturing Engineering for the development enhancement. Legacy (existing) products are typically documented to a higher level when compared to future aircraft manufacture.

Do you agree with this driver and its definition?
Input your descriptions for Manufacturing Documentation of Requirements into the Rating Scale?

Table A3-28 Manufacturing Documentation of Requirements Rating Scale

Very Low	**Low**	**Nominal**	**High**	**Very High**

Table A3-29 Location Variation of Trails and Tests Definition

Location Variation of Trials and Tests
Variation of the trials and tests through the development process, to prove the manufacturing process to full scale (TRL6).

Do you agree with this driver and its definition?
Input your descriptions for Location Variation of Trails and Tests into the Rating Scale?

Table A3-30 Location Variation of Trails and Tests Rating Scale

Very Low	**Low**	**Nominal**	**High**	**Very High**

Table A3-31 Production Rate Reduction Requirements Definition

Production Rate Reduction Requirements
Required production rate reduction to prove the process at full scale demonstration, TRL6.

Do you agree with this driver and its definition?
Input your descriptions for Production Rate Reduction into the Rating Scale?

Table A3-32 Production Rate Reduction Rating Scale

Very Low	**Low**	**Nominal**	**High**	**Very High**

APPENDIX A.4

COTECHMO Direct (Hardware) Cost Model Driver Workshop

Name:

Company:

Department:

Years of Advanced Manufacturing Technology Development Experience:

Introduction

The purpose of this workshop is to define the qualitative rating scale for each Cost Driver. We will systematically work through each, discussing in detail using your experience and knowledge of AMT development. Any historical data from AMT developments to support the ratings would be gratefully received. These will then be used in the Wideband Delphi Study to determine the quantitative weighting for each rating. The final model will estimate the development Direct (Hardware) Cost to prove an aerospace AMT process at full scale, for the direct application (TRL6).

Size Driver

- AMT Physical Hardware Size

Cost Drivers

The Cost Drivers or Cost Multipliers impact the whole AMT development in a multiplicative configuration.

Table A4-1 Number of Geometric Accuracy Requirements Definition

Number of Geometric Accuracy Requirements The number of requirements taken from the manufacturing process customer specification. These can be quantified by counting the conceptual application documentation.

Do you agree with this driver and its definition?
Input your descriptions for Number of Geometric Accuracy Requirements into the Rating Scale?

Table A4-2 Number of Geometric Accuracy Requirements Rating Scale

Very Low	Low	Nominal	High	Very High

Table A4-3 Number of Process Steps Definition

Number of Process Steps The number of process steps can be counted from the customer application specification to prove the process at full scale.

Do you agree with this driver and its definition?
Input your descriptions for Number of Process Steps into the Rating Scale?

Table A4-4 Number of Process Steps Rating Scale

Very Low	Low	Nominal	High	Very High

Table A4-5 Process Capability Requirements Definition

Process Capability Requirements Process capability (Cpk) requirements for the direct application, identified within the process requirements specification.

Do you agree with this driver and its definition?
Input your descriptions for Process Capability into the Rating Scale?

Table A4-6 Process Capability Rating Scale

Very Low	Low	Nominal	High	Very High

Table A4-7 Degree of Process Novelty Definition

Degree of Process Novelty Manufacturing process novelty for the direct application e.g. automated assembly process from an automotive plant, now developed using the TRL for the aerospace domain.

Do you agree with this driver and its definition?
Input your descriptions for Degree of Process Novelty into the Rating Scale?

Table A4-8 Degree of Process Novelty Rating Scale

Very Low	Low	Nominal	High	Very High

Table A4-9 Installation Complexity Definition

Installation Complexity Installation complexity of the manufacturing process to prove at full scale. A highly complex process would consist of many automation equipment installations.

Do you agree with this driver and its definition?
Input your descriptions for Installation Complexity into the Rating Scale?

Table A4-10 Installation Complexity Rating Scale

Very Low	Low	Nominal	High	Very High

Table A4-11 Manufacturing Environment Requirements Definition

Manufacturing Environment Requirements Temperature requirements to prove the process accuracy at full scale application.

Do you agree with this driver and its definition?
Input your descriptions for Manufacturing Environment Requirements into the Rating Scale?

Table A4-12 Manufacturing Environment Requirements Rating Scale

Very Low	Low	Nominal	High	Very High

Table A4-13 Automation Level Requirements Definition

Automation Level Requirements The level and novelty of the automated control used within the process.

Do you agree with this driver and its definition?
Input your descriptions for Automation Level Requirements into the Rating Scale?

Table A4-14 Automation Level Requirements Rating Scale

Very Low	Low	Nominal	High	Very High

Table A4-15 Test Piece Material Complexity Definition

Test Piece Material Complexity Complexity of the test piece material to prove the manufacturing process at full scale application.

Do you agree with this driver and its definition?
Input your descriptions for Test Piece Material Complexity into the Rating Scale?

Table A4-16 Test Piece Material Complexity Rating Scale

Very Low	Low	Nominal	High	Very High

Table A4-17 Process Test and Verification Requirements Definition

Process Test and Verification Requirements Process test and verification requirements to prove the manufacturing process at full scale demonstration, TRL6.

Do you agree with this driver and its definition?
Input your descriptions for Process Test and Verification Requirements into the Rating Scale?

Table A4-18 Process Test and Verification Requirements Rating Scale

Very Low	Low	Nominal	High	Very High

Table A4-19 Metrology Requirements Definition

Metrology Requirements Metrology monitoring requirements to prove the manufacturing process and meet the customer requirements e.g. process capability.

Do you agree with this driver and its definition?
Input your descriptions for Metrology Requirements into the Rating Scale?

Table A4-20 Metrology Requirements Rating Scale

Very Low	Low	Nominal	High	Very High

Table A4-21 Human Factor Requirements Definition

Human Factor Requirements
Human Factor Requirements of the manufacturing process to meet the customer requirements e.g. safety cell around the process to comply with Human Factor Legislation.

Do you agree with this driver and its definition?
Input your descriptions for Human Factor Requirements into the Rating Scale?

Table A4-22 Human Factor Requirements Rating Scale

Very Low	Low	Nominal	High	Very High

Table A4-23 Tooling Requirements Definition

Tooling Requirements
The tooling and fixture requirements to support the manufacturing process.

Do you agree with this driver and its definition?
Input your descriptions for Tooling Requirements into the Rating Scale?

Table A4-24 Tooling Requirements Rating Scale

Very Low	Low	Nominal	High	Very High

Table A4-25 Production Rate Reduction Requirements

Production Rate Reduction Requirements
Required production reduction rate to prove the process at full scale demonstration, TRL6.

Do you agree with this driver and its definition?
Input your descriptions for Production Rate Reduction Requirements into the Rating Scale?

Table A4-26 Production Rate Reduction Requirements Rating Scale

Very Low	Low	Nominal	High	Very High

APPENDIX A.5

COTECHMO Resources (Person-hours) Model Wideband Delphi Round 2

Name:

Company:

Department:

Years of Advanced Manufacturing Technology Development Experience:

Introduction

The purpose of this Wideband Delphi Round 2 workshop is to validate and reach consensus on the final quantitative weightings for each Size and Effort Driver. The final model will estimate the development Resources (person-hours) to prove an aerospace AMT process at full scale, for the direct application (TRL6).

Part 1: Size Drivers

The three Size Drivers identified are listed with their driver descriptions, finalised from the previous workshops. These quantify the functional size of the AMT process for its direct manufacturing application. Each size driver represents an output created from an objective measure (i.e. physical size). For each driver, the average weighting from Wideband Delphi Round 1 has been added. Can you enter your new responses, either agreeing or adjusting the previous Round's averages?

Table A5-1 Number of Geometric Requirements Definition

Number of Geometric Requirements The number of requirements taken from the AMT process customer specification. These can be quantified by counting the conceptual application documentation.

Table A5-2 Number of Geometric Requirements Rating Scale

	Easy	**Nominal**	**Difficult**
Description	- Lower geometric requirements than existing accuracy.	- Replicating existing geometric process accuracy.	- Higher than existing geometric process requirement accuracy.
Previous Weighting (μ)	**0.50**	**1.00**	**3.25**
Your Weighting			

Notes about driver weightings?

Table A5-3 Number of Process Steps Definition

Number of Process Steps The number of process steps counted from the customer application specification to prove the AMT process at full scale, TRL6.

Table A5-4 Number of Process Steps Rating Scale

	Easy	**Nominal**	**Difficult**
Description	- Lower than existing process step complexity.	- Replicating existing process step complexity.	- Higher than existing process step complexity.
Previous Weighting (μ)	**1.10**	**2.00**	**3.70**
Your Weighting			

Notes about driver weightings?

Table A5-5 Number of Test Pieces Definition

Number of Test Pieces The number of process steps counted from the customer application specification to prove the AMT process at full scale, TRL6.

Table A5-6 Number of Test Pieces Rating Scale

	Easy	**Nominal**	**Difficult**
Description	- Lower than existing test piece complexity.	- Replicating existing test piece complexity.	- Higher than existing test piece complexity.
Previous Weighting (µ)	**0.40**	**1.10**	**1.50**
Your Weighting			

Notes about driver weightings?

Part 2: Effort Drivers

The thirteen Effort Drivers identified are listed with their driver descriptions, finalised from the previous workshops. For each driver, the average weighting from Wideband Delphi Round 1 has been added. Can you enter your new responses, either agreeing or adjusting the previous Round's averages?

2a: Development Team Factors

The development team factors represent the skill set, knowledge and understanding of the team assigned to develop the AMT.

Table A5-7 TRL Pack Experience Definition

TRL Pack Experience The level of familiarity of the development team from compiling successful Technology Readiness Level development (TRL) documents.

Table A5-8 TRL Pack Experience Rating Scale

	Very Low	**Low**	**Nominal**	**High**	**Very High**
Description	Completely unfamiliar with the TRL pack.	Familiar with the TRL pack from colleagues/suppliers/ TRL reviews although not utilised for own development.	Utilised the TRL pack to successfully transition from one TRL gate to the next.	Successfully developed 1 development to TRL6.	Successfully complete > 1 development to TRL6.
Previous Weighting	**1.40**	**1.20**	**1.00**	**0.86**	**0.66**
Your Weighting			**1.00**		

Notes about driver weightings?

Table A5-9 Product Application Experience Definition

Product Application Experience The level of product knowledge for the direct application e.g. understanding the existing aircraft manual sealant application to develop an automated manufacturing technology solution.

Table A5-10 Product Application Experience Rating Scale

	Very Low	Low	Nominal	High	Very High
Description	Unfamiliar with existing product manufacturing techniques.	Low level of understanding of existing product manufacturing techniques, many unfamiliar areas.	Fully familiar with existing product manufacturing.	Worked on the development of the existing product manufacturing.	Worked on the development and implementation of the existing product manufacturing.
Previous Weighting	**1.90**	**1.30**	**1.00**	**0.76**	**0.55**
Your Weighting			**1.00**		

Notes about driver weightings?

Table A5-11 Process Experience Definition

Process Experience   The level of experience of the development team in the manufacturing process domain e.g. direct automation development experience.

Table A5-12 Process Experience Rating Scale

	Very Low	Low	Nominal	High	Very High
Description	Unfamiliar with the process domain.	Low level of familiarity of the process domain.	Familiar with the process domain.	Worked on the development of a similar process.	Successfully developed and implemented a similar process.
Previous Weighting	**1.54**	**1.30**	**1.00**	**0.61**	**0.51**
Your Weighting			**1.00**		

Notes about driver weightings?

Table A5-13 Requirements Understanding Definition

Requirements Understanding   The understanding of the requirements from the direct customer e.g. automated drilling hole requirements for their exact product.

Table A5-14 Requirements Understanding Rating Scale

	Very Low	Low	Nominal	High	Very High
Description	Poor: no understanding of requirements.	Minimal: many undefined areas.	Reasonable: some undefined areas.	Strong: few undefined areas.	Full understanding and documentation of requirements.
Previous Weighting	**1.50**	**1.25**	**1.00**	**0.80**	**0.65**
Your Weighting			**1.00**		

Notes about driver weightings?

Table A5-15 Supplier Network Availability and Capability Definition

Supplier Network Availability and Capability   Manufacturing process supplier availability and capability to develop the process.

Table A5-16 Supplier Network Availability and Capability Rating Scale

	Very Low	Low	Nominal	High	Very High
Description	No experience of similar developments.	Low experience of similar developments.	Some experience of a similar development.	Delivered similar developments but with some guidance contact.	Fully proven within the domain and having delivered similar developments with minimal contact.
Previous Weighting	**1.45**	**1.11**	**1.00**	**0.77**	**0.70**
Your Weighting			**1.00**		

Notes about driver weightings?

2b: Demonstration and Application Factors

The demonstration and application factors represent the assigned application for the AMT process and the specified demonstration requirements from the direct customer. The datum complexity driver does not comply with the 5 scale rating.

Table A5-17 Datum Complexity Definition

Datum Complexity Complexity of datum(s) for the manufacturing process application.

Table A5-18 Datum Complexity Rating Scale

	Nominal	High	Very High
Description	Datum's with low access restrictions.	Very complex: datum's with minimal access.	Extremely complex: no datum access.
Previous Weighting	**1.00**	**1.10**	**1.20**
Your Weighting			

Notes about driver weightings?

Table A5-19 Test Piece Material Complexity Definition

Test Piece Material Complexity Complexity of the test piece material to prove the manufacturing process at full scale application.

Table A5-20 Test Piece Material Complexity Rating Scale

	Very Low	Low	Nominal	High	Very High
Description	Very low complexity: material fully proven for manufacture on existing product with selected process.	Low complexity: material proven in 2> same domain of aerospace manufacture with selected process.	Medium complexity: material implemented in 1> same domain of aerospace manufacture with selected process.	Very complex: limited development and implementation of a similar material with selected process.	Extremely complex: material completely novel and not been developed before with selected process.
Previous Weighting	**0.59**	**0.70**	**1.00**	**1.20**	**1.47**
Your Weighting			**1.00**		

Notes about driver weightings?

Table A5-21 Installation Complexity Definition

Installation Complexity Installation complexity of the manufacturing process to prove at full scale. A very complex process would consist of many automation equipment installations.

Table A5-22 Installation Complexity Rating Scale

	Very Low	**Low**	**Nominal**	**High**	**Very High**
Description	Complexity of very low levels: much lower than existing process implementation and existing developments.	Low complexity: complexity slightly lower than existing process installation procedure.	Moderately complex: installation procedure similar to existing process to replace.	Very complex: installation procedure exceeds existing process.	Extremely complex: installation procedure exceeds existing process installation and similar developments.
Previous Weighting	**0.60**	**0.90**	**1.00**	**1.26**	**1.36**
Your Weighting			**1.00**		

Notes about driver weightings?

Table A5-23 Degree of Process Novelty Definition

Degree of Process Novelty Manufacturing process novelty for the direct application, e.g. automated assembly process from an automotive plant, now developed using the TRL for the aerospace domain.

Table A5-24 Degree of Process Novelty Rating Scale

	Very Low	**Low**	**Nominal**	**High**	**Very High**
Description	Process developed, implemented and proven throughout the aerospace industry.	Process developed, implemented and proven within 3> non-aerospace domains.	Process developed, implemented and proven in 1> non-aerospace domain e.g. automotive manufacture.	Process developed to low level (TRL3-6) in 1> non-aerospace domain.	Process not proven or developed in any domain, completely novel.
Previous Weighting	**0.60**	**0.80**	**1.00**	**1.40**	**1.82**
Your Weighting			**1.00**		

Notes about driver weightings?

2c: Project Factors

The project factors represent the requirements, documentation and location of the overall development project.

Table A5-25 Required Development Schedule Definition

Required Development Schedule Required delivery from the customer for the development and deployment of the manufacturing process, proven at full scale for the direct application (TRL6). Very low is an accelerated schedule (schedule compression) with very high having a development schedule slower than the nominal.

Table A5-26 Required Development Schedule Rating Scale

	Very Low	Low	Nominal	High	Very High
Description	≤ 6 months per TRL gate milestone.	≤ 9 months per TRL gate milestone.	≥ 12 months per TRL gate milestone.	≥ 18 months per TRL gate milestone.	≥ 24 months per TRL gate milestone.
Previous Weighting	**1.90**	**1.50**	**1.00**	**1.25**	**1.40**
Your Weighting			**1.00**		

Notes about driver weightings?

Table A5-27 Manufacturing Documentation of Requirements Definition

Manufacturing Documentation of Requirements Specific documentation by Manufacturing Engineering for the development enhancement. Legacy (existing) products are typically documented to a higher level when compared to future aircraft manufacture.

Table A5-28 Manufacturing Documentation of Requirements Rating Scale

	Very Low	Low	Nominal	High	Very High
Description	Completely novel product with no documentation of exact requirements.	Completely novel product with some documentation of exact requirements at TRL1-3.	Legacy product already in manufacture with levels of documentation planned to TRL4-6.	Legacy product already in manufacture with documentation planned to implementation at TRL7-9.	Legacy product already in manufacture with fully detailed documentation.
Previous Weighting	**1.54**	**1.25**	**1.00**	**0.74**	**0.64**
Your Weighting			**1.00**		

Notes about driver weightings?

Table A5-29 Location Variation of Trails and Tests Definition

Location Variation of Trials and Tests Variation of the trials and tests through the development process, to prove the manufacturing process to full scale (TRL6).

Table A5-30 Location Variation of Trails and Tests Rating Scale

	Very Low	Low	Nominal	High	Very High
Description	No location variation of resources, research and testing all carried out in one place.	Location variation of research resources within the same research institution but with different locations over site/complex/institution.	Location variation of research resources within the same county/state.	Location variation of research resources within the same country.	Location variation of research resources outside the same country.
Previous Weighting	**0.78**	**0.81**	**1.00**	**1.23**	**1.49**
Your Weighting			**1.00**		

Notes about driver weightings?

2d: Product Factor
The product factor captures the required production rate of the assigned product.

Table A5-31 Production Rate Reduction Requirements Definition

Production Rate Reduction Requirements
Required production rate reduction to prove the process at full scale demonstration, TRL6.

Table A5-32 Production Rate Reduction Rating Scale

	Nominal	**High**	**Very High**
Description	5% > increase in existing production rate.	10% > increase in existing production rate.	20% > increase in existing production rate.
Previous Weighting	**1.00**	**1.39**	**1.90**
Your Weighting	**1.00**		

Notes about driver weightings?

APPENDIX A.6

COTECHMO Direct (Hardware) Cost Model Wideband Delphi Round 2

Name:

Company:

Department:

Years of Advanced Manufacturing Technology Development Experience:

Introduction

The purpose of this Wideband Delphi Round 2 workshop is to validate and reach consensus on the quantitative weightings for each Cost Driver. The final model will estimate the development Direct (Hardware) Cost to prove an aerospace AMT process at full scale, for the direct application (TRL6)

Part 1: Cost Drivers

The thirteen Cost Drivers identified are listed with their driver descriptions, finalised from the previous workshops. For each driver, the average weighting from Wideband Delphi Round 1 has been added. Can you enter your new responses, either agreeing or adjusting the previous Round's averages?

1a: AMT Process Primary Factors

The AMT Process Primary Factors represent the process complexity and demonstration requirements set at the initial stages of development.

Table A10-1 Number of Geometric Accuracy Requirements Definition

Number of Geometric Accuracy Requirements The number of requirements taken from the manufacturing process customer specification. These can be quantified by counting the conceptual application documentation.

Table A10-2 Number of Geometric Accuracy Requirements Rating Scale

	Very Low	**Low**	**Nominal**	**High**	**Very High**
Description	All geometric accuracy requirements lower than existing.	2 > geometric accuracy requirements lower than existing process; none above existing.	3 > geometric accuracy requirements replicating existing process; none above existing.	3 > geometric accuracy requirements regarded as higher than existing process accuracy.	6 > geometric accuracy requirements regarded as higher than existing process accuracy.
Previous Weighting	**0.50**	**0.71**	**1.00**	**1.58**	**1.90**
Your Weighting			**1.00**		

Notes about driver weightings?

Table A10-3 Number of Process Steps Definition

Number of Process Steps The number of process steps can be counted from the customer application specification to prove the process at full scale.

Table A10-4 Number of Process Steps Rating Scale

	Very Low	**Low**	**Nominal**	**High**	**Very High**
Description	All process steps below existing complexity.	2 > process steps below existing complexity; none above existing.	3 > process steps replicating existing complexity; none above existing.	3 > process steps regarded as higher than existing complexity.	6 > process steps regarded as higher than existing complexity.
Previous Weighting	**0.61**	**0.83**	**1.00**	**1.50**	**1.82**
Your Weighting			**1.00**		

Notes about driver weightings?

Table A10-5 Process Capability Requirements Definition

Process Capability Requirements Process capability (Cpk) requirements for the direct application, identified within the process requirements specification.

Table A10-6 Process Capability Requirements Rating Scale

	Very Low	**Low**	**Nominal**	**High**	**Very High**
Description	Process capability ≥ 1.00 Cpk	Process capability ≥ 1.10 Cpk	Process capability ≥ 1.33 Cpk	Process capability ≥ 1.60 Cpk	Process capability ≥ 2.00 Cpk
Previous Weighting	**0.71**	**0.81**	**1.00**	**1.43**	**1.89**
Your Weighting			**1.00**		

Notes about driver weightings?

Table A10-7 Degree of Process Novelty Definition

Degree of Process Novelty Manufacturing process novelty for the direct application e.g. automated assembly process from an automotive plant, now developed using the TRL for the aerospace domain.

Table A10-8 Degree of Process Novelty Rating Scale

	Very Low	**Low**	**Nominal**	**High**	**Very High**
Description	Process developed, implemented and proven throughout the aerospace industry.	Process developed, implemented and proven within 3> non-aerospace domains.	Process developed, implemented and proven in 1> non-aerospace domain e.g. automotive manufacture.	Process developed to low level (TRL3-6) in 1> non-aerospace domain.	Process not proven or developed in any domain, completely novel.
Previous Weighting	**0.58**	**0.79**	**1.00**	**1.69**	**1.91**
Your Weighting			**1.00**		

Notes about driver weightings?

Table A10-9 Installation Complexity Definition

Installation Complexity Installation complexity of the manufacturing process to prove at full scale. A highly complex process would consist of many automation equipment installations.

Table A10-10 Installation Complexity Rating Scale

	Very Low	**Low**	**Nominal**	**High**	**Very High**
Description	Complexity of very low levels: much lower than existing process implementation and existing developments.	Low complexity: complexity slightly lower than exiting process installation procedure.	Moderately complex: installation procedure similar to existing process to replace.	Very complex: installation procedure exceeds existing process.	Extremely complex: installation procedure exceeds existing process installation and similar developments.
Previous Weighting	**0.75**	**0.85**	**1.00**	**1.15**	**1.30**
Your Weighting			**1.00**		

Notes about driver weightings?

1b: AMT Process Secondary Factors

The AMT Process Secondary Factors represent the process requirements that are determined secondary and separate from the primary factors listed previously.

Table A10-11 Manufacturing Environment Requirements Definition

Manufacturing Environment Requirements   Temperature requirements to prove the process accuracy at full scale application.

Table A10-12 Manufacturing Environment Requirements Rating Scale

	Very Low	**Low**	**Nominal**	**High**	**Very High**
Description	No process temperature control requirements.	Process requires temperature controlled ± 15%	Process requires temperature controlled ± 10%.	Process requires temperature controlled ± 3%.	Process requires temperature controlled ± 1%.
Previous Weighting	**0.74**	**0.84**	**1.00**	**1.10**	**1.26**
Your Weighting			**1.00**		

Notes about driver weightings?

Table A10-13 Automation Level Requirements Definition

Automation Level Requirements   The level and novelty of the automated control used within the process.

Table A10-14 Automation Level Requirements Rating Scale

	Very Low	Low	Nominal	High	Very High
Description	No automated control required.	Semi-automated control required fully proven within the domain.	Process requires a fully automated control proven within the same domain.	Process requires a fully automated control proven in one non-aerospace domain.	Process requires state of the art fully automated control unproven in any domain.
Previous Weighting	**0.60**	**0.80**	**1.00**	**1.55**	**1.84**
Your Weighting			**1.00**		

Notes about driver weightings?

Table A10-15 Test Piece Material Complexity Definition

Test Piece Material Complexity Complexity of the test piece material to prove the manufacturing process at full scale application.

Table A10-16 Test Piece Material Complexity Rating Scale

	Very Low	Low	Nominal	High	Very High
Description	Very low complexity: material fully proven for manufacture on existing product with selected process.	Low complexity: material proven in 2> same domain of aerospace manufacture with selected process.	Medium complexity: material implemented in 1> same domain of aerospace manufacture with selected process.	Very complex: limited development and implementation of a similar material with selected process.	Extremely complex: material completely novel and not been developed before with selected process.
Previous Weighting	**0.63**	**0.73**	**1.00**	**1.20**	**1.40**
Your Weighting			**1.00**		

Notes about driver weightings?

Table A10-17 Process Test and Verification Requirements Definition

Process Test and Verification Requirements Process test and verification requirements to prove the manufacturing process at full scale demonstration, TRL6.

Table A10-18 Process Test and Verification Requirements Rating Scale

	Very Low	Low	Nominal	High	Very High
Description	Process already proven, very low levels of testing required.	Process proven within a similar domain so required testing lower than nominal cases.	Standardised test and verification procedure for a similar manufacturing process.	Test and verification procedure conducted within a similar domain.	Advanced test and verification procedure never performed before.
Previous Weighting	**0.87**	**0.89**	**1.00**	**1.11**	**1.16**
Your Weighting			**1.00**		

Notes about driver weightings?

1c: AMT Process External Factors
The AMT Process External Factors define external process requirements.

Table A10-19 Metrology Requirements Definition

Metrology Requirements Metrology monitoring requirements to prove the manufacturing process and meet the customer requirements e.g. process capability.

Table A10-20 Metrology Requirements Rating Scale

	Very Low	**Low**	**Nominal**	**High**	**Very High**
Description	No metrology required.	Low levels of metrology required all fully proven for application.	Replicating or utilising existing metrology process, fully proven for application.	Metrology process proven within 1 > similar process domains.	State of the art metrology process, not proven within any process domain.
Previous Weighting	**0.62**	**0.69**	**1.00**	**1.22**	**1.45**
Your Weighting			**1.00**		

Notes about driver weightings?

Table A10-21 Human Factor Requirements Definition

Human Factor Requirements Human Factor Requirements of the manufacturing process to meet the customer requirements e.g. safety cell around the process to comply with Human Factor Legislation.

Table A10-22 Human Factor Requirements Rating Scale

	Very Low	**Low**	**Nominal**	**High**	**Very High**
Description	No human factor requirements.	Low level of human factor requirements and all lower than existing process.	Replication of existing process human factor requirements.	Process human factors requirements exceed existing process but proven within a similar domain e.g automotive.	Advanced human factors requirements e.g. robot-human interaction.
Previous Weighting	**0.71**	**0.83**	**1.00**	**1.10**	**1.23**
Your Weighting			**1.00**		

Notes about driver weightings?

Table A10-23 Tooling Requirements Definition

Tooling Requirements The tooling and fixture requirements to support the manufacturing process.

Table A10-24 Tooling Requirements Rating Scale

	Very Low	Low	Nominal	High	Very High
Description	No tooling requirements.	Low complexity: low levels of tooling and fixture requirements all lower than existing process.	Existing complexity: tooling and fixture requirements replicating the existing process.	High complexity: tooling and fixture requirements exceed existing process; developed within a similar domain.	Extremely complex: tooling and fixture requirements state of the art; not developed before in any domain.
Previous Weighting	**0.50**	**0.66**	**1.00**	**1.33**	**1.66**
Your Weighting			**1.00**		

Notes about driver weightings?

1d: Product Factor

The final Cost Driver theme is the product factor. This driver represents the production rate reduction requirements. This does not comply with the 5 scale rating system and only utilises: nominal, high and very high.

Table A10-25 Production Rate Reduction Requirements

Production Rate Reduction Requirements Required production reduction rate to prove the process at full scale demonstration, TRL6.

Table A10-26 Production Rate Reduction Requirements Rating Scale

	Nominal	High	Very High
Description	5% > increase in existing production rate.	10% > increase in existing production rate.	20% > increase in existing production rate.
Previous Weighting	**1.00**	**1.33**	**1.90**
Your Weighting	**1.00**		

Notes about driver weightings?

APPENDIX A.7

Experts Used within the Development of PERFORMO

Table A7-1 AMT Development Experts used to Determine PERFORMO Model Requirements

Organisation	Role	Years of Relevant Experience
A	Manufacturing Research Manager	15
A	Manufacturing Research Engineer	15
A	Manufacturing Project Manager	13
A	Automation Research Engineer	20
A	Manufacturing Metrology Research Engineer	13
A	Manufacturing Implementation Engineer	16
A	Manufacturing Research Manager	17
A	Manufacturing Implementation Engineer	12
A	Manufacturing Research Engineer	19
A	Technology Product Leader	9
A	Technology Development Specialist	22
A	Technology Product Leader	31
B	Internal TRL Developer	18
B	Project Technology Coordinator	6
C	Managing Director	15
D	Manufacturing Commercial Director	8
E	Manufacturing Capability Manager	12
E	Manufacturing Technical Manager	10
G	Professor of Aero-structure Design and Assembly	25

Table A7-2 Performance Forecasting and Decision Making Experts used to Determine PERFORMO Model Forms

Organisation	Role	Years of Relevant Experience
A	Performance and Cost Evaluation	25
G	Decision Science Research Fellow	11
J	Researcher in Manufacturing Decision Making	5
K	Associate Professor (Judgement and Decision Making)	10
M	Software Development Company Owner	35

APPENDIX A.8

PERFORMO Tangible Model Key Performance Factors

Name:

Company:

Department:

Years of Advanced Manufacturing Technology Development Experience:

Introduction

The purpose of this questionnaire is to finalise the Performance Forecasting Model (PERFORMO) Tangible Key Performance Factors (KPFs) for assessment of novel Advanced Manufacturing Technologies (AMTs) at the initial stages of development. These can typically be quantified and have been place into the following Tangible themes:

- Time. KPFs that predict the time impact of the AMT to a baseline operational hours.
- Cost. KPFs that capture the impact of the AMT to a baseline cost.
- Quality. Quality KPFs that capture the quality enhancement or degradation of the AMT for its specific application when compared to a baseline.

Can you fill in the questionnaire either agreeing or disagreeing with the following KPFs?

If you think a KPF is not suitable for the evaluation of AMTs at the initial stages of development can you please justify why in the appropriate section?

Do you think the clustering of the KPFs is suitable for evaluation of novel AMTs?

Time Key Performance Factors

The Time KPFs represent the forecast time of the new AMT development and its comparison to a datum AMT baseline.

Table A10-1 Process TAKT Time Definition

Process TAKT Time
The desired time taken to make one unit of production output.

Do you agree with this KPF and its definition?

Table A10-2 Process Waste Definition

Process Waste
Total time of non-value added actions within the process.

Do you agree with this KPF and its definition?

Table A10-3 Process Man Hours Definition

Process Man Hours
Total man hours utilised to perform the process within operations, resources consumed.

Do you agree with this KPF and its definition?

Table A10-4 Process up-time Definition

Process up-time
The mean time between failures (unplanned shut down of the process).

Do you agree with this KPF and its definition?

Table A10-5 Process Service Cycle Time Definition

Process Service Cycle Time The total time required servicing the process when embedded within operations.

Do you agree with this KPF and its definition?

Table A10-6 Process Lifecycle Time Definition

Process Lifecycle Time Process time in service within operations before non-conformance to specification or becoming obsolete.

Do you agree with this KPF and its definition?

Table A10-7 Process Lag Time Definition

Process Lag Time Total non-productive time of the process prior to start up.

Cost Key Performance Factors

Key Performance Factors that capture the impact of the AMT to a baseline cost.

Table A10-8 Process Recurring Cost Definition

Recurring Cost Total recurring cost of the process for its direct application; typically the programme or manufacturing operations.

Do you agree with this KPF and its definition?

Table A10-9 Non-recurring Cost Definition

Non Recurring Cost Total non-recurring cost of the process, the cost of the process when implemented into the programme or operations.

Do you agree with this KPF and its definition?

Quality Key Performance Factors

Quality KPFs capture the quality enhancement or degradation of the AMT.

Table A10-10 Rework in Manufacture Definition

Rework in Manufacture The number of concessions for the process direct application.

Do you agree with this KPF and its definition?

Table A10-11 Process Capability Definition

Process Capability Process capability performance (Cpk) for the direct application.

Do you agree with this KPF and its definition?

Table A10-12 Number of Inspections Definition

Number of Inspections The number of inspections the process requires to conform to specification.

APPENDIX A.9

PERFORMO Intangible Model Key Performance Factors

Name:

Company:

Department:

Years of Advanced Manufacturing Technology Development Experience:

Introduction

The purpose of this questionnaire is to finalise the Performance Forecasting Model (PERFORMO) Intangible Key Performance Factors (KPFs) for assessment of novel Advanced Manufacturing Technologies (AMTs) at the initial stages of development. These typically can't be quantified and have been place into the following Intangible themes:

- Health and Safety. KPFs that predict the Health and Safety performance of implementing the AMT.
- Flexibility. KPFs that predict the Flexibility performance of the AMT.
- Managerial/Operation. KPFs that predict the Managerial and Operational performance of the AMT.
- Risk. KPFs that quantify the risk for the AMT development and implementation.
- Strategic. KPFs that quantify the strategic performance of an AMT development.

Can you fill in the questionnaire either agreeing or disagreeing with the following KPFs?

If you think a KPF is not suitable for the evaluation of AMTs at the initial stages of development can you please justify why in the appropriate section?

Do you think the clustering of the KPFs is suitable for evaluation of novel AMTs?

Health and Safety Key Performance Factors

The health and safety KPFs represent the impact of the AMT to the health and safety requirements. These subjective requirements can typically form fundamental drivers for many new AMT developments from changes in legislation.

Table A9-1 Process Legislation Performance Definition

Process Legislation Performance Performance of process to meet legislation requirement (s) e.g. automated sealant to remove manual wing box entry.

Do you agree with this KPF and its definition?

Table A9-2 Employee Relations Definition

Employee Relations Performance Performance of process learning, safety hazards or labour productivity.

Do you agree with this KPF and its definition?

Table A9-3 Ergonomics Performance Definition

Ergonomics Performance Process performance enhancement or degradation on ergonomics for its direct manufacturing application.

Flexibility Key Performance Factors

The flexibility KPFs represent the impact of the AMT has on the process and product flexibility.

Table A9-4 Process Flexibility Definition

Process Flexibility
Capability of the process to increase the flexibility for its direct application e.g. decreased waiting time for parts, decreased work in progress.

Do you agree with this KPF and its definition?

Table A9-5 Product Flexibility Definition

Product Flexibility
Capability of the process to enhance the product flexibility e.g. shorter cycle times and setups.

Do you agree with this KPF and its definition?

Managerial/Operations Key Performance Factors

The managerial/operations KPFs represent the compatibility of the process with existing operations, the complexity of implementing with the existing operation configuration and the learning advancement from a business perspective for the specific development.

Table A9-8 Process Compatibility with Existing Operations Configuration Definition

Process Compatibility with Existing Operations Configuration
Process compatibility with desired operational configuration. Higher risks are created from the development of non-legacy products/processes.

Do you agree with this KPF and its definition?

Table A9-9 Technology Expansion Definition

Technology Expansion
Learning advancement, further use, increased product/process innovations.

Do you agree with this KPF and its definition?

Table A9-10 Installation Complexity Definition

Installation Complexity
Complexity of implementing the process within the assigned manufacturing application. A highly complex process would consist of many automation equipment installations.

Do you agree with this KPF and its definition?

Risk Key Performance Factors

The first risk KPF captures the development risk with the second KPF capturing the implementation risk.

Table A9-11 Development Risk Definition

Development Risk
Risk of developing the process – higher risk if process is completely novel.

Do you agree with this KPF and its definition?

Table A9-12 Implementation Risk Definition

Implementation Risk
Risk of the manufacturing process disrupting or impacting the new or existing manufacturing operational infrastructure.

Do you agree with this KPF and its definition?

Strategic Key Performance Factors

The strategic KPFs predict the suitability and alignment of the AMT with future strategic plans. These KPFs are crucial for the future financial and technical success of the business. With large product and operations lifecycles, the aerospace manufacturing domain requires careful planning and documentation of future product manufacturing vision and requirements.

Table A9-13 Manufacturing Vision Definition

Manufacturing Vision Vision and alignment of the process with future manufacturing strategies.

Do you agree with this KPF and its definition?

Table A9-14 Future Product Vision Definition

Future Product Vision Requirements of the manufacturing process for the manufacture of future products e.g. future aircraft programme composite assembly.

Do you agree with this KPF and its definition?

APPENDIX A.10

PERFORMO Intangible Model Key Performance Factor Rating Workshop

Name:

Company:

Department:

Years of Advanced Manufacturing Technology Development Experience:

Introduction

The purpose of this questionnaire is to finalise the Performance Forecasting Model (PERFORMO) Intangible Key Performance Factor (KPF) rating scale. These KPFs are for the assessment of novel Advanced Manufacturing Technologies (AMTs) at the initial stages of development. These KPFs can't be quantified, so require a qualitative rating scale. The rating scales are: Very Low, Low, Nominal, High and Very High. The rating scale ranges from -3 to 3 and are shown in Table A10-1.

Table A10-1 Rating Scale for PERFORMO Intangible Model KPFs

Extra Low	Very Low	Low	Nominal	High	Very High	Extra High
-3	-2	-1	0	1	2	3

Health and Safety Key Performance Factors

The health and safety KPFs represent the impact of the AMT to the health and safety requirements. These subjective requirements can typically form fundamental drivers for many new AMT developments from changes in legislation.

Table A10-2 Process Legislation Performance Definition

Process Legislation Performance Performance of process to meet legislation requirement (s) e.g. automated sealant to remove manual wing box entry.

Input your descriptions for Process Legislation Performance into the Rating Scale?

Table A10-3 Process Legislation Performance Rating Scale

Extra Low	**Very Low**	**Low**	**Nominal**	**High**	**Very High**	**Extra High**
-3	**-2**	**-1**	**0**	**1**	**2**	**3**

Table A10-4 Employee Relations Definition

Employee Relations Performance Performance of process learning, safety hazards or labour productivity.

Input your descriptions for Improved Employee Relations into the Rating Scale?

Table A10-5 Improved Employee Relations Rating Scale

Extra Low	Very Low	Low	Nominal	High	Very High	Extra High
-3	**-2**	**-1**	**0**	**1**	**2**	**3**

Table A10-6 Ergonomics Performance Definition

Ergonomics Performance Process performance enhancement or degradation on ergonomics for its direct manufacturing application.

Input your descriptions for Ergonomics Performance into the Rating Scale?

Table A10-7 Ergonomics Performance Rating Scale

Extra Low	Very Low	Low	Nominal	High	Very High	Extra High
-3	**-2**	**-1**	**0**	**1**	**2**	**3**

Flexibility Key Performance Factors

The flexibility KPFs represent the impact of the AMT has on the process and product flexibility.

Table A10-8 Process Flexibility Definition

Process Flexibility Capability of the process to increase the flexibility for its direct application e.g. decreased waiting time for parts, decreased work in progress.

Input your descriptions for Process Flexibility into the Rating Scale?

Table A10-9 Process Flexibility Rating Scale

Extra Low	Very Low	Low	Nominal	High	Very High	Extra High
-3	**-2**	**-1**	**0**	**1**	**2**	**3**

Table A10-10 Product Flexibility Definition

Product Flexibility Capability of the process to enhance the product flexibility e.g. shorter cycle times and setups.

Input your descriptions for Product Flexibility into the Rating Scale?

Table A10-11 Product Flexibility Rating Scale

Extra Low	Very Low	Low	Nominal	High	Very High	Extra High
-3	**-2**	**-1**	**0**	**1**	**2**	**3**

Managerial/Operations Key Performance Factors

The managerial/operations KPFs represent the compatibility of the process with existing operations, the complexity of implementing with the existing operation configuration and the learning advancement from a business perspective for the specific development.

Table A10-12 Process Compatibility with Existing Operations Configuration Definition

Process Compatibility with Existing Operations Configuration Process compatibility with desired operational configuration. Higher risks are created from the development of non-legacy products/processes.

Input your descriptions for Process Compatibility with Existing Operations Configuration into the Rating Scale?

Table A10-13 Process Compatibility with Existing Operations Configuration Rating Scale

Extra Low	Very Low	Low	Nominal	High	Very High	Extra High
-3	-2	-1	0	1	2	3

Table A10-14 Technology Expansion Definition

Technology Expansion Learning advancement, further use, increased product/process innovations.

Input your descriptions for Technology Expansion into the Rating Scale?

Table A10-15 Technology Expansion Rating Scale

Extra Low	Very Low	Low	Nominal	High	Very High	Extra High
-3	-2	-1	0	1	2	3

Table A10-16 Installation Complexity Definition

Installation Complexity Complexity of implementing the process within the assigned manufacturing application. A highly complex process would consist of many automation equipment installations.

Input your descriptions for Installation Complexity into the Rating Scale?

Table A10-17 Installation Complexity Rating Scale

Extra High	Very High	High	Nominal	Low	Very Low	Extra Low
-3	-2	-1	0	1	2	3

Risk Key Performance Factors

The first risk KPF captures the development risk with the second KPF capturing the implementation risk.

Table A10-18 Development Risk Definition

Development Risk Risk of developing the process – higher risk if process is completely novel.

Input your descriptions for Development Risk into the Rating Scale?

Table A10-19 Development Risk Rating Scale

Extra High	Very High	High	Nominal	Low	Very Low	Extra Low
-3	**-2**	**-1**	**0**	**1**	**2**	**3**

Table A10-20 Implementation Risk Definition

Implementation Risk Risk of the manufacturing process disrupting or impacting the new or existing manufacturing operational infrastructure.

Input your descriptions for Implementation Risk into the Rating Scale?

Table A10-21 Implementation Risk Rating Scale

Extra High	Very High	High	Nominal	Low	Very Low	Extra Low
-3	**-2**	**-1**	**0**	**1**	**2**	**3**

Strategic Key Performance Factors

The strategic KPFs predict the suitability and alignment of the AMT with future strategic plans. These KPFs are crucial for the future financial and technical success of the business. With large product and operations lifecycles, the aerospace manufacturing domain requires careful planning and documentation of future product manufacturing vision and requirements.

Table A10-22 Manufacturing Vision Definition

Manufacturing Vision Vision and alignment of the process with future manufacturing strategies.

Input your descriptions for Manufacturing Vision into the Rating Scale?

Table A10-23 Manufacturing Vision Rating Scale

Extra Low	Very Low	Low	Nominal	High	Very High	Extra High
-3	**-2**	**-1**	**0**	**1**	**2**	**3**

Table A10-24 Future Product Vision Definition

Future Product Vision Requirements of the manufacturing process for the manufacture of future products e.g. future aircraft programme composite assembly.

Input your descriptions for Future Product Vision into the Rating Scale?

Table A10-25 Future Product Vision Rating Scale

Extra Low	Very Low	Low	Nominal	High	Very High	Extra High
-3	**-2**	**-1**	**0**	**1**	**2**	**3**