A cost-based decision framework for advanced manufacturing research

Thesis submitted for the candidature of EngD

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Abstract

Advanced Manufacturing research centres bridge the gap between fundamental academic research and high value manufacturing. There are complexities in terms of decision making and knowledge management across these interfaces in particular surrounding the uncertainties in data. This research provides a solution to this combining cost engineering and Bayesian methods into a framework for use within these contexts.

The research aim is to provide;

A framework to improve value- related decision making when selecting novel manufacturing technologies.

The framework consists of four elements;

Elicit — Ensure that cost related drivers and input parameters are identified early using expert elicitation techniques to capture soft evidence.

Consolidate — Map all cost and value related parameters, uncertainties and their interrelationships.

Analyse — Identify the sensitivities to cost of all parameters.

Communicate —- Provide results as multi-objective outputs useful to a range of decision makers.

Feedback — Ensure that when new evidence emerges this is incorporated into the knowledge base.

Mixed methods were used in this research using a pragmatic approach, incorporating both quantitative and qualitative methods.

The novel framework offers an extension to the field of knowledge management and cost estimation, providing a mechanism for dynamic evidence and uncertainty propagation with feedback loops.

The research demonstrates that providing multi-objective decision making support enhances the 'buy-in' from multiple stakeholder groups.

The research builds on existing cost estimation research into cutting fluids to include many parameters not previously considered.

The case study 1 activity identified the value of robust coolant management and helped to initiative companywide investigation of coolant filtration technologies to enable improved coolant life and quality. This is now yielding significant cost reduction and improved life and sustainability to coolant practices across the company.

The results of case study 1, helped resolve the mitigating factors of inconsistent test results seen in case study 2. New research and industrial investment will now be conducted into coolant filtration and also adoption of improved filtration control in the research environment is commencing.

Acknowledgements

This work is co-sponsored by Rolls-Royce plc and the EPSRC for whom I am grateful for the opportunity to carry out this research. I am grateful to the Rolls-Royce product cost engineering department for initial training and support and for the wider Rolls-Royce group for access to their facilities, expertise and data.

I am also grateful to the AMRC for providing me with a base to carry out this research and access to their facilities, resources, expertise and members and the opportunity to present my work to a range of stakeholders.

I would like to acknowledge the support of my supervisors for their constant support and guidance. Dr Robin Purshouse for directing me up the steep learning curve this has been. Dr James Baldwin, for his expertise and advice in the area of social science. A special thanks to Jamie, who continually kept me focused on the narrative, without you this would not have been possible. I'd also like to pay tribute to my first supervisor the late Dr Steve Wisseall, who was a huge support at the beginning and I'm sorry that he didn't get to see me reach the end.

Statement of Originality

I declare that the work in this thesis, unless otherwise stated in the text, is carried out solely by the candidate in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programs. It has not been submitted for any other academic award.

SIGNED: .... DATE: ....

For

Ian, Oscar, Xandy and Charlie, my wonderful family.

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List of Abbreviations

ABC – Activity Based Costing

AMRC – Advanced Manufacturing Research Centre with Boeing

ANN – Artificial Neural Network

AxRC – Advanced Research Centre network

BLISK – Bladed disk

BN – Bayesian Network

CBR – Case Based Reasoning

CDF – Cumulative Density Function

CER – Cost Estimation Relationship

CME – Coordinate Measuring Equipment

CMM – Coordinate Measuring Machine

CNC – Computer Numerically Controlled

DMAIC – Design Measure Analyse Improve Control

ERP – Enterprise Resource planning

FBC – Feature based Costing

H&S – Health and safety

HPJM – High Pressure Jet Machining

IFDR – Intelligent Fluid Delivery and Recycling

IPT – Integrated Project Team

KPI – Key Performance Indicator

LCC – Life Cycle Costing

LSS – Lean Six Sigma

MCRL – Manufacturing Capability Readiness Level

ME – Manufacturing Engineer

MQL – Minimum Quantity Lubrication

NASA – National American Space Agency

NPT – Node Probability table

OEM – Original Equipment manufacturer

PDF –Probability Density Function

PH – Acidity or alkalinity scale

PPE – Personal Protective Equipment

R&D – Research and Development

Ra – Surface Roughness average measured over troughs and peaks

ROI – Return on Investment

RR – Rolls-Royce Plc

SoR – Statement of requirements

SoW – Statement of work

TRL – Technology Readiness Level

UTC – University Technical Centre

VB – Variation of average flank wear on tooling

WIP – Work In Progress

List of publications

- Presented at the Factory 2050 Conference – Technologies and systems 2015 at the AMRC;
- Poster presentation at RR EngD conference in 2015;
- Presented at the 23rd ISPE Inc. International Conference on Transdisciplinary Engineering in Curitiba, Brazil 2016;
- Published in the proceedings of Crossing Boundaries ISPE TE 2016 -C. E. Jeavons et al. 'A value-focussed decision framework for manufacturing research environments', 2016 [1];
- Disseminated at four presentation sessions at Rolls-Royce in 2016 and 2017, which included key manufacturing specialists;
- Poster presentations at AMRC road-mapping events in 2014, 2015, 2016 and 2017, which included AMRC staff and partners.

1 Introduction

1.1 Motivation

An Engineering Doctorate requires that the research seeks to make an impact in industry whilst making a unique contribution to knowledge.

This research seeks to improve the introduction of novel manufacturing technologies into industry by developing a framework that enables decision makers to more confidently select and mature the most cost-effective solutions during the phases of industrial research and development. Industrial research environments have a requirement to deliver new products, technologies and processes which can be applied in manufacturing environments. In order to deliver the most cost effective solutions to industry there needs to be a robust cost management system in place [2]. Cost engineering provides methods to predict the cost of a new product by comparing a combination of similar products or processes. It is well documented [3]–[5], that the largest proportion of product costs are defined and committed at the early stages of product design and development. Cost engineering therefore provides a critical input to decision making as information increases during technology development.

The environment in which the cost engineering approach will be applied in this thesis is the Advanced Manufacturing Research Centre with Boeing (AMRC) and will focus on civil aerospace projects with Rolls-Royce Plc. To successfully mature an advanced manufacturing technology to full production requires significant investment in research and development (R&D), which must be effectively managed within the technology planning process. Manufacturing sectors have systems in place to ensure consistent process quality throughout development programs.

Manufacturing Capability Readiness Levels (MCRL) are used in these centres to assess and manage each stage of technology maturity [6]. There are nine levels in total, beginning with level 1, fundamental research and technology assessment and ending at level 9 which is full production implementation. These levels can be grouped into three distinct stages (see Figure 1-1). The first (1-3) is the academic research phase where novel technologies are identified, designed and developed through to a stage for physical testing. The next phase (4-6) is the industrial research phase where the technologies can be further developed using industry scale equipment and expertise at the centre. The final stage (7-9) is where successful technologies are fully validated and introduced into the industrial settings. At the interface between research and industry it is essential that the experience and knowledge gained in the research setting can be directly aligned to established production environments ensuring that the transition and implementation of technologies enhances productivity from the onset.

Environment	Academic Research			Industrial Research centres			Industry		
MCRL	1	2	3	4	5	6	7	8	9
	Opportunity	Evaluation		Demonstration	Validation			Delivery	

Figure 1-1 - Technology development across the Manufacturing Capability Readiness Levels

The goal of this research is to propose a way forward with the ultimate aim of an ideal system for technology development. This system would be reciprocal, with multiple feedback loops between industry and research throughout the development phases as the results of research activities and production outcomes emerge. The transition between identification of an opportunity through evaluation, demonstration, validation and delivery should be seamless.

The focus of this research is at the pivotal point of this process, the AMRC, which has the largest bearing on the progression of technology to maturity and also provides and acts within the feedback loop to drive future opportunities.

In order to clarify this approach we can take the example of cutting fluid technology, which will be described in detail in Chapters 3, 5 and 6. Coolant suppliers are developing novel formulations to provide industry with the increased machining performance required to gain competitive advantage in times where material costs and technological challenges are increasing. The AMRC is able to test, develop and demonstrate their capability to industry whilst informing research about the performance of these formulations. Insight into the impact of control and management of cutting fluids within the production environment as the potential recipient of this novel coolant formulation technology provides the opportunity to create, develop and test the framework against a real life example of the complexities surrounding the development of technologies across the MCRL phases.

From the industrial perspective, the drive of manufacturing technology from definition, demonstration and delivery (i.e. through MCRL 3 to 7) is a one directional pipeline with little opportunity for feedback to inform and update the initial decision making process. This means the ability, as we learn, to inform and adapt to significant changes, detrimental or beneficial to the fundamental understanding of the technology, its assessment or exploitation can be missed or not fully explored.

The pre-production stages in which a technology is proven requires investment in industrial scale equipment and materials that represent those used in real production environments. Experienced operators and engineers run the trials and analyse the results, while engaging with industry experts to ensure the technologies can be integrated with current production practices and procedures. The trials must be dynamic and respond to the results and opportunities that arise. Intellectual property rights of novel technologies mean that some of the projects are generic to all partners but some must be effectively managed to protect sensitive information. All these aspects require significant investment commitment by the company. Investments in technology must be balanced with a comparative confidence of success in technology implementation.

High value manufacturing production environments are extremely complex environments. The necessity for stringent quality control demands highly structured, highly constrained and regulated procedures and operational practices. These industries can be multi-dimensional and include large integrated supply chains that must be managed effectively to succeed. The products are technologically complex, of high quality, with high value parts which must offer significant long-life functionality.

There are a range of stakeholders across these industries and each has different objectives which can be measured and communicated in various ways. The scale of knowledge, data and requirements requires significant effort in knowledge management and a range of technology management tools are used such as road-mapping and technology readiness processes which must be aligned to strengthen decision making. Industrial research supports these industries by developing novel materials and processes as well as providing solutions to meet the tighter tolerances, production and cost targets. Increases in material and operational costs require technological advances to deliver step changes in capability.

Manufacturing research centres have evolved to address these challenges by bridging the gap between fundamental academic research into novel technologies and implementation of successfully developed technologies into industry. These centres work with industrial partners to determine which capabilities and technologies offer the best value by delivering research and development outputs to support cost-effective decision making.

The advanced manufacturing research network provides a world class environment to deliver the transformational and step change in capability that industry needs. A combination of financial and technological contributions from partners and government grants are used to assist the development of technological capability to meet the most critical industry drivers.

A major challenge in this pre-production stage is the high level of uncertainty surrounding immature technologies; this can significantly affect a decision maker's confidence when selecting and evaluating alternative solutions. Knowledge is the product of manufacturing research centres; the procedures inside this environment lead to a one directional development process. Providing multiple opportunities to feed this knowledge forwards and backwards between phases has the potential to enhance decision making (see Chapter 4). An appreciation of the interrelationships of decisions, knowledge, data and information within this stage, suggests a level of complexity most likely to have created challenges. Uncertainties and risks surrounding technology development are related to uncertainty in knowledge, information and data as well as conflicting requirements from stakeholders [2], [7]. The aim of this research is to develop a framework which can offer a more robust means of assessing the value *vs* risks involved in adopting new technologies and/or making changes to production processes.

The AMRC sits in between two knowledge rich interfaces on the MCRL scale. The first (Interface 1) is where the industrial research centres must generate data and knowledge from research and development activities driven by knowledge from academic research to mature these or similar technologies to a stage where they can be successfully exploited by industry. The second (Interface 2) is where Industrial partners need to be given an appropriate source of data for decision making. This means the impact on business drivers, costs, confidence, capability and applicability of the technology need to be communicated in a way that enables efficient decision making and includes both tangible and intangible parameters (see Figure 1-2).

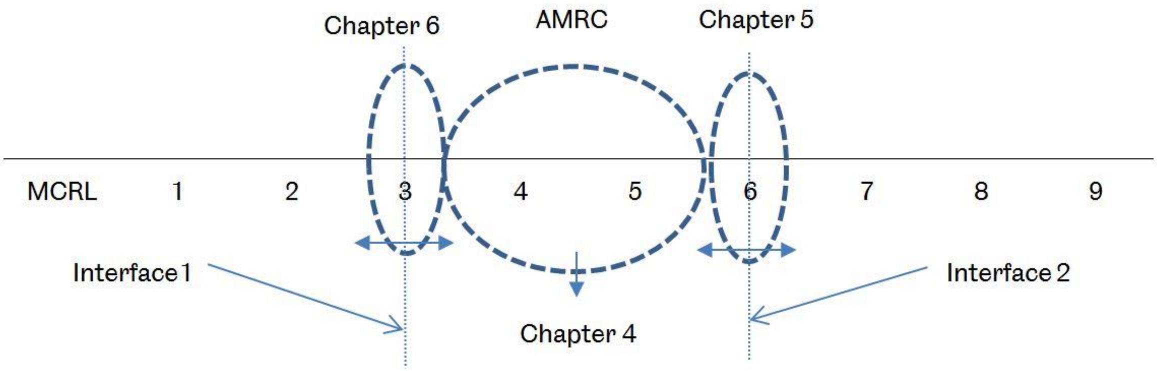


Figure 1-2 -Image showing how the thesis relates to the MCRL process

This research seeks to establish a link between value-related knowledge management and improved decision making in environments with significant uncertainty, by studying the decision making processes at each of these stages in a socio-technical manner, so that both human decision making aspects and manufacturing knowledge are included in the study.

Manufacturing research settings are complex. The environments span internal and external boundaries and involve academic research, manufacturing operations, engineering and customer and supplier requirements. The knowledge and data required to make cost effective decisions across these phases are continuously increasing and a major challenge is to store and communicate these in a way that enables efficient access to up to date information aligned to drivers from all phases. Addressing this problem has the potential to streamline technology adoption as well as identifying technologies that offer potential for future research and development.

1.2 Manufacturing capability decision-making at a major aerospace manufacturer

The pre-production stages in which a technology is proven require investment in industrial scale equipment and materials that represent those used in real production environments. Centres such as the AMRC, described in 2.2.2 provide the facilities and expertise for industry partners to carry out advanced manufacturing research. Experienced operators and engineers are needed to run the trials and analyse the results, while engaging with industry experts to ensure the technologies can be integrated with current production practices and procedures, and provide data in a compatible format. As these projects are of a research and learning nature, the trials must be dynamic and respond to the results and opportunities that arise. There are further complications due to intellectual property rights of novel technologies, so some of the projects are generic to all partners but some must be effectively managed to protect sensitive information. These aspects require significant investment commitment by the company. The funding for research and development at the interface between research and implementation is less readily available than earlier stages and the technological challenges involved in maturing the technologies to a commercial scale are significant. Investments must be balanced with a comparative confidence of success in technology implementation [8], [9].

High value manufacturing production environments are extremely complex; they are fast paced with considerable pressure to meet operational targets due to the significant economic value and reliability requirements of their products. The products are technologically complex, of high quality, with high value parts which must offer significant long-life functionality and reliability due to the significant consequence of failure [10]. The necessity for stringent quality control demands highly structured, highly constrained and regulated procedures and operational practices [6]. These industries often include large integrated supply chains that must be managed effectively to succeed [11].

The stakeholders across these industries may be working towards different objectives and drivers. These can be conflicting or perceived as conflicting, as the way in which they are measured and communicated often varies. In fact, these are interrelated but due to the scale of knowledge, data and requirements, departments act as separate entities which may conflict with one another especially where short, medium and long-term drivers vary. The decision making processes differ amongst these stakeholders, for example, quality, production, maintenance, central services, environmental and commercial managers will have alternative procedures which do not necessarily relate to one another in terms of decision making [11], [12].

Industry drivers which generate the need for industrial research include product developments such as novel materials and novel processes as well as meeting the requirement for tighter tolerances, more challenging production targets, cost reduction and shortened technology adoption times to increase competitive advantage [13].

Increased material and operational costs drive the need for technological advances that can deliver step changes in capability and productivity to meet short, medium and long-term objectives. Operational efficiency improvements can lower operational costs and these practices have become more widespread [14]. However, fuel burn is amongst the highest operating cost and contributor to environmental impact in the aerospace industry. Demands from customers and society to provide more efficient products drive performance targets such as reduced weight, noise and waste reduction and lifetime operating cost reduction which require fundamental research and technology development so are, for example, the focus of two thirds of the annual £1.3bn R&D spend at Rolls-Royce Plc [15].

The desire to invest in technological advancements can be restricted by economic constraints or uncertainties in data and knowledge but is a fundamental requirement to gain competitive advantage. Business and product investment strategies are managed in different ways by different stakeholders and a range of technology management tools such as technology road mapping, technology readiness and knowledge management are used across an organisation to meet these targets [6], [16]–[18]. These tools are often used in isolation; this dislocation can cause complications when communicating objectives and strategies, causing re-discovery of existing knowledge and overlapping efforts. Where the inputs and outputs of these tools are aligned, then multi-departmental decision making can be improved [4].

1.2.1 Manufacturing capability acquisition at Rolls-Royce

Manufacturing capability acquisition is the process that Rolls-Royce uses to enable their Businesses to identify and deliver new manufacturing technologies. This includes the definition and communication of requirements and risk, with 'manufacturing capability readiness levels' (MCRL) used to monitor the progression of technology throughout its maturity against a set of standards. The MCRL is based upon the Technology Readiness Level (TRL) approach developed by NASA and was modified to provide a more manufacturing specific approach which is now widely used by the aerospace sector [6].

The MCRL process involves a sequence of nine maturity stages, from technology assessment and proving through to production ramp-up, which enable the governance of technology maturity through a set of defined stage gates (see Figure 1-3**Error! Reference source not found.**).

9	Production Ramp-up	Fully production capable process demonstrated on full range of parts over extended period, benefit case metrics achieved and project learning recorded and actively shared (through process demonstration and optimisation across all business metrics & buy-in)
8		Fully production capable process demonstrated on full range of parts over significant run lengths (through process demonstration and optimisation with statistical assessment & buy-in)
7		Capability and rate conformed via economic run lengths on production parts and equipment, in the production location (through process demonstration and optimisation with assessment & buy-in)
6	Pre-Production	Process optimisation, using production equipment, complete. Process sealed and handed over to operations for further capability and proving (through process demonstration and proving with control, assessment & buy-in)
5		Basic capability demonstrated using production equipment (through process demonstration and proving with assessment & buy-in)
4	Technolo	Process validated in laboratory using representative development equipment (through process demonstration with assessment & buy-in)

3		Experimental proof of concept completed (through trial or read across with assessment & buy-in)
2		Applicability & validity of concept described and vetted (through trial or read across with assessment & buy-in)
1		Process concept proposed with scientific foundation (Concept or buy in)
MCRL	Activity	MCRL Description (stage gate requirement)

Figure 1-3 A diagram of the MCRL process at Rolls-Royce [Rolls-Royce capability acquisition internal handbook]

At Rolls-Royce, all manufacturing capability acquisitions must be aligned to future requirements, as determined by the business individual product strategies. Each project must gain funding by submitting an outline business case which includes a cost justification of introducing the technology weighted against potential improvements. There are numerous opportunities for internal and external funding to be leveraged but all depend critically on the benefit of ultimately maturing and exploiting the manufacturing technology.

Rolls-Royce are industrial partners at 31 University Technology Centres (UTCs), which are collaborative centres for scientific research, and of seven so-called ‘AxRCs’, which are a network of advanced manufacturing research centres that enable industries to achieve world class capability across the full portfolio of manufacturing technologies. Rolls-Royce uses this network to fund the advancement of technologies up to MCRL 6 (see Figure 1-4)[15].

Environment	Academic Research (Universities & UTCs)			Industrial Research centres (AxRCs)			Industry		
MCRL	1	2	3	4	5	6	7	8	9
	Opportunity	Evaluation		Demonstration	Validation			Delivery	

Figure 1-4 - Technology development across the Manufacturing Capability Readiness Levels

[RR capability acquisition internal handbook]

1.2.2 Research centre partnership model

The AMRC is a world leading industrial research centre specialising in manufacturing. The AMRC is the first of the seven high value catapult centres, which has been replicated across the UK and internationally to bridge the gap between scientific research and manufacturing productivity gains. Each centre specialises in a particular aspect of advanced manufacturing.

The advanced manufacturing research network aims to provide a world class environment that can deliver the transformational manufacturing capability that industry needs to increase productivity in an ever more competitive global environment. A combination of financial and technological contributions from partners and government grants are used to assist the development of technological capability to meet the most critical industry drivers [9].

There are eight research groups at the AMRC. These are: machining; composites; structural testing; design and prototyping; medical; castings; and the integrated manufacturing group. Each group includes technical and research staff to develop techniques which aim to significantly improve machining of high performance materials [19].

There are a number of project types: ‘generic projects’ are of shared interest and the cost is shared amongst membership; ‘directed generic projects’ are chosen and directly funded by individual membership subscriptions; ‘company specific projects’ are privately funded by partners and by over four hundred non-members to engage in research specific to their requirements, the results of which are confidential to the specific funders [20].

The membership model in 2018 consists of over one hundred fee paying partnerships, which range from large Original Equipment Manufacturers (OEMs) such as Boeing, Rolls-Royce and Sandvik Coromant to local small businesses and specialist suppliers. There are two levels of partnership: 'tier 1' which requires a large in-kind or cash contribution, and enables the organisation to join the board of directors of the centre, with influence over directed generic projects; and 'tier 2' which requires a small in-kind or cash contribution, and a communal representative on the board [19].

Knowledge management in advanced manufacturing research centres is complex due to the range of projects such as machining trials, process monitoring, design, modelling and metallurgy based research, and the resulting data that is being produced across numerous sectors with differing levels of data security. The research centres have machinery to industrial specification, but is not a production environment – the testing and machining of components is carried out for research purposes only and so insight from industry is required to align industry requirements with research focus.

For the purpose of this research it was necessary to understand how cost is measured and applied to decision making across the MCRL phases, including how the cost and benefit of a novel technology is predicted and tested in production, and how data and uncertainty is managed. This insight can potentially be used to align research from the AMRC more effectively to inform industry of which technologies have the most potential.

To successfully mature an advanced manufacturing technology to full production requires significant investment in research and development, which must be optimally managed within the technology planning process [21]. Manufacturing sectors have systems in place to ensure consistent process quality throughout development programmes. The pre-production stages in which a technology is proven for production require significant R&D investment. These stages are particularly difficult to traverse as funding for R&D is less readily available than earlier stages and the technological challenges involved in maturing the technologies to a commercial scale are significant. The necessary investment can be high and must be balanced with a comparative confidence of success in technology implementation [8], [22].

This work aims to establish a link between value-related knowledge management and improved decision making in environments with significant uncertainty, by studying the decision making processes in a socio-technical way.

1.3 Aim and objectives

The research aim is;

A framework to improve value- related decision making when selecting novel manufacturing technologies.

The main research objectives are to:

(O1) Study existing decision making processes in novel technology development to identify gaps in cost related knowledge;

(O2) Capture the requirements for cost modelling;

(O3) Identify and elicit the extant quantitative and qualitative knowledge, and interrelationships;

(O4) Identify the most suitable methods for handling uncertainty, changing information, and to support value-related decision making;

(O5) Develop and validate the framework, using multiple case studies across the technology development phases.

1.4 Research questions

The aims can be described by two research questions.

(RQ1) “What is the link between value-related knowledge management and improved technology decision making in environments with significant uncertainty?”

(RQ2) “What mechanism will improve value-related knowledge management to support novel technology selection across MRCL?”

1.5 Thesis structure

Following on from the introduction the remainder of the thesis is organised as follows:

The **Literature review** (Chapter 2) Describes existing research in the fields of cost engineering and alternative methods for decision making in environments with uncertainty. The chapter also includes existing research in the use and cost modelling of cutting fluids which is the focus of the research application.

Chapter 3 provides a description of the research methodology.

Chapter 4 describes the framework developed to meet the industrial aims of this study, which is to provide the AMRC with:

A framework to improve value- related decision making when selecting novel manufacturing technologies.

The framework structure consists of five stages:

- Elicit;
- Consolidate;
- Analyse;
- Communicate;
- Feedback.

The chapter covers objectives (O1)-(O4), includes some aspects of (O5) and provides insight into both RQ1 and RQ2.

The chapter entitled **Coolant management technology selection** (Chapter 5) describes Case Study 1 which resides at interface 2 (see Figure 1-2) and investigates how a novel technology is moved from pre-production to industry. It provides recommendations for identifying the most useful outputs required by manufacturing research and development in support of multi-criteria decision making.

This case study works through each objective of the research and is the first of two case studies required for objective O5.

The case study provides the opportunity to investigate research question RQ1, and also provides a solution to research question RQ2.

The case study is set within the Rolls-Royce production environment. The decision making process for technology adoption here is the business case and involves a previously untested coolant filtration technology. The industrial driver for the trial was the reduction of non-conformance on the finish machining of a high temperature nickel-based super alloy which is causing undesirable levels of rework.

A previous study at another Rolls-Royce production facility suggested coolant contamination as a possible cause, hence the decision to consider the assessment of next generation coolant filtration technologies.

First, the coolant cost model presented in Chapter 3 was built upon to provide a detailed cost model of the current process with a structure that allowed the new technology to be introduced. The results of this model supported the business case for the purchase of the technology in order to trial its efficacy on quality improvement.

Subsequently, the framework detailed in Chapter 4 was applied iteratively to the Case Study (and underpinning model) providing evidence of each of the parameters in the framework across input, process, output and feedback to enhance the decision making in the Case Study.

The results of Case Study 1 are a comprehensive cost model which includes cost parameters not typically included in coolant use evaluation and a Bayesian Network of the process which shows the confidence around outputs of productivity, cost and the environment, enabling a value stream aligned to a range of stakeholder drivers across the business to be identified.

Case Study 2 involves the **Cutting fluid technology selection** (Chapter 6) and resides at interface 1 (see Figure 1-2Figure 1-2) and follows the development of an improved assessment procedure for new cutting fluid formulations.

The chapter begins with a description of the problem, then describes the historical Rolls-Royce coolant approvals assessment before moving on to describe how the new procedure was developed over stage 1 (initial fluid screening) and stage 2 (fluid machining trials). The role of the researcher was that of an observer at this stage – capturing the evolving new procedure and identifying where missing pieces were and what implications these missing pieces had. Ultimately the Case Study provides the information needed to produce a model of the process, and each step gives insight into alternative aspects of the framework.

The Input phase of the framework covered aspects of stage 1 of how to determine the business case for coolants. Initially, in phase 2, the metrics were set as productivity for tool life and coolant cost. This formulation excludes other parameters such as sump life, so the process stage of the framework is used to synthesize information requirements from industry and identify the gaps. Understanding how the variables are related to parameters from Case Study 1 helps to test the output stage of the framework.

The next section describes an application of the framework methods and tools. Bayesian models require underlying data to support decision making. Missing areas and metrics not being identified earlier in the MCRL phases mean that industry is not provided with the level of confidence required to justify technology investments. So the framework is used to create a Bayesian model to see how using information in this Case Study can affect the usefulness of the output metrics, and can help direct decision making earlier on in the R&D process.

Finally the **discussion and conclusions** chapter (Chapter 7) reflects on the studies, discusses empirical findings and contributions to research and the ability to meet the industrial aims and provides information on limitations and recommendations for further research.

2 Literature review

2.1 Cost engineering

Cost engineering refers to the application of scientific principles and techniques to solve a variety of cost related problems. The practice is carried out at specific phases or throughout the project life-cycle using techniques, cost models, tools and databases, whilst employing expert judgment concerning the specifics of the activity of interest and the information that is available. Often the output of cost engineering is the input to a decision making process [23].

Cost engineering methods for decision making in manufacturing industries have been documented in the literature over recent decades and span many industry sectors including aerospace, automotive and health as demonstrated in [24]–[27]. It is well known that targeting cost reduction in early stages of product design is beneficial as described by [3]–[5], [28]. However, very few publications specifically target cost during the early stages of R&D and tend to focus on design (novel and adaptions), or new and existing processes [29]. In addition methods compare alternative designs, processes and, to a lesser extent, technologies [26], [30], [31] but do not offer a decision making solution capable of identifying where technology research and development opportunities exist, based on comprehensive cost models.

Product and process cost modelling links customer cost requirements back to decisions which are made throughout the research, design and development phases and so frequently the modelling maps a product (or process) parameter (or feature) to an economic value [29], [32], [33]. The method is used to determine the cost drivers and their sensitivities within a system.

2.1.1 Cost estimation techniques

Cost estimation techniques are well documented [25], [28], [34], [35], and the classification by Niazi et al. A good representation of the range of approaches is given in [34] (see Figure 2-1). Arguably, the qualitative techniques are not all correctly classified in Niazi et al.'s tree diagram, others [2] describe fuzzy set theory and neural networks as quantitative methods. Decision analysis would be classed as a quantitative technique also, and the figure reflects these changes. The pros and cons of different conceptual cost techniques have been described. The results show that although some approaches such as the bottom up approach and estimating by analogy are detailed and enable cause and effect respectively, they are both hard to implement due to the granularity of data required for validation. The parametric method is described as quick and relatively simple to implement but lacks cause and effect relationships and requires detailed forecasting, which again is hard to validate [36].

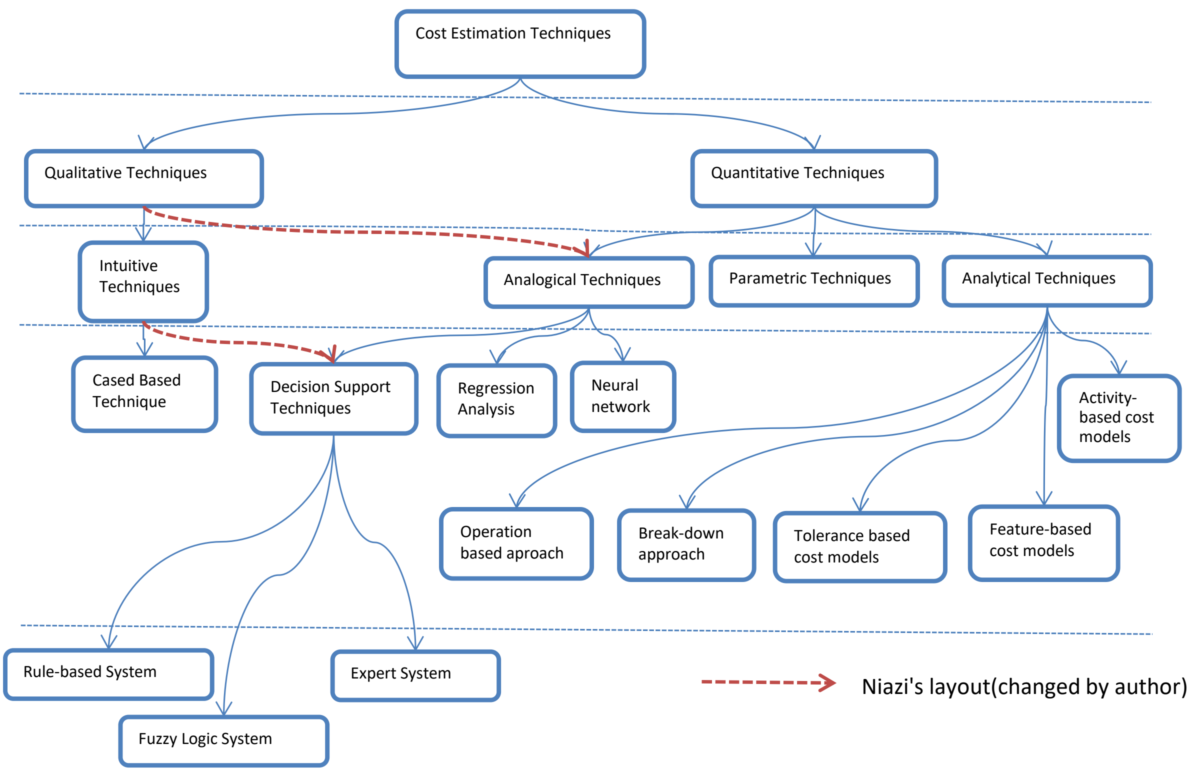


Figure 2-1- Detailed classifications of cost estimation techniques (adapted from [8])

Qualitative techniques are based on intuition and experience of both the estimator and the similarity of the new product to a previously estimated product. Most of the historical static models use this technique. *Quantitative techniques* characterise the product based on analytical parameters from the manufacturing process. *Feature based cost estimation* methodology identifies associated design or process related costs from a product's features. *Activity based costing (ABC)* is used to calculate the cost of activities within a production process to make a product. ABC is able to bridge the gap between design and manufacturing operations. *Artificial Neural network systems (ANN)* are developed using artificial intelligence in cost estimation systems.

The system is programmed to learn the functional relationships between features or activities and cost. This enables the system to influence decisions [23], [37].

With less data available and less accuracy required earlier in the design and development stages, qualitative methods provide a rough cost estimate. Quantitative methods are used when comprehensive information is available and an accurate cost estimate is required [35]. In this research it will be necessary to use both qualitative data and quantitative data as it emerges.

Over 100 journal articles were identified using the search terms cost estimation techniques and this provided 38 relevant studies which were reviewed in detail (See Appendix D). These articles used cost methods : (1) ABC – based on production activity costs [4]; (2) Case Based Reasoning (CBR) which uses design attributes from previous cases to estimate costs of related designs [38], [39]; (3) Life cycle costing (LCC) – which is used to establish the cost of a product from early design stages to disposal [40]; Parametric techniques uses high level relationships between variables to estimate cost and duration [41], [42]; Target costing – the design and development of products driven by an initial target cost [43]; Feature based costing (FBC) – where cost parameters are linked to product design features [33] or a combination of techniques (see Figure 2-2). When compared to Niazi et al.'s classification, the majority of the literature uses quantitative techniques.

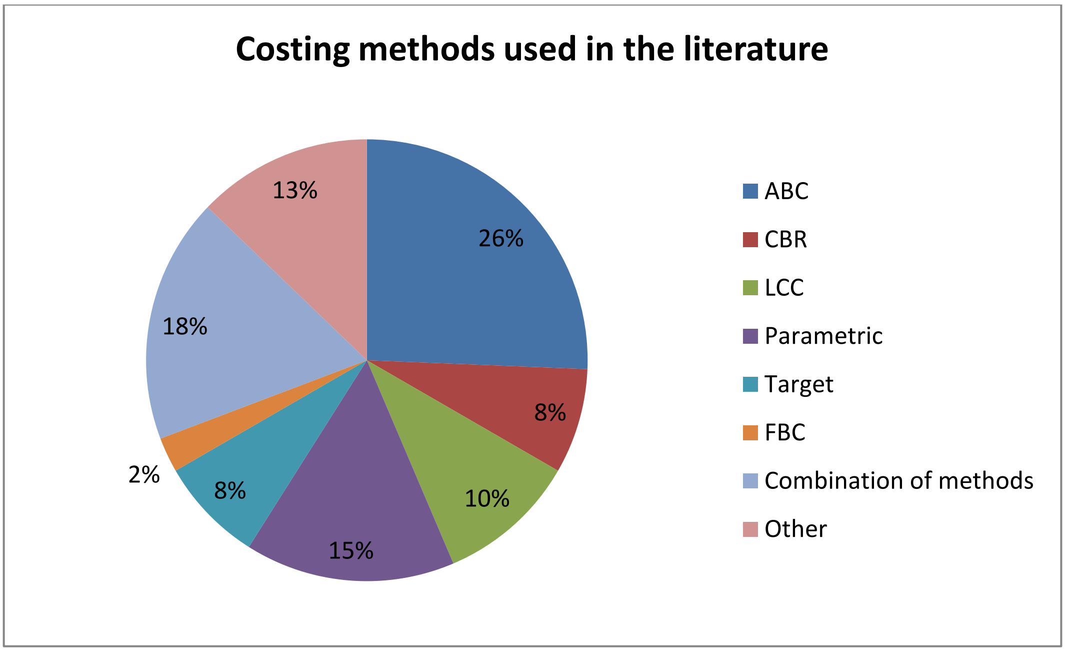


Figure 2-2 – Chart showing cost estimation methods used in selected literature

Activity based costing is the most common method used in this literature search (see Figure 2-2), but in the research and development stage the activity data is rarely available and so assumptions need to be made or other methods need to be incorporated. This is evident in the combination of methods section which comes as a close second. ABC driven by target costing [44], Value engineering with target costing [45] and quality driven costing [46] are all methods used to ensure that the cost and/or quality targets are adhered to while the costing data emerges.

A mixture of case based, parametric, ABC and expert judgement has been used as a method of creating the cost estimate based on available data using a comparator to combine existing technology costs to the new technology costs [30]. This combination is appropriate for the research as the framework needs to incorporate data from sources that span the MCRL stages, including qualitative and quantitative data from experts, stakeholders and must also include evidence from industry and research and development. These authors are effectively using a toolbox of methods where appropriate based on the data available at the time of constructing a model [47]. This seems appropriate to the research because at lower stages in technology maturity as it will be less likely to limit the accuracy of the estimate, as evidence emerges from both R&D and industry, cased based, feature based and activity based costings can be applied.

2.1.2 **Cost data management**

Management of data is critical in the early stages of product development. The data may be limited, inaccurate, from many sources and evolving. Explicit and implicit data and knowledge capture is clearly necessary. Data structures can use changes in product through the development stage to categorise data (from Level 3 with detailed geometry and tolerances, Level 2 which has geometry of the major parts and assembly information, and Level 1 which has only the overall dimensions and primary materials) [5].

Many authors [48], [36], [49], [50],[51]–[53] suggest methods of creating separate databases to store similar data types, such as historical, estimated, actual, financial and operations from multiple sources to populate cost models. Chapter 4 describes how this research gains knowledge about the processes and procedures within the AMRC environment available for knowledge capture. In the AMRC a centralised knowledge base which manages data sensitivities specific to partners would be preferable.

Separating new and existing technologies when collecting data is suggested as an approach to data management [54] . Cost Estimation Relationships (CERs) are defined from the current technology and then comparators are identified for the new technology, which could be useful where novel technologies are based on existing technology parameters.

2.1.3 Managing uncertainties in cost engineering

Difficulties in accurately estimating the cost of new systems, technologies, products and processes is greatly compounded by the uncertainty in the data available at early stages of development. Three fifths of the papers in the literature review address this problem.

The requirement for tools to support incomplete and uncertain data has been raised [55]–[57]. One suggested method is to build an uncertainty factor into the model [58]. This factor is applied to estimates (as a multiplier) and is altered as product definition increases. This would require detailed assumptions to be made by stakeholders, to appropriately select and update the uncertainty factor which may prove problematic. Another method described demonstrates the learning effect on different process cost elements, with the aim of enabling managers to direct their efforts on areas of learning which would provide the largest positive impact on cost [53]. Technical risk and design maturity parameters have also been suggested using full time test hours of the design and a maturity scale similar to the TRL scale developed by NASA [36]. Confidence intervals can be used to represent the cost estimates elicited from experts [30]. This approach helps manage the risks associated with uncertainty by representing data in a more realistic distribution and in the context of this research would be a useful way to model and validate both qualitative and quantitative data.

Monte Carlo methods can be used to model the uncertainty in costs. Static values in a model, for example cycle times can be replaced with a distribution, from which values are sampled using a random number generator and this capability is available within cost estimating software [49]. Many of the activities in activity based cost modelling are dependent on resources which rarely behave in an entirely predictable way and so ways to represent the uncertainty of these data are critical.

There are a range of options for uncertainty management used in the literature but there is a lack of clarity or guidance as to which methods to adopt. These include the use of neural networks to enable a system to learn the effects of attributes in relation to cost, fuzzy based theory to assign probabilities to vague knowledge about future costs, and CBR to compare similar systems [59],[60]. A dependency matrix is used to model the cause and effect of changes to cost elements during the life cycle of a product [61]. Bayesian Networks and Monte Carlo simulations are used to run predictive scenarios.

2.1.4 **Cost estimation for decision making**

A group of studies have used cost information to inform designers. Designers need substantial predictive cost information to inform design choices (including the costs of design and development), facilitated via a target costing system [44]. Identified cost savings can be shared across supplier and customer. The value to all stakeholders, for each design choice, is included in the model by Cheung et al. [49]. A knowledge base is used to store cost information related to design attributes and an inference engine applies logical rules to identify new information. The system is used to determine weight and cost implications of design decisions that change the stored information. A methodology that draws on the multidisciplinary knowledge of engineers to aid first time right design is provided by Curran et al. [47].

Web-based tools should be developed to interact with the enterprise resource planning (ERP) systems so that process decisions can be made according to Shim et al. [48]. Within the research and development stage these systems rarely exist; however, data from existing systems of a similar design could be used.

A detailed structure that includes statistical distributions that represent the uncertainty for both the product and the manufacturing process can aid validation and transparency of decision making [58]. These aspects are particularly important in this research as the stakeholders are often the experts and decision makers and so any model will need to clearly show data as well as the inter-relationships between system variables.

Some studies have used cost information to inform the selection of alternative technologies. One method is used as decision support for selecting new technology in the concept stage by breaking down the product into current and emerging technologies and uses parametric, analogous and detailed estimating techniques to provide the cost expert with data to form comparators and develop a new estimate [30]. Benefits, opportunities, costs and risks, priority ranking and lessons learned logs can also be used for selecting between technology alternatives [51] [62][63]. Ensuring that this information is captured within the MCRL process at the AMRC is essential.

Digital models can be used to capture cost modelling knowledge, to be used by others. The model can be calibrated using historical product and cost data. Cross departmental drivers and assumptions are next added to the model to ensure that data is kept concurrent. This is beneficial in ensuring that future cost decisions are informed by past experience and have enhanced validity and quality [64].

Gate stages are useful for assessing potential changes to drivers and calculate the probability of that change which affects the nominal state of the driver occurring and the resulting impact on cost [61]. The gate stages in the quaity procedures at the AMRC provide an opportunity to monitor the impact on changes to data. Value analysis, quantifying the value of each component and the function of the product, can be used to link functionality to cost [65], and this could be extended to technologies, where investment in R&D can be justified against improved technological capability.

It is clear from this review that, while the influence of the cost decisions depends on the requirements, it may be the case that many of the decisions could be addressed by a common set of data. If cost modelling boundaries are widened then the information could potentially improve decision making across many areas of a business.

2.1.5 **Gaps in research**

Leading contributors to cost engineering research in the UK recently reviewed the current state of research in cost engineering for manufacturing [3], discussing the issues surrounding a method for modelling cost throughout the different stages of manufacturing from conceptual design through product development and life cycle. The research gaps identified in the review are summarised in Table 2-1.

Gaps in cost engineering research	
Managing uncertainty	A framework for capturing critical uncertainties that impact life cycle costing
	Methods which consider aleatory and epistemic uncertainties separately
	Approaches for the qualitative affordability factors
	Trade-offs between customer affordability and manufacturer profitability
	Recognition of uncertainty throughout the life-cycle
	Improved understanding of uncertainty variation through the full life cycle
	Verification and validation of epistemic uncertainties in cost estimation
	More representative LCC model
Knowledge management	Automated cost modelling from computer aided production planning information
	Methods to adjust for the stochastic nature of LCC
	Improved storage of information in a centralised-controlled environment for cost analysis
	Improved mechanisms for sharing product and manufacturing information
Design stage	Improved knowledge of design rework impact factors
	Accuracy of early design stage cost estimation
	Support for detailed design stage and quotation process planning
	Early design phases availability prediction

Table 2-1 -Gaps in cost engineering research from [3]

The prominence of uncertainty and knowledge management related research in Table 2.1 may signify the difficulties that managing the uncertainty can have on the accuracy of cost estimation, and so the present research will attempt to provide insight into these aspects.

2.1.6 **Reflection**

Three general themes emerge from the cost modelling literature:

- Cost elements can be uncertain and are interrelated;
- Knowledge management is a dynamic process that must align with existing governance;
- Inter-relationships cross organisational boundaries.

These themes will be discussed in more detail.

2.1.6.1 Cost elements can be uncertain and are interrelated

There are interdependencies within cost drivers and these must be made explicit for cost estimates to be realistic and accurate. A methodology is created by Ferguson et al. [61] for the early design stages using Bayesian methods and Monte Carlo simulation to quantify uncertainty, enable qualitative inputs and visually represent data relationships. It is important to consider the underlying drivers of activities, and the interdependencies, including the probability of output parameters [46].

The concept of uncertainty evolving is useful [25]. Uncertainty is influenced by data availability, design changes, material availability, competition as well as many other unplanned events. This means that, throughout the development phase, uncertainty evolves and increases in complexity as more attributes are included and details emerge. This is very important and rarely discussed; often uncertainty is a static value which is not revisited. A high degree of uncertainty is present at the conceptual stage, but less so later on and this should be captured.

2.1.6.2 Knowledge management is a dynamic process that must align with existing governance

Typically, in research and development environments: (1) required data to support models is initially unavailable; (2) assumptions must be made in the models; (3) more data arrives over time, which needs to be incorporated; (4) the modelling must be responsive to the timings of overarching governance.

Several studies propose methods for handling different types of data. The requirement of two cost models is discussed by Roy et al. [30], one for current technology and one for new technology. They then identify cost drivers from these two models by means of sensitivity analysis. Reverse engineering is in Ibusuki [45] to break down activities linked to cost where similar product information is available. New product versus derivative product cost are similarly linked by Lorell et al. [36]. A transparent marginal analysis approach is used by Tan et al. [63], which allows alternatives to be evaluated against each decision criteria to improve clarity of decision making. The authors argue that mathematical analyses are unusable in industry as they are too complex to implement widely, so a combination of quantitative and qualitative data capture, over extended time, before a decision is made, would benefit from this approach. Although more complex mathematical approaches could increase complexity, industrial decision makers require clear transparent models where assumptions are explicit to ensure confidence in the output data.

Knowledge management is particularly important in industries where the cost estimates are produced many years before production starts. Lessons learned regarding good judgment, complex issues and any heuristic rules applied by experts should be applied to future estimates. Tacit and explicit knowledge should be captured separately, creating a knowledge base to categorise data for use in rule-based decision systems [52], [62], [47].

As conditions change and learning increases during the phases of technology development, adjustments to programme objectives, scope and costing must be possible. Cost drivers and their interdependencies must be understood and made explicit to improve estimates. Assumptions, constraints and trade-off decisions underlying the estimate should be well documented and iterative validation of these models should be included in the framework. The method developed by Ferguson et al. [61] includes intuitive visual representation of data to explicitly model influential data relationships. The cost anchor and calibration technique is similar to the LEAN notion of standardisation and could work well for cost modelling. Learning theory is a consideration to assist in decision system development. Cost evolution of new technologies is related to changes in material as well as learning curves in the organisation [53]. Inter-dependencies between costs means trade-offs can exist between costs and other criteria when making a technology decision. Information regarding any trade-offs must be clearly communicated to decision makers [47].

Integration of cost decisions into existing governance processes is vital for ensuring consistency and buy in from the research environment [66]. To achieve this, integration of the system must incorporate process, operation and financial models [60].

2.1.6.3 **Inter-relationships cross organisational boundaries**

Cost drivers which cross organisational boundaries should be collaboratively addressed. Cost management of new technologies should be the responsibility of all stakeholders – from suppliers to customers. Discussions across boundaries can be evaluated using knowledge from previous in house methods or other inter-operational practices. This evaluation will capture changes which can influence design and technology decisions down the supply chains that influence cost. Cost management should be extended to suppliers and other partners, enabling cost reductions to occur in the concept and development stage [67]. Value chain analysis can be used to identify these cost driver activities.

Expanding decision systems to all stakeholders can develop best practice and to turn qualitative insights and uncertain data into useful knowledge [48]. Uncertainty can be influenced by the quality of the information right across a network: it is therefore beneficial to exploit a range of perspectives to formulate solutions and develop tools [59].

To inform decision making in a meaningful way, the new framework will need to demonstrate the value of each option, it will need to combine data and knowledge with expert judgement from a range of stakeholders whilst managing uncertainties.

An overview of cost engineering literature offers good practices relevant to the development of the proposed framework:

1. Definitions of cost and value should be agreed [59].
2. Data should be classified and centrally stored to ensure that information is current and to enable knowledge sharing, sensitivity analysis and updating to occur [3], [47], [52], [68], [69].
3. Uncertainty and change is inherent in data from research and development environments. Methods to capture, represent and manage this are vital [30], [53], [70]–[72].
4. Choices of cost estimation method depend on the level of detail available [3], [29], [30].

5. Feedback loops facilitate model learning so data remains current and non-experts are able to use experts' knowledge to better inform their decisions [69], [73].
6. Stakeholder thinking and knowledge elicitation techniques reduce the likelihood of bias disrupting the accuracy of the data [74],[75].
7. Effective cost management systems should be aligned with the current governance [26], [52].

No existing study has addressed the requirement of a holistic approach to value-focused decision making which can span the full lifecycle of applied manufacturing research and development and represent the uncertainty, overcoming complex data issues. Several previous studies have noted that there is a lack of research which addresses the impact of uncertainties on cost estimation [2], [3] and the correlations between variables with uncertainties [7], [76].

2.2 Beyond cost engineering

To inform *value-focused decision making* in a meaningful way, a new framework will need to demonstrate the value of each option across *multiple criteria*, taking account of the preferences of *multiple stakeholders*, and accounting for *uncertainties* resulting from the integration of data with knowledge captured from experts. This section provides background information related to these themes, in the context of manufacturing R&D decision making.

2.2.1 Value-focused decision making

Value-focused decision making should incorporate the relationship between data, information, knowledge and decision making. Figure 2-3 depicts a way of dividing the elements of knowledge into: knowledge process – the understanding of information by an individual; and knowledge element – the information aspect. Information is also broken down into formal and informal elements. By representing decision elements in this way, knowledge management systems can be better developed to represent the differences between each element and enable more effective capture, storage and re-use of knowledge [77].

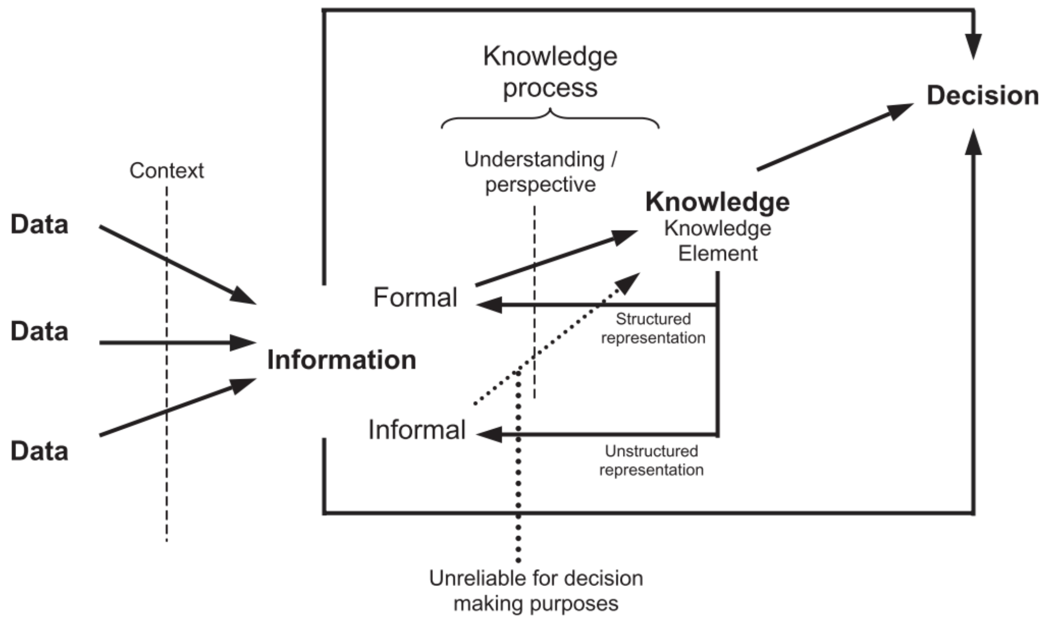


Figure 2-3 - Information in the context of decision making [77]

The types of knowledge that are required for value based decisions are described in Table 2-2.

Variable	Type	Example	Processing requirements
Cost estimates	Quantitative	Time Cost rates Resource requirements Depreciation Fixed and variable costs	Causal relationships Uncertainty Units
Capability	Quantitative & Qualitative	Performance data Environmental data	
Expert opinion	Qualitative	Lessons learned Estimates	Expert elicitation Bias Uncertainty

Table 2-2- Knowledge requirements for the value-focussed decision framework

Models that map the causal relationships between variables are useful when making decisions. This is the case in both risk and value analysis with consequences determining which field they reside [78], [79].

The cyclic process in Figure 2-4 presents considerations from the field of value-focussed decision theory [77]; in this framework, the need to continuously readdress a decision and adjust those decisions which have been affected by new information.

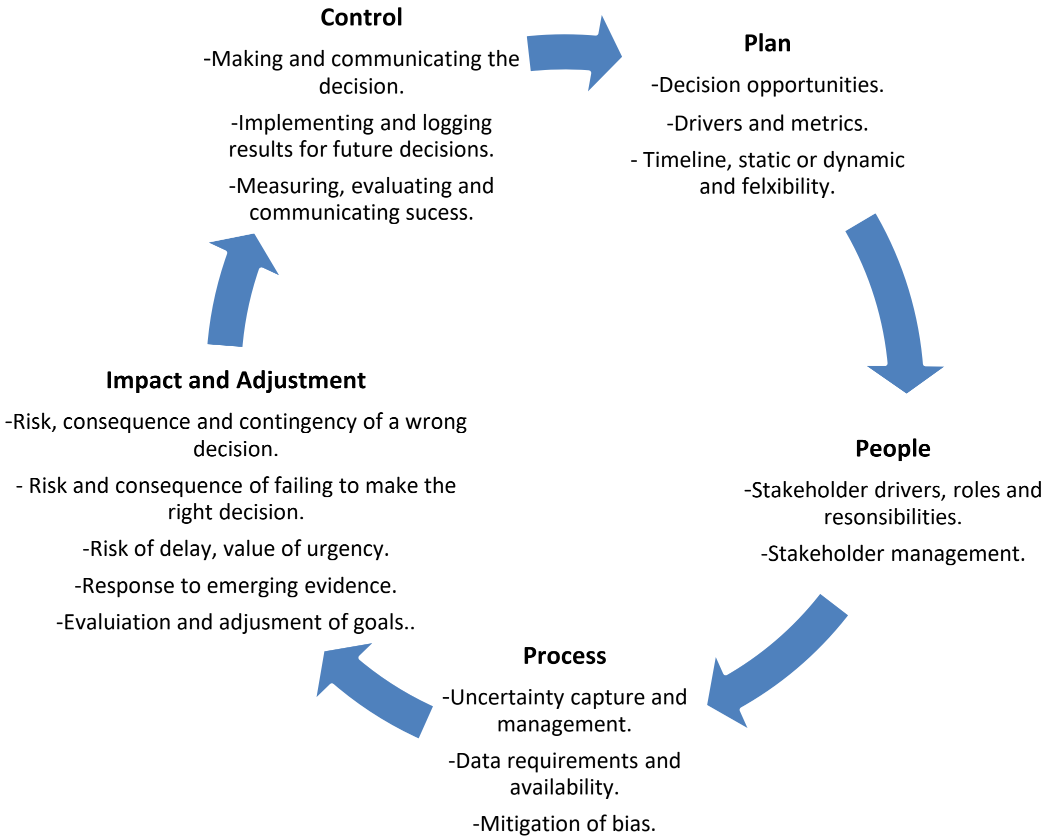


Figure 2-4 - The decision making cycle (developed from [77]**)**

2.2.2 Multiple criteria decision making

With value-focused decision making, the decision opportunities evolve from the requirements and drivers of the stakeholders [80]. In the context of this thesis, the potential costs and benefits must be identified to enable an informed trade-off between alternative opportunities.

One approach to handling the variety of costs and benefits is to aggregate them into some form of utility. Using this model, decisions can be made using expected utility theory, (Equation 2-1). In this theory there are a finite number of possible decisions (d_1, *d2*...), a number of uncertain events (θ_1, θ_2......), and associated probabilities $P(\theta_1, \theta_2 \dots \dots)$. Utilities $u(d_i, \theta)$ are assigned to consequences (d_i, θ_j). The decision maker then chooses the decision with the maximum expected utility $\bar{u}$ for a number (n) of events.

$$\bar{u}\,(d_i) = \sigma(n, j = 1)u(d_i, \theta_j)P(\theta_j)$$

Equation 2-1

Expected utility theory dominated the academic world of decision making for many years until this was challenged. In the presence of deep uncertainty, the probabilities of events aren't well specified and so it is hard to calculate an expected value. An alternative theory called prospect theory, which argues that people make decisions based on the potential value of individual losses and gains rather than the net outcome [81].

In prospect theory, value is assigned to gains and losses rather than final assets and decision framing affects people's preferences. A decision maker builds a representation of activities, possibilities and outcomes relevant to the decision and in then evaluates the value of each prospect and chooses between them.

There are many widely used decision making methods that use a combination of these concepts, such as multi attribute utility theory, analytical hierarchy process, fuzzy theory, case-based-reasoning and data envelopment analysis [82],[38], [83]–[86]. Each method aims to provide the decision maker with a process that will identify the solution that provides the best value. Utility approaches require preferences to be elicited before the set of solutions are known (so-called 'a priori' approaches). But where this is difficult to achieve, preferences are elicited at the end (after the performance of different options has been shown) – so-called 'a posteriori' approaches – where preferences are elicited during the search for solutions. In the context of this thesis, an a posteriori approach will be used. The decision process already exists in the form of a business plan template, and to support effective decision making, it is appropriate to create decision framing, to deliver a set of values and consequences with a level of confidence (probability) without assigning a utility but to demonstrate the impact of each choice in terms of cross functional drivers. This would demonstrate to all stakeholders the impact of decision opportunities.

2.2.3 **Uncertainty in valuation**

2.2.3.1 **Sources of uncertainty**

A level of confidence must be included in the framework to enhance expert opinion when subjective judgments are made in uncertain situations. Information can be taken from existing databases or collected via interviews. Qualitative research literature gives insight into the most appropriate theories and methods to elicit and analyse the expert knowledge whilst including methods to reduce the impact of bias [87]. Semi-structured interviews provide a reliable method in this type of application [88]. The way in which a question is asked when eliciting the uncertainty surrounding an estimate can also generate different responses. Asking specific questions for epistemic (knowledge) uncertainty and aleatory (natural) uncertainty can alleviate this effect [89].

The requirement for single versus multiple experts depends on the problem. Some methods can be performed with one expert but will not easily provide a level of uncertainty [90]. Using multiple experts will automatically provide this level of uncertainty. This does mean that the responses from multiple experts must be synthesised. For single expert elicitation, face to face elicitation is recommended, and a feedback cycle is used to validate the responses [91], [92]. Choosing an elicitation technique that centres on data that the expert has the highest confidence in is preferred [93].

A range of elicitation methods are available. Probability, frequency, quantity or weighting/rank methods should be selected depending on the model requirements and the confidence in the expert to provide a meaningful value [94]. It is possible to frame a question for example instead of a probability into a frequency statement, e.g. out of n number of parts, how many (i.e. x) do you expect to have non-conformance? The uncertainty in this estimate can then be represented probabilistically using a binomial distribution. The probability can then be communicated in the feedback phase. Weighting / rank methods are recommended when interpretability is an issue [95].

Indirect elicitations can be converted into probability distribution representations of prior beliefs (usually referred to simply as 'priors') in ways such as [95]:

- **Frequency –** converted to proportion for each expert so mean and standard deviations can be used to form a prior.
- **Weighting/rank –** a median is taken from expert rankings and interquartile ranges are used as the prior.
- **Category –** categories are converted to numbers by selecting the *median* of each category's quantifiable interpretation made by experts. The *mean* and *standard deviation* are then calculated across all experts to form a prior.
- **Relative measure –**responses from experts are converted into a numeric value(increase *+1* etc.) *mean* and *standard deviation* are then calculated across all experts to form a prior.

The different mechanisms of bias in decision making have been described as optimism bias (event based), over confidence (judgement), self-serving bias (own actions) and wishful thinking. In the presence of cost related decisions, event based optimism bias is the only problematic form of bias which needs to be addressed [96]. By carefully managing elicited knowledge there are ways in which the impact of bias can be reduced [93]. The recommended process for improving efficacy of elicitation of expert opinion is shown in Table 2-3Table 2-3. The structure of the elicitation plays an important role in mitigating many of the issues when attempting to acquire the most relevant information from the most relevant expert [97]. The consensus among practitioners is that providing feedback can help to alleviate many issues with opinion bias from a group of experts, offering an opportunity to revise original estimates [97]–[99]. In terms of bias from the researcher, systematic reviews [100] are advised.

Issues	**Interpretation**	**Possible solution**
Overconfidence	Overestimating the accuracy of beliefs or underestimating the uncertainty in a process.	Incorporating a feedback mechanism to enable revisions to be made.
Conservatism	The process of an expert understating their belief	
Representativeness	Opinions based on situations assumed to be similar	
Availability	Basing a response on current information not on past events	Consider the resources available - time and money to collect data and carry out elicitation. Availability of experts. Create a modelling

<table>
<tr><td></td><td></td><td>framework. Identify the data and how it will be structured into the Bayesian model.</td></tr>
<tr><td>Anchoring and adjustment</td><td>Groups tend to anchor around (any) initial estimates and adjust their final estimate to this irrespective of its accuracy</td><td>Elicit the uncertainty around responses.
For multiple experts, synthesize their responses</td></tr>
<tr><td>Misunderstanding of conditional probabilities</td><td>Confusion of the definition of conditional probability and misuse of the methodology</td><td rowspan="2">Design the elicitation technique around the available expert(s) and their understanding of statistical techniques.
Structuring the elicitation to enable information from experts to be translated into prior probabilities and distributions for use in the model.</td></tr>
<tr><td>Translation</td><td>Confusion in the translation of a response to alternative scale</td></tr>
<tr><td>Affect</td><td>Experts emotions entering into the judgment making</td><td rowspan="3">Structure a sensitivity analysis to examine the impact of priors. Where empirical data are available, running the models with and without the influence of informative prior information can aid this.</td></tr>
<tr><td>Hindsight bias</td><td>Expert places too much emphasis on past events and outcomes</td></tr>
<tr><td>Law of small numbers</td><td>Experts generalise their opinion from small pieces of information</td></tr>
<tr><td>Linguistic uncertainty</td><td>Misunderstanding the question and / or applying different interpretations to the same term</td><td>Clearly articulate the research question to design the study, collect data and provide the model structure.</td></tr>
</table>

Table 2-3 - Bias in expert elicitation [93]

Explicit data such as capital expenditure and historical data is taken from project reports and databases at the facility at relevant stages in existing governance such as trade studies, gate reviews [101] and road mapping sessions (a time-based strategic management diagram which links commercial and technological viewpoints) [16], [102].

2.2.3.2 **Accounting for uncertainty**

Uncertainty is complex and does not necessarily result from a lack of knowledge – it can also occur in situations with a lot of available information [70]. The many examples of data uncertainty categories include:

1. Reliability (precision, credibility, uncertainty of the information);
2. Completeness (gaps, inconsistencies);
3. Accessibility (availability, access restrictions, communication, format);
4. Relevance (usefulness for decision making);

5. Representativeness (boundary issues, quantification);
6. Repeatability (variation due to learning curves, consistency and ability to reproduce data collection methods) [103].

The level of uncertainty in research and development environments is the major source of risk and causes the most complications in terms of developing a robust decision system, so a way to manage this uncertainty is critical [3], [7], [59], [103]. Ward and Chapman [104] describe the need to understand the origins of the many sources of uncertainty before trying to manage them so that bias is reduced.

There are a number of approaches for handling uncertainties in manufacturing knowledge. There are simulation based approaches which tend to be for explanatory rather than predictive analyses [105], so these fall outside of the scope of this research. The most common approaches used in manufacturing cost modelling are Bayesian methods, Artificial Neural Networks (ANN), and Fuzzy systems. Bayesian probability theory and specifically Bayesian Networks (BNs) are particularly useful for handling the uncertainties that have been described [106], [107]. A major advantage of BN over alternative methods such as neural networks is their ability to represent the data in a transparent and visually interpretable way. Artificial Neural Networks generally form a 'black-box' which inhibits the interpretation of cause and effect relationships [108]–[111].

ANNs are computational models which map input-output relationships from a set of given patterns. They are trained to understand causal relationships and so can be used to form predictions for environments where there is uncertainty [112]; ANNs are widely used in cost modelling communities due to their ability to model nonlinear cost estimation relationships [113].

The ANN, however, needs a large data source for training and so are unsuitable for situations which include novelty or innovation [23]. As this research concerns situations with little or no existing data, these systems do not generally provide a solution to the problem. However where existing data is available, for example where the novel technologies are developments of existing systems then Monte-Carlo methods can be used to represent uncertainty. Input parameter distributions can be assumed or derived from existing data, next randomly generated parameter values are created for each distribution. Each combination of values can then be used in the ANN model as training data [114].

White-box models (such as BN) are derived from prior understanding, which makes them easier to interpret (the network structure provides valuable information about conditional dependence between the variables in an intuitive way). ANNs always have to learn from scratch – they do not have a capability of providing insight into the characteristics of the data [115]. A Bayesian network uses a probability distribution, whereas a neural network uses mapping between a set of input values and a set of output values. Bayesian methods are grounded in a robust mathematical theory that is capable of managing the model complexity in the data structure [116]. ANNs have the advantage that the underlying distributions of life cycle data do not need to be assumed prior to running the model [2], [25].

Fuzzy inference systems use fuzzy set theory to map inputs to outputs, they are an approximate reasoning method where the characteristics of the variables are represented by vague sets [117]. They are useful for representing vague or fuzzy data for use in decision systems [29]. Fuzzy theory can be considered as an extension to BN [118] [119], and has a similar advantage to BN in that the solution to the problem can be communicated in terms that operators can understand.

To better describe how the fuzzy systems represent uncertainty, a toy example is provided. The two input parameters for this example are Sump Life and Changeover Time, and the output parameter is Cost of changeover. A well-established fuzzy inference engine Mamdani is used in this example. A detailed description of this approach can be found in [120]. The process involves a number of steps. First a decision table is created which describes the fuzzy rules which are the relationships between input and output variables (see Table 2-4). Next the inputs are fuzzified using membership functions, which categorise the variables using terms such as long, medium, high and estimate the degree of membership for each category (see Figure 2-5). The fuzzy inference engine then combines the functions using the fuzzy rules to estimate the rule strength for each decision scenario based on either crisp or uncertain data inputs (in this case both inputs are uncertain to reflect the research). The consequence of the rule is obtained by combining the rule strength with each output membership function. These consequences are finally combined to create an output distribution which reflects the uncertainty over all input combinations to the output variable (see Figure 2-6).

If	And	Then
Sump life	Changeover time	Cost of changeover
Long	High	High
Long	Low	Medium
Short	High	Medium
Short	Low	Low

Table 2-4-Fuzzy decision rules

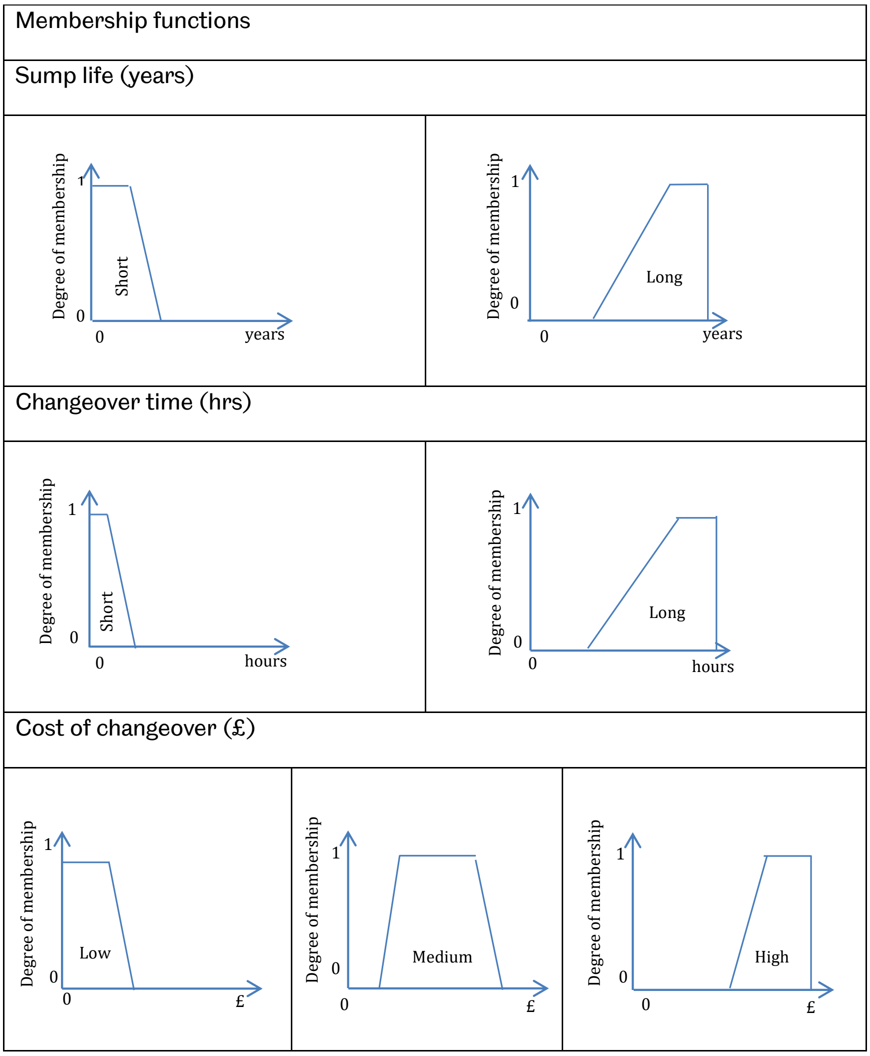


Figure 2-5 - Membership functions including degree of membership for Input and output variables

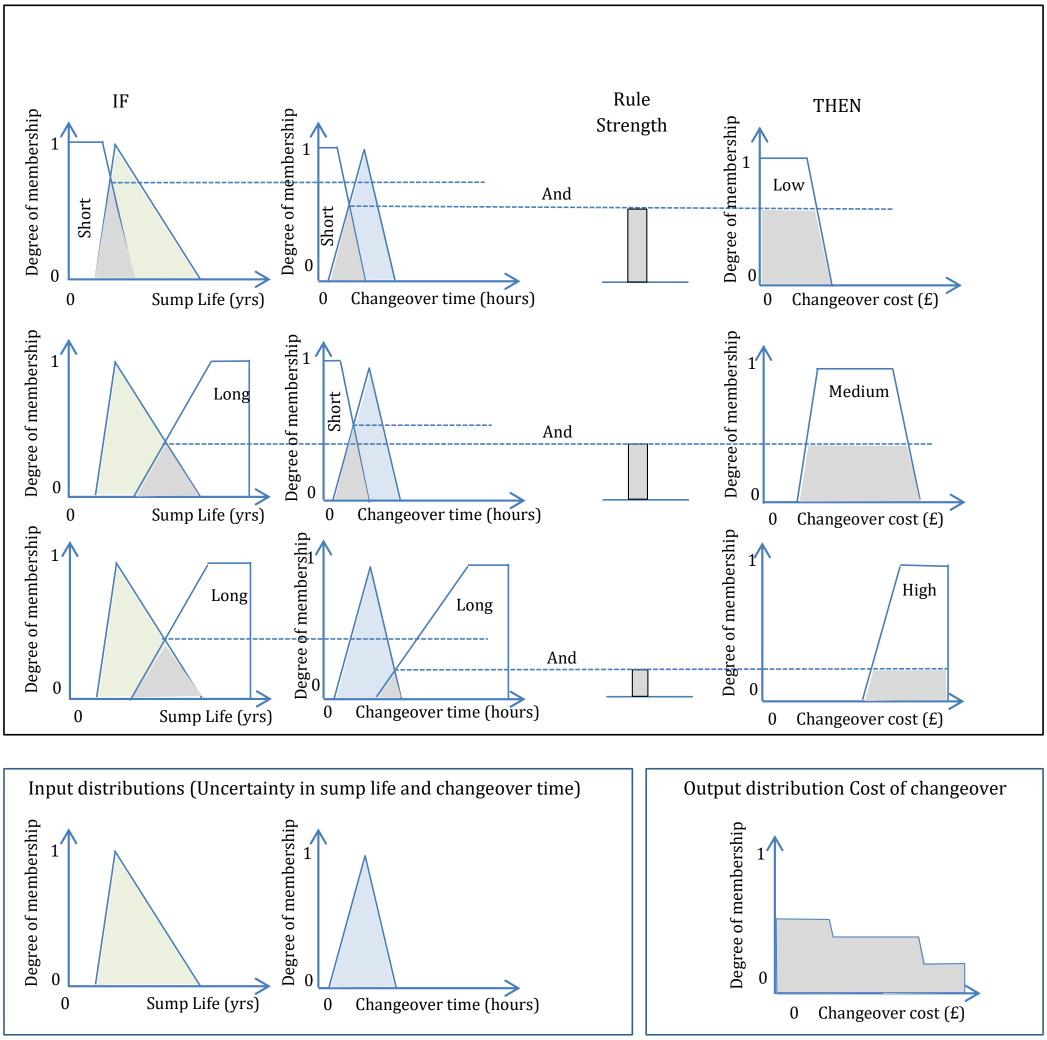


Figure 2-6 - Using Fuzzy (Mamdani) inference system to determine cost distribution with uncertainty

Although the fuzzy based system is capable of representing uncertainty in data the capability for many types of reasoning (predictive, diagnostic and adductive) with BNs is based on a robust representation of the processes involved, as opposed to the basis of relationships between data, and provides a model with a higher level of confidence than fuzzy systems [108].

Advantages of BN over alternative methods have been listed as: "the suitability for small and incomplete data sets, the possibility of structural learning and combining of different sources of knowledge, the explicit treatment of uncertainty and decision support"[107]. The Bayesian framework can offer many advantages over alternative modelling approaches according to [121]. These include the decision support capability enabling the maximisation of the expected utility and the consistency of model output enabled by the functions inside the model and changes can be made 'smoothly' as small alterations do not significantly affect the model. The flexibility is also an advantage in the sense that BN can be used for both predictive and explorative data mining applications. Finally the improved clarity in the representation of data and ability to represent the knowledge alongside an estimate of confidence (or importance) of the prior information is a major advantage of BN in terms of transparent decision making. Uncertainty in the prior beliefs and data must be handled consistently and be updated as soon as new evidence appears. In a fuzzy system further 'imprecise observations' are represented by pairs of jointly possible input or output variables with a combined "guaranteed possibility" distribution [119]. Bayes theorem provides a rigorous and mathematically sound mechanism for representing the process of incremental knowledge – after an event is observed posterior probabilities are updated (given new evidence) using Bayes Theorem [78], [122]

Using the same example as the fuzzy example above an example of how a Bayesian Network can incorporate uncertain data is described. The sump life and changeover times are parent nodes and can be represented as probability density functions to account for uncertainties (e.g. $Normal\ (\mu, \sigma), Exp\ (\lambda), Beta\ (\alpha, \beta), Gamma\ (\alpha, \beta))$ (see Figure 2-7 and Figure 2-8). The node probability table for cost of changeover is represented as a mathematical expression. This is an important difference compared to the fuzzy approach. Cost engineering generally lends itself well to precise equations. (see Figure 2-9), where the labour cost rate is $50£/hr$, cost of fluid is $£10/L$ and sump size is $3000L$ and are represented as constant values in this example. Any distribution and/or mathematical relationship can be mapped according to the situation. Bayes theorem is then used to propagate the model (see Figure 2-10). A further benefit is the ability to do both forward and backward Bayesian inference. This is useful for questions such as "if I knew sump life was x, then what would that imply for my uncertainty over cost?" and "if I observed that cost was y, then how uncertain am I now about sump life?"

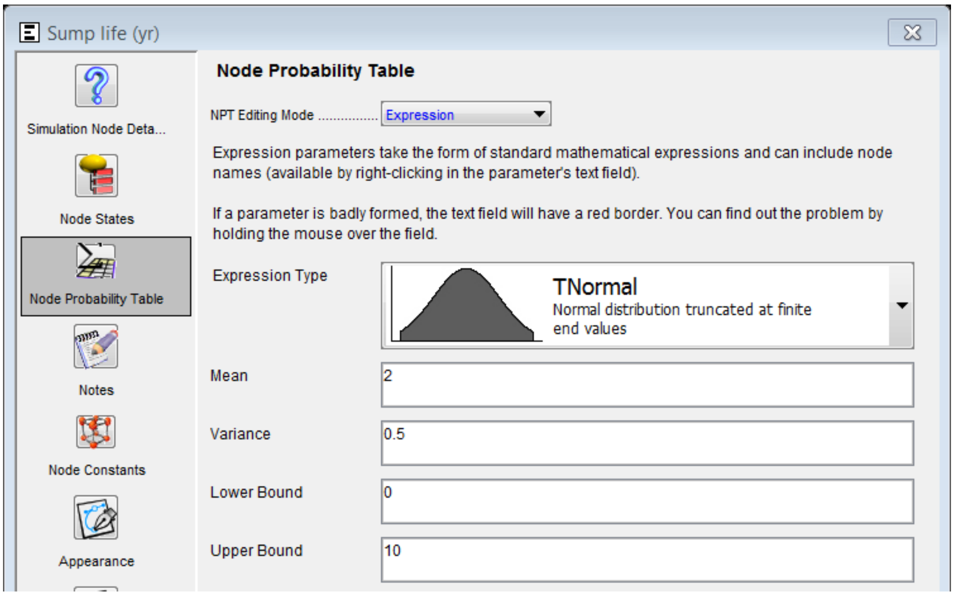


Figure 2-7 - Node probability table for Sump life

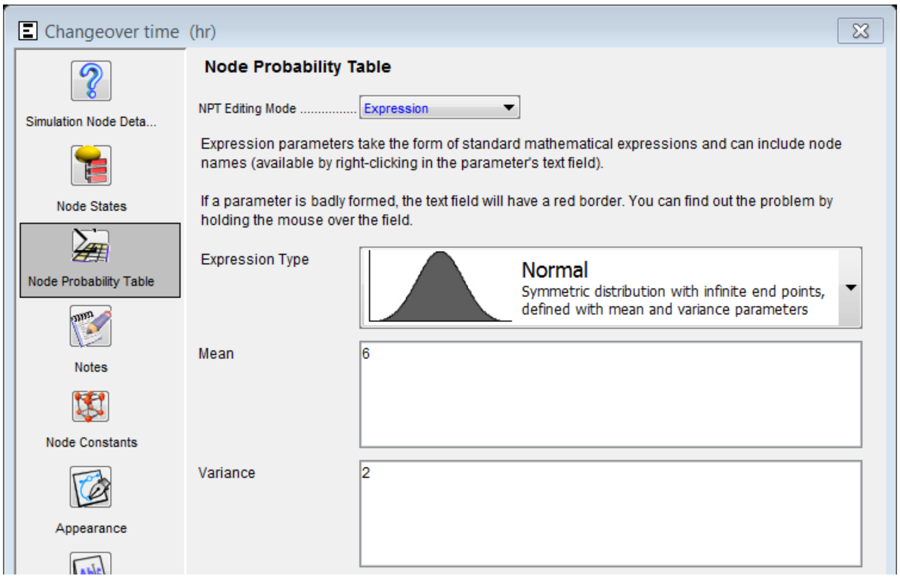


Figure 2-8 - Node probability table for Changeover time

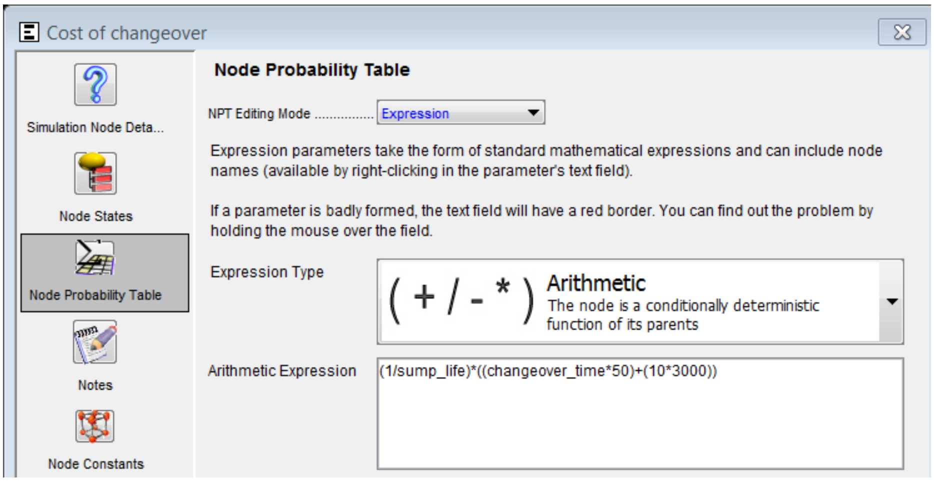


Figure 2-9 - Node probability table for Cost of changeover

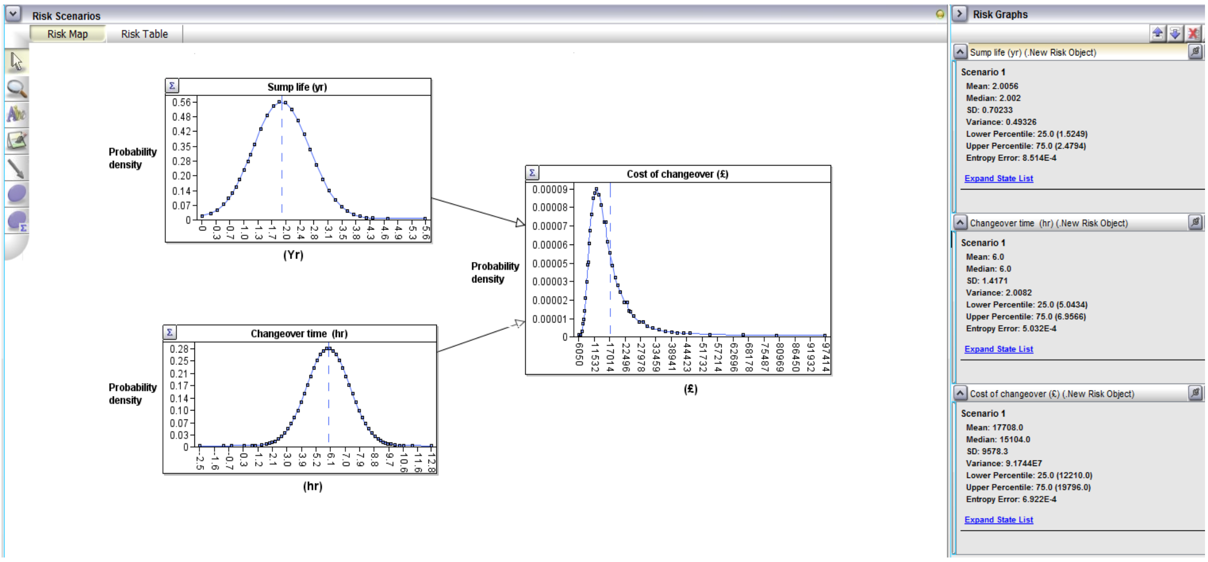


Figure 2-10 - Bayesian Network model for Cost of changeover

No evidence has been found of the use of BN for cost related decision making in this particular environment. The method provides a way to model the complex relationships in data in a transparent way, manage uncertainties in information and provide a way to represent output data with a level of confidence, and so will be used in this research.

2.2.4 **Multiple stakeholders**

Requirements for knowledge management and elicitation techniques are instrumental in the design of a successful of framework such as the one discussed. Knowledge can reside across internal and external boundaries and with multiple stakeholders. An appreciation of the range of stakeholders holding this knowledge and influencing and driving the industrial requirements is essential for improved decision making and will be an essential part of the framework.

An appreciation of the range of stakeholders at the AMRC, demonstrates the level of interest and influence across organisational boundaries (see Figure 2.13). A stakeholder analysis matrix such as this can be used to map and manage each stakeholder's level of support and influence across technology development [123].

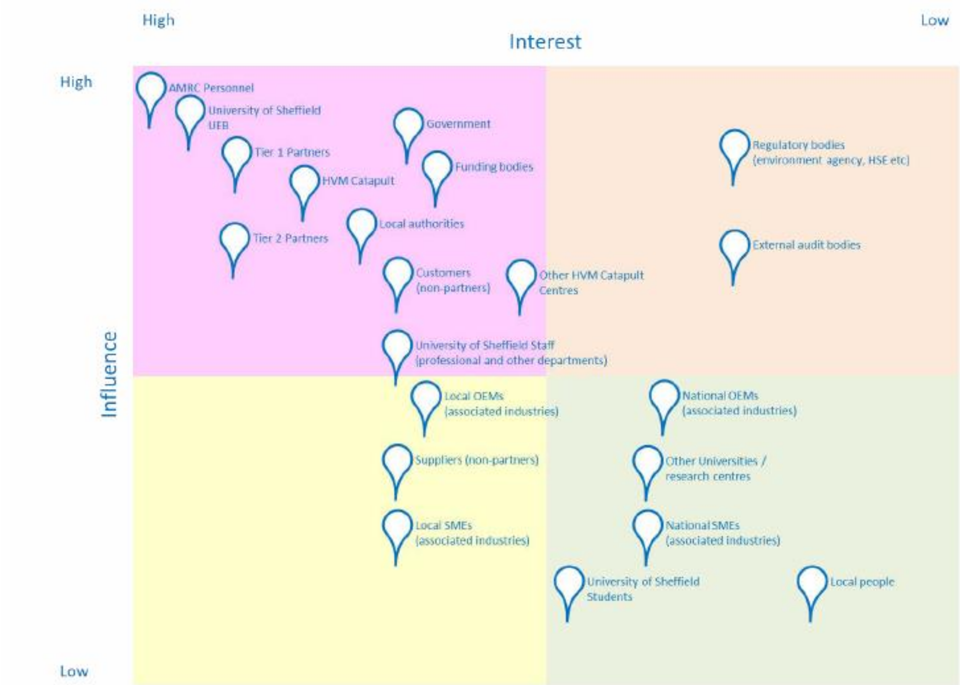


Figure 2-11 - AMRC stakeholder analysis matrix [Internal AMRC business planning handbook]

In the context of this research there are a range of stakeholders who may have drivers that reflect either of the positions of utility or prospect theory described in Section 2.4.2; for example the manufacturing engineer and the global environmental manager for a large OEM. For these individuals the trade-off between high risk and financial gain will be different as their drivers, influence and expertise may vary significantly and in certain sectors the strategic product development cycles may be many years as opposed to the shorter production cycles in manufacturing and this may affect decision making behaviour.

The classical definition of a stakeholder in an organisation has been described as "any group or individual who can affect or is affected by the achievement of the organization's objectives" [124]. The stakeholders not only influence decisions but in many cases provide the knowledge that is required to make those decisions. Three perspectives of stakeholder theory have been classified as instrumental, descriptive and normative views. The first assigns a value to each stakeholder which is strategically biased towards the needs of the organisation and involves methods such as risk management and the drive for identification of opportunities. The second describes and classifies each stakeholder but does not assign a value to the individual. The normative perspective aims to balance the rights and concerns of all stakeholders [125].

The theory most relevant to this context is the normative approach. The stakeholders include staff, customers, industrial partners, suppliers and funding bodies which cross both internal and external boundaries. The level of interest and influence from each stakeholder will vary throughout the development phases but the balanced, normative approach offers the best overall method of stakeholder management.

Stakeholder analysis can be used to determine the level of interest and influences; views and expectations of all stakeholders as well as determining where the most valuable knowledge resides. This information is captured within a gated project-review process [6] in centres like the one described.

At the AMRC the project management gate review procedure helps ensure that the multiple stakeholders within a particular project are involved in decision making at key intervals. The partnership model described in Section 2.2.2 provides an opportunity for a range of stakeholders to sit on the AMRC board so that strategic decision making at the AMRC is made by representatives from across stakeholder groups. Research collaboration between university departments and other universities encourage wider stakeholder engagement in research direction and opportunities. Road-mapping sessions and technology portfolio events provide an arena for stakeholders to share the results of board generic project and collaboratively set the future direction of research and development (see Chapter 4).

2.3 Cutting fluid cost modelling

This thesis describes the application of this research study to the use of cutting fluids in advanced manufacturing.

Difficulties in the machinability of materials have been addressed over many years by the use of cutting fluids. The increase in use of more difficult to machine materials in advanced manufacturing have attracted heightened interest in more advanced coolant technologies.

There are many commercially available fluids and they are categorised into soluble oils, straight oils, synthetic and non-synthetic oils. The main functions of the cutting fluid are lubrication, cooling, corrosion protection, and chip flushing during machining operations. This can result in less wear on cutting tools, the use of higher speeds and feeds, improved surface finish, reduced power consumption, and improved control of dimensional accuracy [126]. However the costs involved with the use of cutting fluids in machining has been estimated to be 7-20% of the total cost of the machining process [127], [128] and sometimes double the tool-related costs [129], as well as causing undesirable health and safety and environmental problems.

The elimination or reduction in the use of these fluids is attracting heightened interest and the development of technologies to enable this trend is extensive [130] [127], [131], [132]. Cryogenics, dry machining, and minimum quantity lubrication (MQL) are being developed to reduce or eliminate the use of conventional cutting fluids, but due to difficulties in machining materials required for the aerospace industry their use is limited [133]. There is therefore a requirement for industries to gain a better understanding of the cost and impact of conventional cutting fluids use so that changes to their operation and management can be directed to those parameters that have the greatest impact on overall machining cost, while emergent technologies are being established.

A better understanding of the cost drivers and sensitivities of cutting fluid parameters in current production processes could not only provide a benchmark to build business cases for technology investment but also improve operational decisions in terms of cutting fluid use and management according to a range of stakeholders interviewed during the course of this research (described in Chapters 2, 5 and 6).

Coolant suppliers and manufacturing personnel have stated that cutting fluid variables are typically captured under maintenance and consumable costs, and performance improvements such as increased feeds and speeds and tool life are often combined with other process improvements that can be affected by a number of parameters. A cost/benefit model which can offer an overview of the total cost of cutting fluid use in a manufacturing process could therefore support strategic decision making.

It is well known that in production environments there are uncertainties over the multiple causes of tool wear, available cutting feeds and speeds and non-conformance. It is difficult to determine the root cause of problems and often a combination of factors is at play. Coolant use, and effective management in terms of chemical stability and cleanliness can have positive effects on fluid maintenance and downtime costs, tool life, surface finish, operator health and safety and hazardous waste disposal [134].

2.3.1 **Cutting fluids**

Cutting fluid consists of a range of ingredients in quantities specifically selected for the machining requirements and environment that the machining takes place (see Table 2-5).

Emulsifiers	• Fatty acid soaps • Surface active agents
Lubricity additives	• Mineral oil • Esters • Antiwear additives • Glycol based polymers
Bio protection	• Boric acid • Biocides • Amines
Rust inhibitors	• Carboxylic acid amine salts • Fatty amides
Coupling agents	• Water • Glycols

Table 2-5 -Constituents of cutting fluid

It is widely accepted that cutting fluid technologies have provided cost saving opportunities related to cooling and lubrication. They have simultaneously shown to improve the overall performance of machining processes [131].

Issues with their use in machining have, however, raised environmental, health, economic, and safety concerns. The chemicals used in coolant formulations and their management raises significant environmental complications in terms of handling and hazardous waste disposal as well as health complications caused by dermal interactions and inhalation [134]–[137].

When cutting fluids are used they are contaminated with microorganisms, a build-up of metal particles and tramp oil (hydraulic oil which has come from other mechanisms and mixed with the coolant). The contamination reduces their effectiveness [136], [138]. When levels of bacterial growth and/or pH levels remain consistently outside agreed limits the fluid must be recycled or disposed.

The contaminants which need to be removed in order to recycle the coolant are [139]:

- Lubricants and process oils (tramp oils);
- Materials from fines and swarf – these can be centrifugally removed from the oil, drained, washed (unless cryogenic machining) then compacted for transportation;
- Dissolved water constituents;
- Bacteria and fungi;
- Dissolved gases;
- Fluids deposited by material from previous processing.

Other foreign matter can also be introduced into the coolant, such as cleaners, concrete dust, food scraps, paper, cigarettes, etc. Costs involved in recycling the fluid are the coolant management costs, filtration, and separation and chip management.

A range of in-process recycling technologies have been created to remove tramp oil and metal chips and bacteria from the coolant to increase sump life [140]. Tramp oil skimmers are widely used in high-value manufacturing but are limited in that they will only remove the tramp oil which is on the surface and not that in suspension within the coolant sump tank. These are often used with paper media and cartridge systems; however the consumable media used in these systems contribute to more hazardous waste disposal. Centrifuge systems can remove finer particulate but may need significant maintenance due to the wear from the abrasive fines. Membrane filters can remove tramp oil fines and bacteria but can deplete fluid constituents and are more often used for pre-disposal treatment. There are recent developments in hydro-cyclone systems that can remove tramp oil and contaminants down to less than 10 microns, stabilise the chemistry, prolong sump life and deliver the clean coolant back to the cut.

The trigger for a coolant change could be a costly occurrence of quality related non-conformance so regular maintenance is required for cutting fluids in order to control their performance-enhancing qualities. The sump environment in which they operate is ideal for the growth of bacteria and fungi unless chemical stability is controlled.

Chemical stability is affected by: metal and oil contamination; bacterial growth; changes in fluid concentration due to fluid management; water evaporation and misting and losses due to leaks and where fluid is removed on components and swarf. Microbial growth can split the emulsion, and qualities such as corrosion protection and lubricity can be significantly affected. Over time selective depletion of additives has a negative effect on operational performance. Part and machine corrosion can occur, lubricity is reduced which affects cutting parameters and tool wear, foaming occurs and bad odours are omitted due to the bacterial growth. More expensive cutting fluid technologies provide the means to inhibit this depletion [139]. The pH level is also affected which increase the risk of corrosion on the machine tool and workpiece as well as creating health and safety implications for the operator. Common effects of chemical instability are given in Table 2-6.

When concentration is too high	**When concentration is too low**
Skin and respiratory irritation risks increase Foaming increases Usage cost increases	Bacterial contamination increases Increased risk of corrosion Poor cutting performance Short sump life High cost of disposal

Table 2-6 - The effect of chemical instability of cutting fluids

Treatment is required when problems are identified; these are listed in Table 2-7.

Problem	**Treatment**
Bacteria	Biocide
Odour	Acticide
Fungal Infections	Acticide
Foaming	Anti-Foam Agent
Corrosion	Inhibitor
Low pH	Additive

Table 2-7 - Cutting fluid treatments

Testing is carried out periodically to ensure that the chemistry of the fluid remains acceptable [141]. Bacteria and fungi are measured with a dip slide to assess the pH level of the fluid, as they produce acids which reduce the emulsion pH. Concentration is tested with a refractometer. These interventions have implications in terms of additional labour costs.

There is legislation in place to reduce the impact on the operator while using cutting fluids. The Health and Safety Executive's *Guide to Metalworking Fluids* gives a detailed description of these regulations [142]. This additional documentation, procedures, training, and consumables such as personal protective equipment (PPE) will affect the cost. Most modern machines have extraction systems fitted as standard which will remove the mist. However this de-misting time will add cost to the process.

There are many different methods of fluid delivery, as described Kuram et al. [130]. These are flood; micro-flood; high pressure jet assisted machining (HPJM); Minimum Quantity Lubrication (MQL); cryogenic; cryogenic with MQL and CO_2 with MQL. The use of the more recent technologies such as near dry, minimum quantity and cryogenic machining have evolved to address the volume of lubricants used in more traditional techniques. There are many authors researching these technologies [127], [131], [132], [143]–[145] and the potential for reduction of fluid use and environmental benefits are clearly stated.

2.3.2 **Cutting fluid cost analysis**

Research has shown that companies lack accurate cutting fluid cost information though a wide range of cutting fluid costs have been reported over the years [131], [135]. Each estimate appears to be based on differing granularity of production related parameters and is motivated by different drivers such as comparison between cutting fluid formulations, different delivery mechanisms or environmental and health and safety concerns. A selection of the more extensive models have been studied to understand which cost elements could be used in the cost model proposed in this chapter and to compare and contrast results to support model validation.

The impact of cutting fluid decisions for three key performance indicators (KPIs): total cost of production, system cost sensitivity and system cost inefficiency related to cost per unit volume removed are studied by Hubbard et al. [146]. The authors built a model with cost and performance parameters and performed local sensitivity analysis on each parameter against the cost per unit volume removed. The results show that to have the most significant effect on the total cost of production, the cutting fluid must reduce cost associated with machining time and tool wear. To have a significant effect on system inefficiencies, the fluid maintenance and disposal costs must be reduced. The direct coolant cost and its relationship to cost per unit volume removed (C_{PUVR}) by the machine is shown in Equation 3.1 and Equation 3.2.

$$\boldsymbol{C_{PUVR} = \frac{C_m + C_{MT} + C_{DT} + C_{po} + C_{tf}}{\sum_{i=1}^{n_t} T_{mi} M_{rri}}}$$

Equation 2-2

$$\boldsymbol{C_{tf} = (\sum_{i=1}^{n_t} T_{mi} P_{mi}) \frac{C_p}{60} + C_f T_f + C_w T_w + C_{mf} + C_d T_d}$$

Equation 2-3

Where:

C_{PUVR} = cost per unit volume removed	C_f = coolant costs
C_m = raw material cost	C_p = cost of electrical power
C_d = fluid disposal cost	C_{mf} = fluid maintenance costs
C_{DT} = tool disposal cost	T_d = spent fluid discarded

C_{MT} = material (on) machine time

C_w = water cost

C_{PO} = cost of power required

C_{TF} = direct coolant / lubricant cost

T_w = water required recharge/maintenance

T_{mi} = machining time

M_{rri} = material removal rate

T_f = recharge/maintenance costs

P_{mi} = power required to maintain machine tool efficiency

When the equations were applied to two process specific experiments, the following findings were identified:

1. "The total cost of production is relatively insensitive with respect to changes in fluid and fluid-maintenance costs;
2. The costs associated with tool wear represent relatively large proportion of the system's cost inefficiency;
3. The total cost of production is sensitive with respect to changes in the costs associated with machining time and tool wear, both of which may be affected significantly by coolant/lubricant decisions;
4. For each production volume mix considered here, the more expensive fluid provides the lowest total cost of production"[146].

Local sensitivity analysis assumes very small variations to parameters and looks at variations to each parameter, while fixing the others. As previously highlighted, there are a range of uncertainties in coolant cost parameters and so to manage these, a global sensitivity analysis using stochastic inputs in the model would be required once relationships and dependencies are mapped.

An in depth technology evaluation of the sustainability of conventional, cryogenic, and high pressure jet assisted machining has been carried out by Pusavec et al. [135]. The costs elements considered in their paper are shown in Table 2-8.

Cutting fluid	Cleaning costs	
Usage cost rates	Part	Swarf
Concentration % Cost of fluid Disposal cost Maintenance labour cost Life of fluid	Energy cost Labour cost	Separation cost Compression/preparation cost

Table 2-8 - Cutting fluid cost parameters from [135], [147]

The authors' Case Study referred to the machining of high-temperature Ni-alloy (Inconel 718) [135], [147] . The aim of the study was to compare additional sustainability related cost or benefits of using cryogenics or HPJM over conventional flood coolant machining. Their results show that tooling costs represent a significant fraction of the total production cost, which contradicts previous statements of cutting fluid cost referred to earlier in the paper. The authors explain that this significantly high tooling cost is likely to be due to the hard to machine materials having a significant effect on tool life. The tooling cost was examined, taking into account tool change costs in terms of labour and downtime. Volume usage and disposal costs were estimated, however no detail was given for sump changes and top-up in terms of labour and downtime and inspection requirements as this was out of scope of the paper.

Major infrastructure costs represent a significant portion of cutting fluid costs according to Skerlos [138]. This is interesting as details of fluid delivery, filtration, chillers and coolant farm parameters have been largely overlooked in the other models apart from Winter et al. [148], who include fluid filtration elements.

An activity based cost model to determine machining costs was developed by Narita [132] – this included coolant costs, with the equation reproduced in Equation 3.3. Narita includes top-up requirements due to evaporation and drag out losses in the system; he also considers disposal cost, however does not include the cost and disruption caused by coolant changeovers.

$$Cc = \frac{CUT}{CL} \times \{(CPc + CDc) \times (CC + AC) + WAc \times (AWAQ + WAQ)\}$$

Equation 2-4

Where:

CUT= Coolant usage time NC program [s]

CL= Mean interval of coolant update [s]

CPc= Purchase cost of cutting fluid [£/l]

CDc = Disposal cost of cutting fluid [cost/l]

CC = Initial coolant quantity [l]

AC = Additional quantity of coolant [l]

WAc = water distribution costs [£/l]

WAQ = Initial water quantity [l]

AWAQ: = Additional water quantity [l]

The research also demonstrated the impact of cutting speed on machining cost and shows the cost parameters used to develop the cost model of the machining operation. He considers cutting fluid, lubricant oil production, disposal and dilution as well as chip processing and cutting tool parameters. The study found that coolant requirements will reduce as the cycle time reduces when speeds are increased, an efficiency parameter not previously considered.

A German automotive manufacturing plant was analysed by Brinksmeier et al. [149]. In their model, the coolant costs make up a significant part (16.9%) of the overall machining costs – of those costs, the majority (54.1%) relate to depreciation and waste disposal.

A selection of coolant cost parameters has been identified from these previous research studies; these are summarised in Table 2-9.

Coolant influencing factors	Cutting force Temperature Speed of cut Depth of cut Energy use Tool life Surface integrity Chip formation Sump life
Coolant system	Purchase Maintenance Upgrade/refurbishment/development Set-up/deployment (space allocation, transport, Integration, installation) Operating costs (labour, energy– pump, filtration) Change management costs (training, workflow, process, documentation) Infrastructure (heating, cooling, lighting, extraction) Environmental (legislation adherence) Insurance and security Financing costs Disposal Depreciation
Cutting fluid	Price Coolant mix concentration Volume Inspection, monitoring and treatment Maintenance (labour and consumables) Operational interventions Changeover (labour and consumables) Water (delivery, treatment, storage) Life of coolant Loss (evaporation, mist, chip, tramp oil) Disposal and recycling H&S costs (consumables and time) Environmental costs
Part	Cost to wash, dry and protect from corrosion
Swarf	Cost to collect Cost to wash Cost to recycle

Table 2-9 - Coolant cost parameters identified in literature

2.4 Reflections

The background chapter has been fundamental in establishing the problem context. The industrial research problem is the need for 'improved value-related decision making support for novel technology selection' and delving into the complexities that exist between research and industry enable a more comprehensive appreciation of the challenges involved in providing a solution to RQ1 and RQ2.

Sections 2.3 and 2.4 contribute to O4 by investigating cost engineering and other approaches for handling uncertainty, changing information, and to support value-related decision making. Section 2.4 also contributes to the challenges defined in O1 and the conceptual model introduced in Section 2.6 provides the foundation for the framework in O5.

These findings provide some recommendations for a process required to improve value based decision making:

1. Standardised collection of the variables, drivers and uncertainties in cost-related data for the current system;
2. Collecting available knowledge/evidence on the novel technology from a range of internal and external stakeholders;
3. Establishing the requirements for comparison and justification of existing decision systems such as the business case;
4. Building a model to reflect the interrelationships of the variables;
5. Using the model to analyse a range of likely scenarios together with range of stakeholders;
6. Communicating the results in a way useful for decision making by a range of stakeholders;
7. Developing a means of updating and feedback to occur.

The results of this chapter demonstrate the clear need for a novel framework in value-focused decision making. This framework will be informed by a deeper study with active participation in the research process. The research methodology is presented in Chapter 3, and then a major version of the framework is presented and refined during subsequent chapters.

3 Research methodology

3.1 Situational context

An Engineering Doctorate requires that the researcher carries out the research from within an industrial setting, to solve an industrial problem with academic knowledge and rigour [150].

The context in which this study takes place is complex in a number of ways; not least, the involvement of four parties:

- The Advanced Manufacturing Research Centre - a translational research organisation;
- Rolls-Royce Plc- a major multinational company;
- The University of Sheffield – a research-led university;
- And the researcher.

As previously stated, Rolls-Royce have identified that there are issues surrounding their confidence in selecting the most cost-effective novel technology solutions for use in industry; particularly in terms of the knowledge flow across the two main interfaces of the MCRL phases from fundamental academic research to applied research and from applied research to industrial application. This requirement has been translated into two research questions:

(RQ1) "What is the link between value-related knowledge management and improved technology decision making in environments with significant uncertainty?"

(RQ2) "What mechanism will improve value-related knowledge management to support novel technology selection across MRCL?"

The involvement of multiple stakeholders creates a fluid and uncertain environment for the research project. There are a range of people, priorities, permissions, processes and practices which each interact and affect the flow of knowledge and the ability to use this knowledge for confident decision making.

The careful selection of an appropriate research methodology to capture both quantitative and qualitative knowledge in this complex environment is therefore required. For the purpose of this study, quantitative data will include machine and resource data which has been or can be collected. Qualitative data includes the subjective knowledge of experts in the form of their opinions or beliefs.

3.2 Epistemological and ontological position

Epistemology deals with the philosophical position on the nature of knowledge and what knowledge is acceptable in a field of study. Ontology deals with the philosophical position on the nature of reality or being [87].

To ensure that the research design is aligned with the aims and objectives of the study, a range of philosophical positions were considered. Saunders et al. [87] describe options for formulating the research design using the so-called 'research onion' (see Figure 3.1).

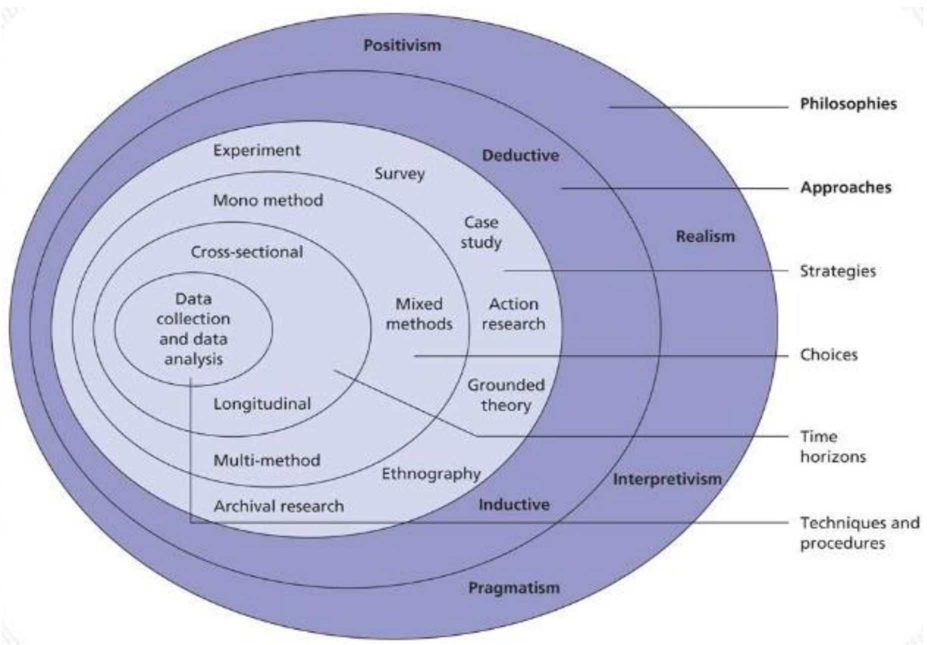


Figure 3-1 - The research onion by Saunders et al. [87]

The four main philosophies described are:

- Positivism – Often adopted by natural scientists. In the positivist position, data is collected from observable reality and knowledge (in the form of universal laws) is generated from the generalisations that are made about the regularities in that data [151] .

- Realism – Similar to positivism, this philosophy adheres to a scientific approach to knowledge generation. In the realist position, objects are considered to exist independently from the human mind and the objects' behaviours can change the researcher's understanding of the objects under study [87]. Realism does not hold that there are universal laws, but that context-specific causal relations can, in principle, be established.
- Interpretivism –This philosophy moves away from a law-like understanding of the research data, towards the notion of knowledge as a subjective concept, gained by learning from interactions between the people under study in their organisational roles [87].
- Pragmatism- This philosophy encourages a more flexible approach to knowledge generation in that " the quality of dealing with a problem in a sensible way that suits the conditions that really exist, rather than following fixed theories, ideas, or rules" [152]. Pragmatism is concerned with the usefulness of knowledge for effective decision-making and prediction, rather than a concern for what is, or what is not, reality.

The Engineering Doctorate lends itself well to the philosophy of pragmatism – the process is driven by the industrial research question, applying a practical approach while drawing on different perspectives to collect and interpret data.

This thesis involves socio-technical research within the context of advanced manufacturing industries. Due to the complex and dynamic environment as well as the need to create a practically useful decision making framework as an outcome of this research, the most appropriate epistemological and ontological position for the researcher is **pragmatism**. The pragmatist view, unlike the others described, does not rely on clear cut judgements and allows for the observation of participants as well a data collection to deal with ambiguity and complex situations. The pragmatist draws on practical experiences to generate knowledge [153]. Both qualitative and quantitative methodologies can therefore be combined [154]. This allows for the tacit and explicit data to be captured providing richer knowledge source thus overcoming the weaknesses of the two approaches if considered separately [18], [155] .

As many stakeholders, processes and drivers are involved it is necessary for the researcher to develop knowledge and progress the research dynamically throughout the study as opposed to having a strict methodological approach in the first instance. Pragmatism allows for dynamism and evaluates the success of the research in terms of its utility or 'practical adequacy' [156] in this case in terms of how useful the final framework is to Rolls-Royce and the AMRC in aiding decision-making at different stages of technology development. The final decision making framework is required to capture, represent, synthesise and use knowledge about processes/components/systems where a decision is needed. In knowledge management systems, knowledge is variously defined which has consequences for the role of knowledge management within organisations (see Table 3-1).

Table 3-1- knowledge definitions, adapted from [157]

Definition	Description	The role of Knowledge Management
Knowledge in the hierarchy of data and information	Knowledge (personalised information) Information (interpreted data) Data (raw numbers/facts)	Expose people to potentially useful information and aid assimilation
State of mind	Knowledge is the state of understanding and knowing information	Expose people to potentially useful information and aid assimilation
Object	Knowledge are objects which can be collected, stored and manipulated	To build and manage the stock of information using gathering and coding techniques
Process	Knowledge is the process of applying expertise	Managing the flow of knowledge from creation to distribution
Access of information	Knowledge is in the form of access to information	Access and retrieval of relevant information
Capability	The building of competencies through knowledge	The development of strategic organisational and staff competencies

The purpose of the framework is primarily to communicate the most useful information required for decision making. So the definition of knowledge used throughout this research is: knowledge in the hierarchy of data and information.

Figure 3-2 depicts how knowledge evolves as the value of information increases from data captured in its raw form to the ability to make an informed decision. All forms of knowledge are present to varying degrees in industrial research centres and the specific requirements for elicitation and management need to be addressed.

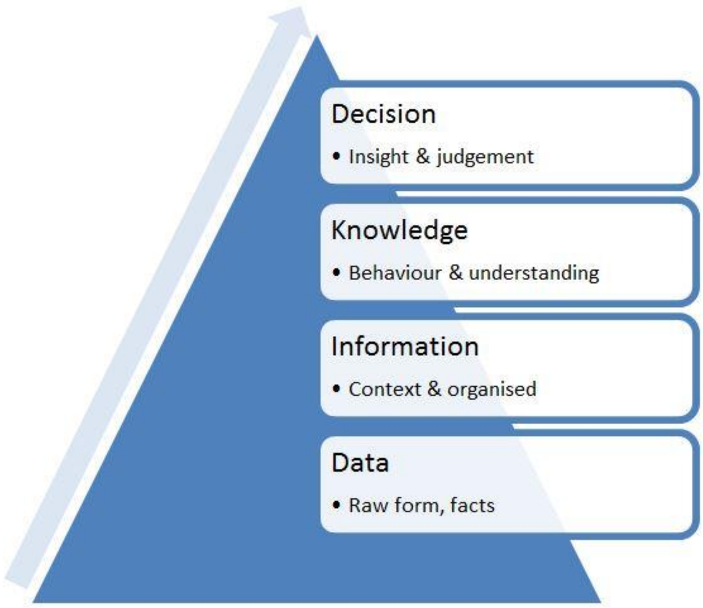


Figure 3-2-Evolving knowledge- adapted from the wisdom hierarchy [158]

The fundamental definition of learning is knowledge acquired through study, experience, or being taught [158]. In the context of this research it refers to the knowledge accumulated through previous research outcomes and experience of stakeholders.

The knowledge at the AMRC is stored in databases, reports and in the minds of experts, and is subject to a range of security restrictions. With this in mind some major risks to the project are in regard to access and ethics. The research design must provide a mechanism to mitigate these risks. A research ethics application was submitted and approved by the relevant university department along with the participant information sheet and consent form prior to the commencement of the case studies (see Appendix A).

Negotiating access to data was initially problematic, particularly with access to expert knowledge. This was perhaps due to suspicions about the justification of the project, perceptions about the researcher, the supervisory team and the student status. The qualitative research field was studied for methods to overcome these issues. As descried by Saunders et al [87], these issues can be mitigated by open, honest and transparent behaviour whilst carefully following work practices. Clearly explaining the research study and how the participant may help, while providing assurances regarding confidentiality and anonymity. Demonstrating respect towards the individual and appreciation of their time and support also improved communication. Ultimately, following this advice resulted in open discussions and respect both ways when obtaining the relevant information. In addition, the researcher tried to create common ground and align motivations. Attending road mapping sessions to better understand particular group drivers and providing evidence that the study will support their vision was beneficial. Active participation in these sessions also improved credibility, along with oral and poster presentations at internal events, and participation in working groups [87]. Identification of the most appropriate expert in terms of knowledge, approachability and availability was vital, so developing a good understanding of group activities was a priority. In terms of availability, adequate time was given to organise interviews and diligently respecting time keeping.

With regard to data sensitivity, a Non-Disclosure Agreement (NDA) was established for this project and a strict protocol was established for the sharing and publishing of data. This was adhered to at all times. Also negative perceptions of the AMRC or partners was avoided by appropriately wording reports and presentations to emphasise that the project is offering an enhancement to practices as opposed to replacing bad practice.

3.3 Method selection

To answer the research questions a synthesis of research methods is required. With the complexities of data and knowledge capture and management one method alone would reduce the potential value of the research. To meet the objectives of the research, the resultant framework must include identification and thorough knowledge of stakeholders and their requirements (O1).

Furthermore the framework must have the ability to identify, capture and analyse different forms of data (O2) and to develop and validate a framework which handles uncertainty (O3) and enhances decision making at different stages of technology development (O4). To comprehensively meet these objectives in this dynamic environment a range of methods must be used. Johnson and Onwuegbuzie [159] define mixed methods as the combination of qualitative and quantitative research, thus producing more conclusive knowledge required to be informative to both theory and practice. In addition mixed methods can combine approaches, methods, data and types of analysis which is undoubtedly necessary for this study [159]. Whilst Grounded Theory and Action Research are the more typical methodologies used in participatory research they offer insufficient flexibility within this context.

3.4 Mixed – Methods Research design

In keeping with a pragmatic orientation, the researcher considered all of the stakeholders who contribute to the decision-making process and how they might become involved in the development of the decision-making framework. In order to maximise the potential input of these stakeholders a fully mixed concurrent equal status mixed methods research design was chosen [160]. This design provides a study that combines qualitative and quantitative research across elements of a single research study. Research questions, required data and knowledge, means of analysis and inference evolve throughout the study.

In a fully mixed design, both quantitative and qualitative data have equal status – the cost and manufacturing data are equally as important in the research. This enhances the value of the results and provides the level of confidence required by the stakeholders, expert knowledge must reinforce existing data, and the data must evolve through further research and knowledge as the technology progresses through the MCRL phases. This level of confidence and range of knowledge enables the decision makers at each of the interfaces to select the most cost effective technologies for progression to industrial deployment.

Mixed methods research justifies the use of multiple methods for answering research questions, and does not constrain researchers' choices [161]. The research questions are fundamental to the study and the methods adopted should provide a way to combine the qualitative and quantitative data to answer those questions most thoroughly. Quantitative research is driven by inference, estimation, validation, testing, reasoning, data collection and statistical analysis. Qualitative research is conversely driven by induction, investigation discovery, and hypothesis generation. The researcher needs to understand and combine the strengths and weaknesses of each to enact the most comprehensive study [162].

The research design used [Figure 3-3] shows where both quantitative and qualitative methods are incorporated throughout the study.

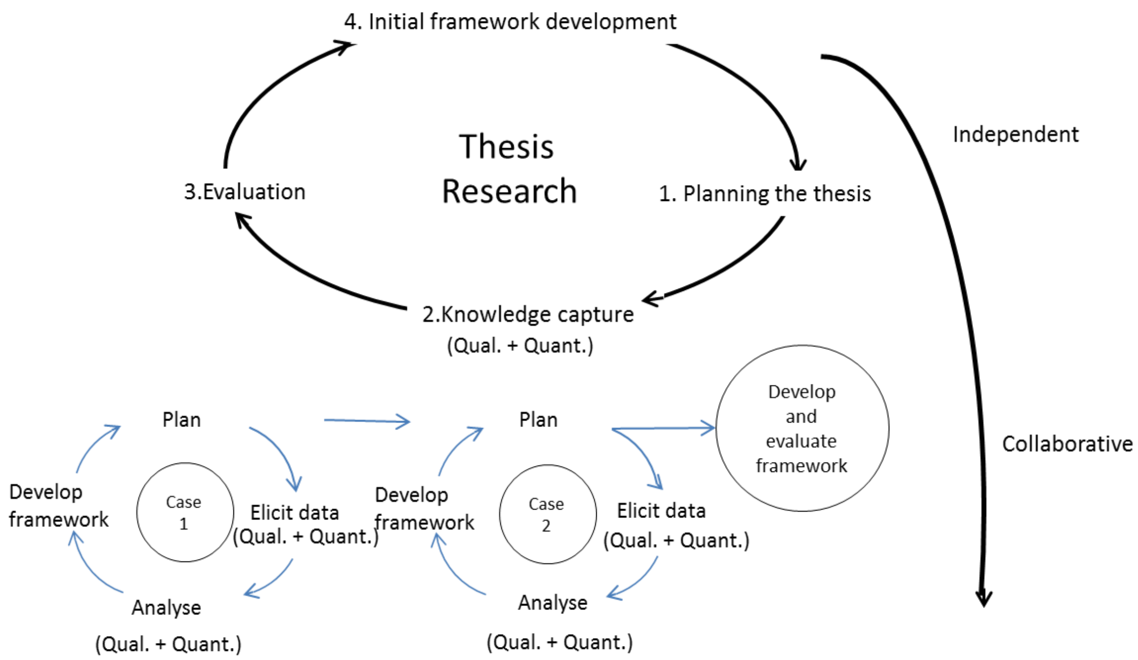


Figure 3-3 - Research design

3.5 Chosen research methods

Within a mixed-methods research study a range of methods can be used from qualitative and quantitative fields where appropriate. So a number of well-established research methods were used to capture the baseline data [87]: a questionnaire to staff at the AMRC; a facilitated workshop; observations at knowledge sharing events at the AMRC; a focus group at Rolls-Royce and a semi-structured interviews with a range of stakeholders. A document review was later performed to determine where cost is incorporated in the quality management reports.

3.5.1 **Questionnaires**

Initially self-completed questionnaires were used as a first step in understanding cost and knowledge management practices in the AMRC. These enabled a range of views to be elicited from AMRC staff and provided a starting point for developing answers to the research questions. The questionnaires were designed to capture qualitative data. Although questionnaires do not provide comprehensive information, as they are not regarded as a quality means of eliciting multiple open ended questions [87], these were designed to identify common issues and views from a selected group of engineering staff in the particular area of cost management (see Appendix D).

A questionnaire was sent out to 40 staff at the AMRC. All project engineers, technical leads and technical fellows in the machining group were invited to participate. Each provide improved machining solutions to a range of partners. The questionnaire was designed to capture how cost is identified in projects. Ethics approval was obtained for this and can be found in Appendix A.

A response rate of 25% was achieved. Whilst this rate would typically regarded as quite low [87], the quality of the data received was sufficient to draw insights that were subsequently useful for framework development.

3.5.2 **Semi-structured interviews**

Semi-structured interviews were used at both the initial knowledge capture stage and throughout the case studies. These were used to gain a more detailed understanding of the research questions and provided the most appropriate method to elicit knowledge and data from stakeholders who had limited time to engage with the research. The interviews were often carried out within active working environments. They captured a range of qualitative and quantitative data directly from experts, identified stored data and where further knowledge resided. These interviews were performed within workplaces at the AMRC, at Rolls-Royce facilities and at several Italian companies. In accordance with [87], semi structured interviews were used so that the questions could be somewhat designed in advance; however the order and number of questions could be altered as the interview progressed and new questions could be included during discussions. This flexibility was vital to both the interviewer and interviewee as the interviewees were experts that had gained knowledge from different roles in the organisation due to the nature of manufacturing and so could provide several different perspectives which could be captured during the interview. The interviews lasted approximately one hour and were recorded by note taking, since audio recording was not viable within a working factory environment. The notes were transcribed verbatim. The results of these interviews are provided within chapters 5, 6 and 7 of this thesis.

3.5.3 **Stakeholder events**

The researcher exploited was able to situate further data collection within existing practices in the AMRC.

Three times a year, the AMRC bring together partners and staff on AMRC premises to showcase research, developments, research direction and results of projects (reproduced in Table 3-2). These forums have been applied since the AMRC was founded; they are based on road mapping [163]. They provide an opportunity for stakeholders to share ideas, best practice and challenges faced across sectors. These forums also present a research opportunity, which was exploited in this study, to gain insight into the interest in cost analysis across stakeholders during discussions about achievements, requirements and the direction of future research.

Road Mapping	**Technology Portfolio Planning**	**Tech Fellows Conference**
The Road Mapping sessions are designed to enable the AMRC to understand what technologies will bring important benefits to members in the future, whether the AMRC already have the capabilities to support those technologies and what capabilities they might need to develop.	All members can attend and participate in Technology Portfolio Planning for group updates, road map reviews and to develop future activities identified during road mapping.	The Tech Fellows conference gives members an opportunity to learn about the progress and achievements of AMRC Research Groups and the outcome of completed board generic projects.

Table 3-2 - An overview of AMRC partnership events [20]

Technology road mapping is a management tool that is widely used by organisations to address strategic and innovation goals. It aids communication, decision making and the provision of action plans, bringing together commercial drivers and technical abilities in a common language that focusses on the strategic alignment of businesses.

The method is a visual multi-layered time-based representation. It seeks to address the challenge of technology management by aligning current and future business needs. The impact of future technologies, along with uncertainties relating to future developments can be identified along with the identification of where and how businesses can exploit new technologies.

The road mapping sessions periodically bring together a range of stakeholders to identify and communicate multiple perspectives along with drivers, resource allocation and requirements in a workshop environment [16], [164].

The types of technology that are discussed in roadmaps are [16]:

- Emerging technologies – early research stage, where the impact is unknown but considered promising;
- Pacing technologies –which have the potential for step change, although are not yet part of a product or process;
- Key technologies – products and processes offering high impact;
- Base technologies – essential to the business widely used but offering little or no impact.

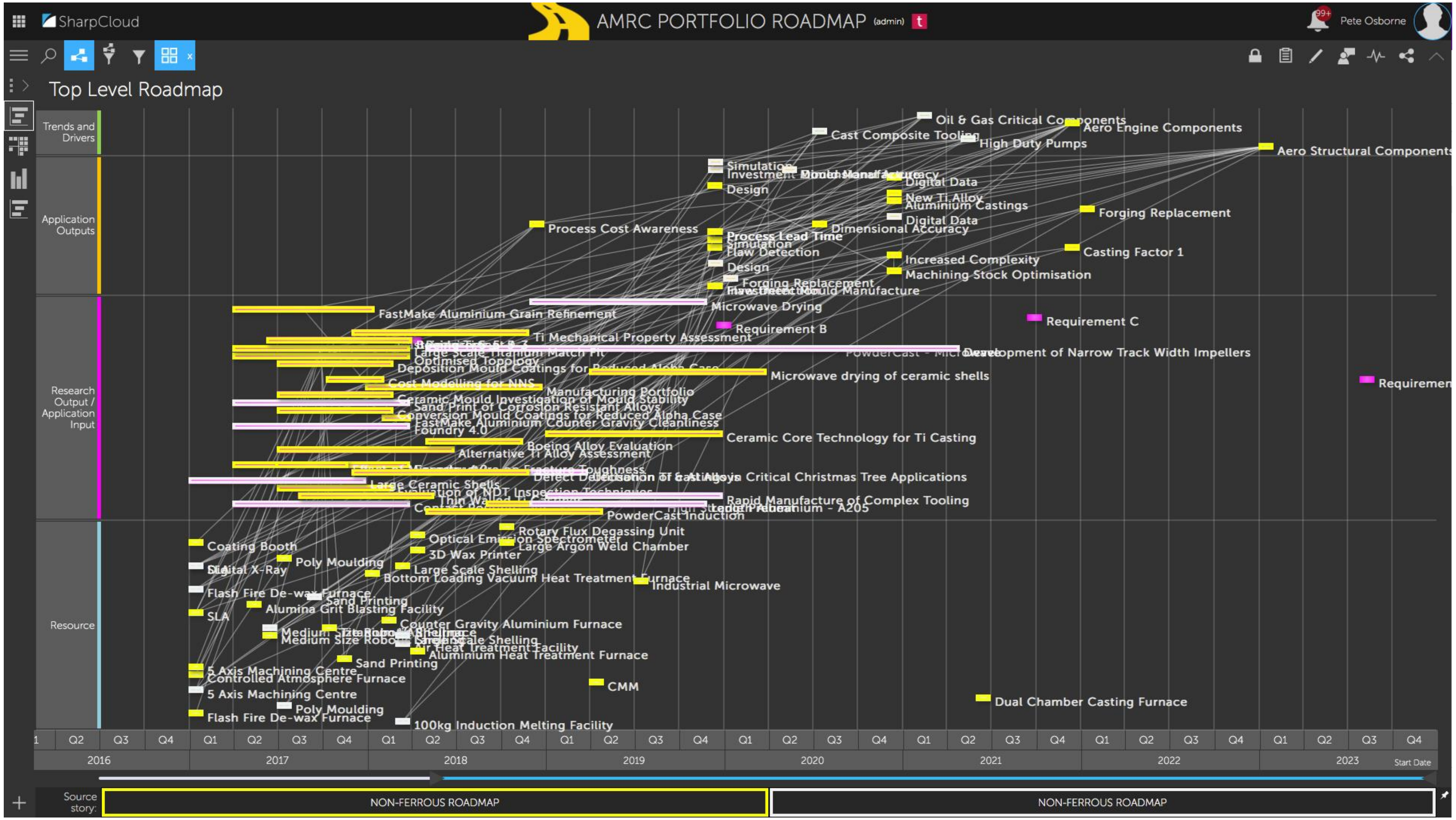


Figure 3-4 - A roadmap example for non-ferrous metals at the AMRC

The roadmap is made up of layers addressing the following questions [165]:

1. Where do we want to go? Where are we now? How can we get there?
2. Why do we need to act? What should we do? How should we do it?
3. What short-medium-and long terms actions are needed?

An example of an AMRC roadmap is shown in **Error! Reference source not found.**. There are four layers in the roadmap, referred to here in descending order of presentation. The first layer represents identified industry-specific and customer trends, needs and requirements; the second represents application outputs; the third represents research output/application input; and the fourth represents resources. The horizontal timeframe depicts horizons of importance, up to several years ahead.

During the roadmap development sessions, an overview of each group is presented, highlighting achievements, challenges and also provides an opportunity to develop future research projects. The existing roadmap for the group is presented and questions are taken from the audience, who are made up of cross-departmental staff at the AMRC and partner organisations from all tiers. The number of participants varies between road mapping sessions but over fifty participants is typical at any one session. Towards the end of the session, break-out workshops are constituted across a range of themes identified by the roadmap and small group discussions facilitated by a technical lead relevant to the subject are used to identify parameters for the next roadmap. A poster is used to separate trends and drivers, product, systems and services, technologies and resources for current, short, medium long term and vision timelines (see Figure 3-5). Post-it notes are used to capture views of the participant [166]. Each group moves between the themed breakout sessions to ensure a range of perspectives are captured (see Figure 3-6). The outputs of these sessions are built into the future roadmap.

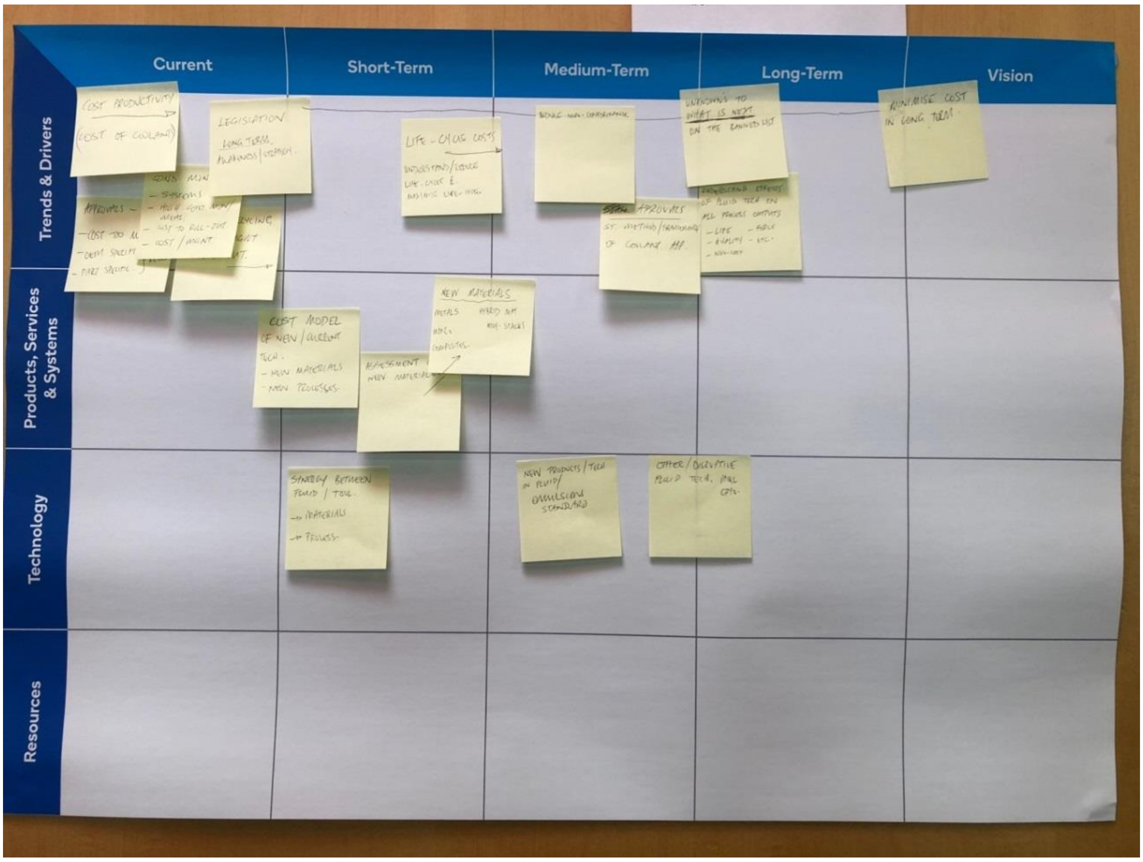


Figure 3-5 - Road mapping breakout session data capture poster

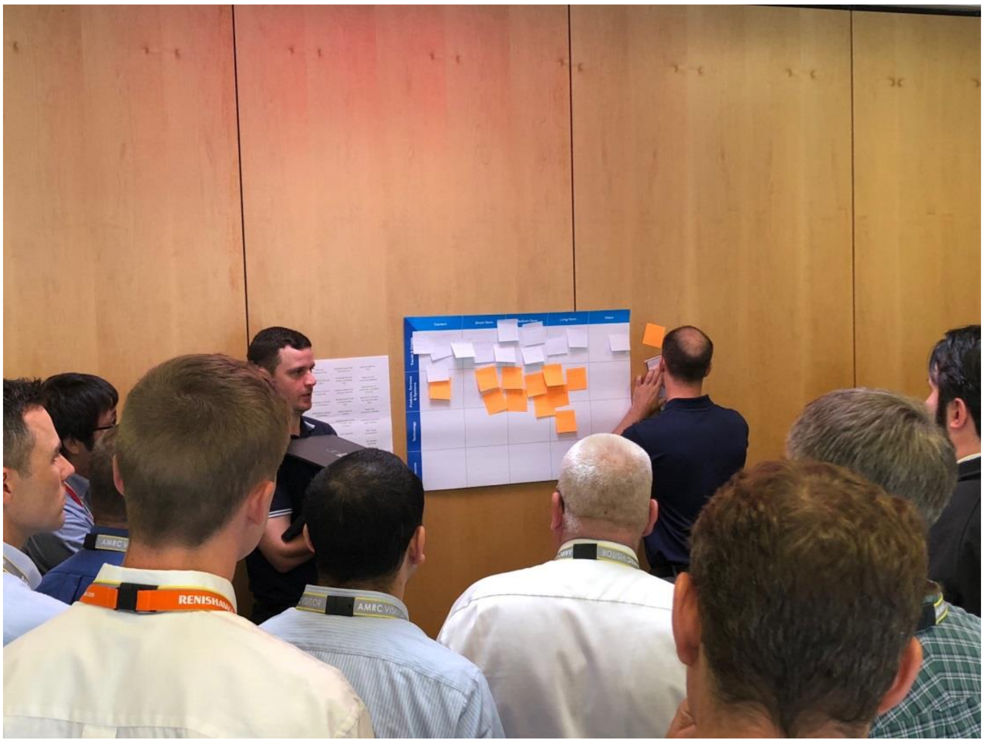


Figure 3-6 - An example of a themed breakout session during road mapping at the AMRC

3.5.4 **Workshops**

A workshop was organised during the road mapping week in 2017 with a range of stakeholders to understand the current challenges when incorporating costs into the projects involving the introduction of novel technology.

The workshop involved 24 participants: 17 members of staff from the AMRC across each of the technology groups and 7 partner representatives, including global organisations and specialist suppliers.

The aim of the workshop was to establish how cost is managed and represented in projects, how the communication and recording of cost is established from industrial requirements, and how this cost is communicated between stakeholders.

The workshop was organised into three sections: data variability and detail; sharing data; and data availability and requirements. Each discussion was led by a facilitator to encourage all participants to identify areas of knowledge and experience. Discussions included current practice and suggested improvements for cost related knowledge management during technology development. Comments were noted on post-it notes similar to the road mapping sessions. The information was collated and each participant was sent a copy of the results and feedback was invited to ensure that the results reflected the workshop and to avoid researcher bias [87].

3.5.5 **Focus groups**

A focus group was used in industry to provide an environment for multi-stakeholder views to be captured, and an arena for discussions so that the views and data could be combined and cross validated by other stakeholders with different subject knowledge and expertise, reducing bias [93]. This group was particularly useful for disseminating knowledge across stakeholders and as a means to capture and agree on subjective data for use in the models. The focus group lasted for 90 minutes with 10 participants including technical experts, environmental managers and manufacturing engineers.

The session was used to capture subjective data for the cost model and to identify/clarify common/specific drivers across the range of stakeholders.

3.5.6 **Document review**

The document review included Projects at the AMRC which follow a gate review process (see Table 3-3). A minimum of two of the gates (launch and completion) need to be signed off for each project. Sign off is by the full project team, which includes the AMRC project staff and the customer or their nominated representative.

Gate	When	Why
Scoping	The scoping phase must be completed, the phase gate review held and the phase signed off before a Statement of Work is formally issued to the customer.	To understand the customer requirements. To agree deliverables, timescales and acceptance criteria. To make sure that the work contributes to the organisational aims and objectives. To ensure that we do not commit to work that is outside our capability or capacity.
Launch	The launch phase in a project is the phase during which most of the creative work and idea generation will take place. There may be more than one launch phase throughout the life of a project if there is more than one opportunity for brainstorming and idea generation.	To generate ideas and identify potential solutions. To investigate technologies and techniques that might offer innovative solutions. To review all of the ideas. To ensure that all of this work has been captured. To ensure that where decisions have been made this has been recorded and that all of the documentation is in place to ensure that smooth running of the rest of the project.
Readiness	A readiness phase will be required whenever there is a period of preparation required in order to undertake a significant piece of work / activity. If there are several blocks of significant activity you may want to split the readiness phase into separate stages / blocks of work too.	To prevent delays and unforeseen problems it is beneficial to prepare fully for your significant periods of activity. To consult with the wider project team to check over preparations To make sure that nothing has been overlooked.
Data collection and review	A data collection and review phase could be a period of data collection suitable to your project, if your project is long and there will be a significant amount of data collection you may wish to break this up into several chunks in order to reduce complexity and to reduce the risks	Data collection is at the core of what the AMRC do, carrying out research activity. The data collection phase is vital to the provision of useful information to our customers. The purpose of the gate review at this stage is to review that data being

	that anomalies or errors are missed and that large amounts of rework will be required.	collected, check that there is nothing unexpected, that the data is accurate and reliable and that sufficient, useful data is being collected that will enable the provision of a report with the information required by the customer.
Closure	Activity relating to reporting will be carried out throughout the project; however the final reporting can of course only take place when all of the trials / experiments are completed and all of the data collected and analysed. This phase of the project will therefore take place either at the end of the project or at the end of a significant experimental phase.	Our product is knowledge, often shared in a project report. It is important that we capture all of the knowledge acquired during the life of a project both to report to the customer and to inform future project work. The purpose of the gate review at this stage is to reflect of the project as a whole and to capture all of the lessons learnt, both technical and in relation to the way that the project was managed so that this information can be used to inform future work.

Table 3-3 - The gate review process at the AMRC [167]

The gate stages in this process provide an opportunity for the framework to be incorporated. For example, scoping and launch gates provide the opportunity for elicitation, the data collection and research gate provides an arena for the consolidation and analysis stages and the closure gate would enable communication and feedback to occur.

Each project has a set of specific requirements. Of 30 project reports studied over a full calendar year (2017), only two had incorporated cost modelling to determine the novel technology or approach in terms of cost implications for manufacturing processes.

3.6 Chapter summary

Careful consideration was given to the methodological approach to this research. Mixed methods was chosen due to the requirement for combining different types of knowledge from a range of sources. The industrial environments required a flexible approach to research as people/priorities/projects/requirements were often changing.

The following chapter describes how the framework was developed in detail including methods for evidence gathering and the toolsets used.

4 Framework development

4.1 Introduction

This chapter describes the framework developed to meet the industrial aims of this study, which is to provide the AMRC with:

"A framework to improve value-related decision making when selecting novel manufacturing technologies."

This chapter introduces the proposed new framework for cost related decision making within the AMRC. The baseline of current practice is first established. Next the four main sections of the new framework are fleshed out: specifically (1) elicit; (2) consolidate; (3) analyse; and (4) communicate.

4.2 Establishing a baseline

To establish a baseline the existing people and procedures were studied at the AMRC to identify where and how cost and other factors are incorporated in decision making. There are many decision makers at the AMRC including technical leaders, project managers, project engineers and partner organisations. There are also systems designed to capture the knowledge from across the organisation and quality procedures to ensure a standardised approach for project management and reporting.

4.2.1 A conceptual model for future manufacturing capability decision-making

Novel technology selection can be described as a decision problem with two or more alternatives. The existing technology provides benchmark and each novel technology along with associated uncertainties are assessed against this benchmark to provide cost benefit information to the decision maker.

Stakeholder requirements may vary and so the output parameters must be aligned to stakeholder needs, based on an overarching business driver. Tacit (intuitive, experienced based) and explicit (formalised and codified) knowledge must be combined to provide enough data to compare the alternative technologies against industry key performance indicators. A mechanism to run scenarios to compare the alternative solutions should be transparent and useful for decision making (see Figure 4-1).

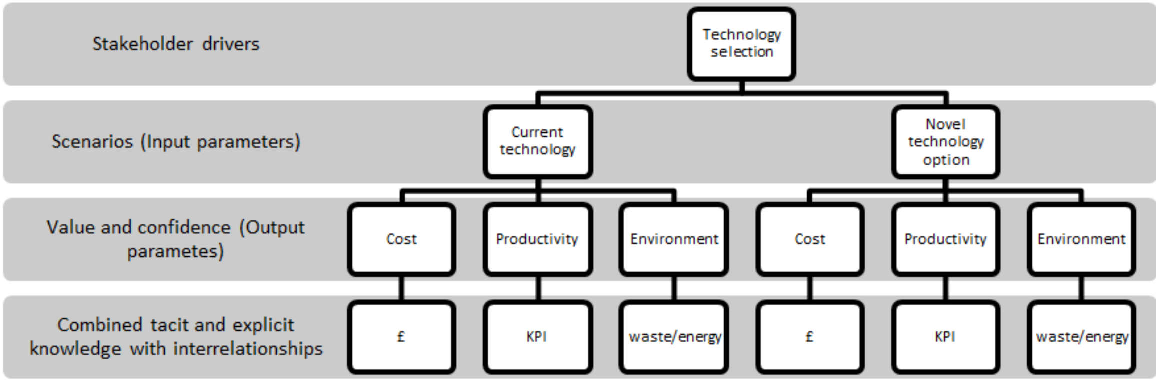


Figure 4-1 - Diagram showing novel technology decision problem definition

To gain further insight into the significance of the complexities described in the research enquiry, a piece of exploratory research was conducted on a representative project from within a manufacturing research environment. The aim of the project was to determine the most appropriate tooling for the machining of a novel material. The requirement originated from the driver to reduce the weight of an aircraft. Significant investment is required to establish new manufacturing regimes and so experts at the centre were employed to identify the most cost efficient solution. The project lead was asked to describe the flow of information and requirements throughout the project and the results were captured in a conceptual model (see Figure 4-2 **Error! Reference source not found.**).

The project team were required to select and test tooling solutions for the machining problem. Data requirements and information flow were captured over the course of the project through direct conversations with project personnel, project meeting attendance and a document review.

The findings were synthesised into a conceptual model. Decision and data variables were captured and added to the model and interrelationships were mapped. Complexities were identified in discussions with personnel and are highlighted in red.

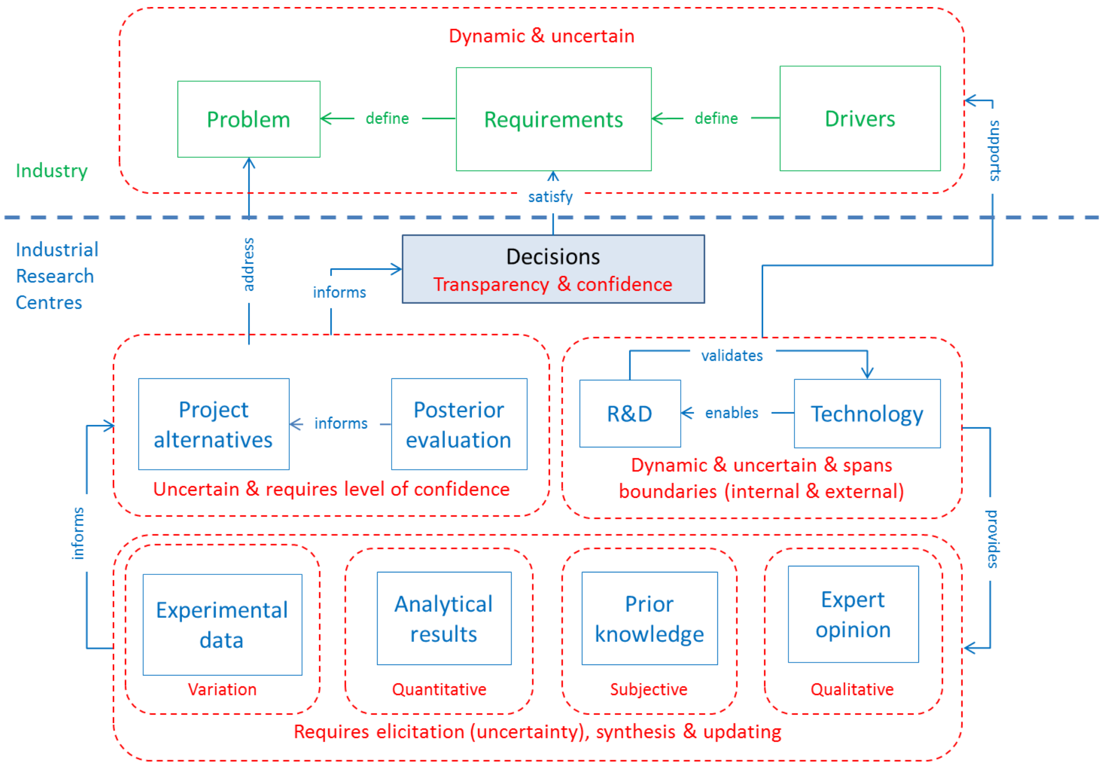


Figure 4-2 - Conceptual model of decision making results and suggestions in manufacturing R&D

Drivers and technology developments define the set of requirements and ultimately describe the problems that are brought by industry for the manufacturing research centres to solve. Typically these drivers will be related to gaining competitive advantage from a combination of increased productivity and reduced cost. The experts must draw from existing knowledge to select a set of alternative solutions from which to conduct research and development to provide the most cost effective solution to the problem. Due to the uncertainty associated with the novel material, down selection of tools to progress for machining trials was complex and risky. Elicitation from experts spanned internal and external boundaries and the information was in a range of formats. The project team reported changes in requirements during the project lifecycle and difficulties in providing confident and transparent support for the most cost effective solutions.

When assessed against the findings from the knowledge base there are similarities in terms of considerations for decision making such as uncertainty representation, data format and availability and requirements which span internal and external boundaries.

4.2.1.1 **Results**

4.2.1.2 **Questionnaire**

A questionnaire was sent out via email to 40 staff at the AMRC. All project engineers, technical leads and technical fellows in the machining group were invited to participate. Each provides improved machining solutions to a range of partners. The questionnaire was designed to capture how cost is identified in projects. Ethics approval was obtained for this and can be found in Appendix A. Table 4-1 documents a verbatim of the results of the ten responses to the questionnaire.

Question	**Verbatim of responses** Project engineers (PE1-6) Technical leads (TL 1-3) Technical fellow (TF)
What cost related data is or could be captured in project reporting?	Typically simple cost models are produced based on machining outputs but only when requested by customers.(PE1-6)
	Most cost related data could be captured in principle, but are not captured due to timescales. (TL 2, TF, PE2,5,6)
	Normally costs are generalised rather than individually captured e.g. utility costs could be incorporated in consumables. (PE4, TL 1, 3)
Is existing cost related data easily accessible?	Many projects have an acronym as their project title. If this is the title of a folder there is no way to know what the project is about without going into project documentation (Statement of Work, etc.). (PE 1-3, TL 1,2)
	This depends on the projects, e.g. in some cases there are many sub-projects within a main project (TF, TL3, PE4,5)
	Project Review Documents should all be made available to staff via the quality management server (Windchill) however due to access restrictions this can be problematic. (TF)
	It would be useful to use abstract and key words to help identify useful internal literature. (PE1,2)
	There could be improvements here. When we start scoping a project a title is given, however when going more in depth, most of the time, the scope changes but it is too late to change the name. (TL2)
When is cost reported?	If there are results from experiments, this data is either included in the project report (main text or appendix, depending on size). (TL1)
	The data in the report is usually a summary of more extensive data held in a spreadsheet. (PE1, TF)
	Impacts of health and safety issues are hard to cost in and report. (PE3)

	We have data but ways in which they are exported and displayed vary. (PE2,TL3)
	In a Standard Op Sheet we could add cost but don't as standard. (PE5)
	Cost analysis of our experiments is not as much of a focus when looking at technology development; it will become more of a focus at higher TRL. (TF,PE6)
	We would not readily report our machining times or set-up etc., as the focus is more on getting the technology working that machine uptime. This is more relevant to platform groups... (PE4)
	Depends on projects but at - Lockdown Readiness a review if costs are correct could be incorporated before Closure. (TL 2)
Is uncertainty captured?	Not as standard. (PE 1,2,4)
	For technical data we always include a +/- for error. (PE3,5,6, TL1,2)
	This is project and data dependent which then leads to Customer Dependent & Risk Management (how much of a risk do you want to take? How accurate and confident are you in the quality of your data?).(TF)
Is subjective knowledge captured?	Not as standard, amendments should be made to the strict reviewing process, as most lessons learnt are often diluted down and not mentioned at all in the report. (TL1)
	There should be an "engineers" section to allow personnel to write comments about anything that caused problems. (PE1-6)
	Subjective knowledge is captured in the report due to the stating of the assumptions. (TF, TL2)
Do knowledge and data management problems add to timescale?	Rarely. (TL1)
	As exemplified by our own industrial partners, who "cry out" for reports, our staff do not have the latest information or data at their disposal to save time/costs. (TF)
	Not possible to quantify time/cost implications due to the variation in projects. (PE 3,6)
	There are not enough technical forums or discussions to build new technology to apply it, as most of the time it's around project management. (PE1,2)
	Most of the time, someone else has already at least thought of it or tried it. (PE 4,5)
	The main issue the timescale is affected is when receiving data from others. As the standard of format varies with each company, time is wasted in converting the data into AMRC standard format & also understanding the data. (TL2)
Would an improved knowledge management system improve cost related data capture?	Yes if a system be developed that is capable of capturing data across the wide variety of projects that are undertaken at the AMRC? (TL 1, PE 2,3,6)
	A centralised, keyword-searchable capture of project lessons learned docs would be beneficial.(TF)
	We should incorporate cost into standard op sheets / procedure and standardise costs into projects. (TL2, PE1,4,5)

Would a level of confidence help?	If people are honest with their confidence. (PE 1-6)
	Better to be conservative (i.e. pessimistic), as uncertainty can be misinterpreted as a subset of incompetence, or badly estimated. (TL1)
	If there is low confidence I cannot based on logic take the data seriously. (TL2)
	Very useful as a confidence factor will be vital in managing risks (TF)

Table 4-1 - Responses from the AMRC staff cost questionnaire

Although 10 responses are difficult to draw conclusions from, insights are:

1. There are no standard cost related reporting mechanisms within the quality management system.

During the gate reviews, cost of technologies is not included in the requirements; a cost model is not an embedded stage of the procedure.

2. Cost data, where included, is project specific and based on specific customer requirements;

Only where customers specifically ask for a cost analysis this is included and typically a simple ‘excel’ spreadsheet cost model is used.

3. There are opportunities to include uncertainty and qualitative data during the project specifically in the lessons learned log however this is not routinely used.

There is a lessons learned log within the gate review procedure which could be used to capture information related to cost analysis, risk and qualitative information from the project team throughout the project. This is not used routinely and not populated post-project, where cost-related information could be stored for future reference.

4. The current system does not lend itself to enable easy searching of cost related data for knowledge sharing.

Projects use a naming convention related to a project code so specific elements of the project are hidden; an understanding of the project statement of work would be required to search relevant documentation. Often projects are embedded within other projects and therefore the titles may not contain relevant information or this may change throughout the project. There may be access restrictions for sharing knowledge.

4.2.1.3 Semi-structured interview with cost engineer

A semi-structured interview was conducted with the cost engineer at the AMRC to determine his perception of the use of cost estimation at the AMRC, the interview lasted for one hour. The cost engineer works for the Manufacturing Intelligence (MI) team, which is made up of one cost engineer and two discrete event modellers, providing a central resource for process modelling, cost estimation and trade studies within projects across all departments. The interview transcript is shown in Table 4-2. This transcript was sent to the interviewee post-interview to confirm the content was accurate.

Question	Response
In your experience how is cost estimation incorporated or used at the AMRC?	Cost interest is low and is not a driver in projects as standard. Due to the above there is no appetite in the value of cost related data storage in a systematic way. There is one cost engineer and no standardised cost data management structure so each time cost is analysed the data collection has to start from scratch and the data is not easy to access. Cost engineering is not a fundamental part of the MCRL gate review process. A cost element is only included when asked for by a customer. Cost analysis is only used systematically when the objective of the project is cost reduction.
What challenges do you face in the adoption of cost engineering in the AMRC?	Cost analysis takes a long time due to the issues described about and so from a financial point of view is not regarded as good value by project managers, it is sometimes removed / unjustified in project cost. Due to short time frames of projects cost analysis not given enough time in project, or not enough money. Process analysis often doesn't include detailed cost, even optimisation projects. Data collection is a major issue, often data is not available, hard to find or validate, improvements here would reduce timeframes and could support cost model justification in more projects.
In your opinion what would improve the uptake of cost analysis in projects?	If cost data collection is systematic and a quality obligation this would greatly reduce the time to provide cost analysis. Project teams cannot see the value of cost as it is only included in a few projects and the information and value has not been shared across groups.

	If the uptake is higher this would have a significant impact of the value being shared.

Table 4-2 - Transcript from an interview with the AMRC cost engineer

The cost engineer's views correlate well with the results of the questionnaire, placing emphasis on the lack of standardised reporting mechanisms for cost data collection. All cost modelling requires detailed cost data capture which is time consuming and increases the cost of providing this additional service. If the data is captured systematically then cost estimates would be more efficient and as a result more widely used and this in itself would demonstrate the value of cost analysis across the organisation to all stakeholders, thus providing an enhanced service to the customer.

4.2.1.4 **Road mapping**

During these biannual events typically projects that are proposed aim to achieve productivity enhancements to processes, for example improved quality, monitoring and faster cutting feeds and speeds, or increased tool life. A value analysis of the technology has not been presented in any of the sessions attended by the researcher over the space of three years. The requirement for a cost and capability matrix has been raised a number of times during these sessions by AMRC staff, suggesting that this would aid knowledge sharing and reduce overlap of projects as well as being a repository that the AMRC could use to inform customers of the best and most cost effective technologies. The suggestion made by the AMRC is to have a central data repository where staff and partners can easily search for similar projects/lessons learned/expert data in terms of both cost and capability. Roadmaps from across departments include the driver for more cost effective solutions and yet cost engineering data is not readily captured in project documentation.

4.2.1.5 **Cost workshop**

The workshop involved 24 participants: 17 members of staff from the AMRC across each of the technology groups and 7 partner representatives, including global organisations and specialist suppliers and was conducted at the AMRC in 2016.

The aim of the workshop was to establish how cost is managed and represented in projects, how the communication and recording of cost is established from industrial requirements, and how this cost is communicated between stakeholders.

As described in Chapter 3 the workshop was split into three main areas of interest: data variability and detail; sharing data; and data availability and requirements. Each area was discussed while being facilitated by the researcher to encourage all participants to identify areas of knowledge and experience. Discussions were designed to capture current practice and highlight potential improvements for cost related knowledge management. All comments were noted on post-it notes like in the road mapping sessions. The information was collated in Table 4-3. Each participant was sent a copy of the table and feedback was invited to ensure that the results reflected the workshop.

Data Variability & Detail	**Sharing Data**	**Data Availability and Requirements**
Show suitability (validity) of data from previous work	Robust security in place for sharing data	Design intent methodology could be used for best practice
Improve transferability of results (accuracy & evaluation)	When defining the requirements (parameters) we must know what is available and what is the weighting (ranking) that each parameter holds for each stakeholder	Each group will have different ratings and requirements
Populate the model as more detail emerges	We need to market the MI capabilities better (on the website?)	The cost/capability should be incorporated into quality procedures (early on)
Colour coding (TRL scale?) for confidence in data	Customers may be reluctant to spend time getting the data	Must be put into the SOW – understand the data that s needed from the start
Maturity of data along the project timescale (with a level of confidence)	MI should be technical support for whole AMRC	Include perspectives and bias from different data sources (people), this needs to be carefully managed
Need to incorporate interrelationships and impact of data	MI reps are needed from each department (to define parameters)	Standardised methodologies for data capture and management
More details need to be added to the trade-study	We need better communication of project data across departments	Data on lead time often doesn't incorporate time between processes. Can we include a Value Stream

		Map to find waste (time and process)
Data must be able to drive elements of the model	There should be standard templates (details/aims/objectives/deliverables / lessons learned) with searchable keywords	Early capture is needed and to manage the maturity of the data, and to understand the boundary conditions
Phasing of data accuracy from broad limitations to detailed data points	The AMRC should be the (anonymous) front end to industry knowledge.	Brainstorm the data with all the stakeholders to ensure alignment
	We need user friendly data storage software	
	A catapult project could help to unwrap the knowledge	

Table 4-3 - Cost workshop results

Common suggestions were captured in the workshop:

1. Standardising methods of data capture, management and knowledge sharing;
2. More detailed trade studies and cost analysis with improved data capture;
3. Ensuring that the AMRC is an independent front end to identify and communicate the most cost effective solutions to partners.

Identification of the range of data capture methods was key. Concerns over the access to knowledge across departmental groups and external partners were raised. This requirement emphasises the need for a cost and capability technology matrix mentioned in road mapping sessions, effectively providing a centralised knowledge base to capture and store quantitative and qualitative data across AMRC departments. When a customer approaches the AMRC for expert advice, this repository could be accessed to share best practice and provide information about the value proposition of alternative technologies previously tested as well as insights from technologies under investigation.

Trade studies and cost modelling were acknowledged as useful tools however the use of these is limited, potentially due to a lack of understanding around their value for decision making since these are typically used when a customer specifically asks for them, not as standard. Presumably if AMRC staff and customers better understand the value of these methods, this will generate the need for value related aspects to be built into the quality procedures.

Partners want the AMRC to be an independent source of cost effective solutions. Partner specific projects have data sensitivities which impede knowledge transfer across stakeholders so access restrictions would need to be in place. Board generic projects, however, should be used to identify where technologies have the potential, and if customers begin to request value analysis of the alternative solutions this would both enhance the offer from the AMRC to customers and provide evidence for the knowledge base.

4.2.2 **Summary**

Consolidation and comparison of the qualitative data has provided a greater understanding of the current situation. This has enabled an appreciation of the challenges and complexities involved in the knowledge management of cost related data, leading to a better understanding of how these can be incorporated in the framework.

Mechanisms and standardised procedures for data capture are required. Existing gate review procedures provide ideal stages to capture and analyse the data during technology development. Better understanding by all stakeholders of the value of including information on the cost effectiveness of technologies is needed. This will come about if the data required to demonstrate the value proposition is collected as standard so that mechanisms to provide results (such as cost modelling, trade studies and value analysis) can be more efficiently included in all projects.

4.3 A new framework

Many authors from the field of value-focussed decision theory consider good structure a fundamental requirement of effective decision making. Framing of the decision problem in terms of choice, people, both input and output process variables as well as communication, emphasising the need to continuously readdress a decision and adjust those decisions which have been affected by new information [77], [168], [169].

This provides the foundation to design a framework around five recommendations from the field of cost engineering and decision theory. **Elicit** and model the problem including metrics, data, stakeholder requirements and constraints and collect existing cost related knowledge (e.g. for materials, processes, applications), including the uncertainties in this knowledge. **Consolidate** this knowledge by synthesising the sources of data, building models and mapping the interrelationships. **Analyse** the models using interrogation techniques such as sensitivity analysis to determine the drivers and impact. **Communicate** the knowledge and uncertainties in a way useful for decision making and ensure learning by including a **feedback** loop, (see Figure 4-3).

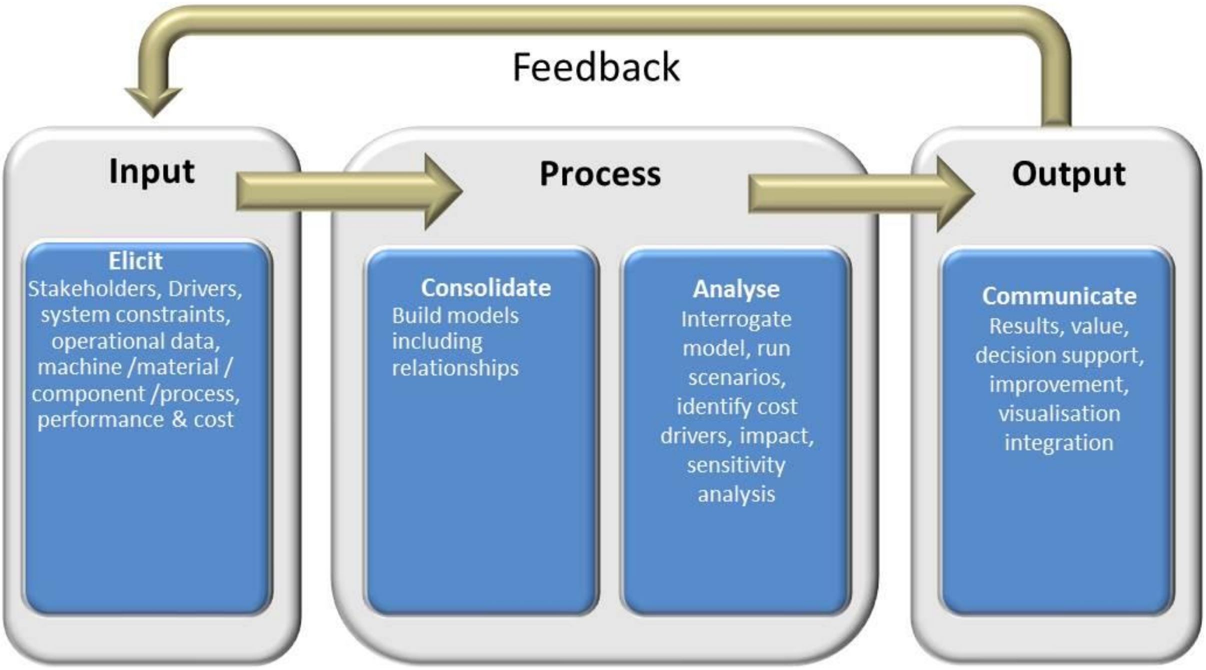


Figure 4-3 - Outline framework for value focussed decision making

A method and process is required to develop and implement the framework. Immersion in the Chapter 3 study and insight from literature was the prelude to the framework concept. The framework was iteratively developed, trialled, and refined over the two case studies which in practice happened with some overlap. The development was conducted mainly in Case Study 1, since the Case Study 2 trial did not demonstrate any need for significant refinements. For coherence of the presentation of the thesis, in this chapter, the framework is presented in its final established form. The *use* of the (evolving) framework is deferred until Chapter 5.

4.4 The framework in detail

This section describes the process for implementing the framework which was developed during the case studies.

4.4.1 Evidence gathering

Evidence is represented in the model, for each node, by probability density functions (pdfs), constant values and mathematical relationships between the nodes. This implies that both hard evidence (i.e. measurements) and soft evidence (i.e. expert opinions) need to both be represented using probability density functions. Appropriate methods must be used to collect both types of evidence.

4.4.1.1 Hard evidence

Hard evidence includes measurements such as production metrics, waste volumes, consumables, resource costs and quality metrics.

Input parameter	Mean Value	Units	Uncertainty
Cycle time	2	hr	(raw data available)
Machine cost rate	40	£/hr	n/a
Tool life	.42	hr	+/- 10%

Table 4-4 - Example of data input sheet

The process required for collecting hard evidence is:

1. Identify the input parameters.
2. Create a data collection sheet (e.g. Table 4-4) containing the required input parameters including a level of uncertainty and ensuring consistency of units.
3. Identify the sources and format of data (documents and or directly from staff).
4. Collect the data and populate the input sheet.
5. Where possible validate the data by showing the input sheet to multiple experts.

6. Populate the model with the data.

For uncertain data (as the case for Cycle Time in Table 4-4) we need to find the parameters that fit the distribution of the data.

One method of estimating the parameters of a distribution is the maximum likelihood method. If we have observed data then this can be used to determine parameters which best fit a distribution to the data. The process for estimating the maximum likelihood is described below.

Maximum likelihood parameter estimation

We will assume the data for a cost model parameter (e.g. cycle time) has been generated from a Gaussian process (a normal distribution). Maximum likelihood estimation can be used to calculate the hyper parameters μ (mean) and σ (standard deviation) needed to represent the data in the model [170].

Given data $X = \{x_1, x_2 \ldots x_n\}$

And parameters to be estimated = $\{\mu, \sigma\}$

The probability density of observing a single point value from a Gaussian distribution is:

$$P(x_i : \mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} exp\left(-\frac{(x_i - \mu)^2}{2\sigma^2}\right)$$

Equation 4.1

And the likelihood of parameters μ and σ given data point x_i is:

$$L(\mu, \sigma | x_i) = \frac{1}{\sqrt{2\pi\sigma^2}} exp\left(-\frac{(x_i - \mu)^2}{2\sigma^2}\right)$$

Equation 4.2

Rearranging for μ gives:

$$\hat{\mu} = \frac{\sum_{i=1}^{n} x_i}{n}$$

Equation 4.3

Applying the same approach to σ gives:

$$\hat{\sigma} = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \mu)^2}{n}}$$

Equation 4.4

To show how the formulae work with data, an example is described with some randomly generated data in this case.

Some normally distributed data is randomly generated for $X = (x_1, x_2 \ldots x_n)$, where $x = 200$, $\mu = 259.47$ and $\sigma = 100$.

When these values are inserted into Equation 4.3 and 4.4 the maximum likelihood estimates are $\hat{\mu} = 255.14$ and $\widehat{\sigma} = 98.62$.

The contour plot in Figure 4-4 represents the likelihood for a range of μ and σ estimates within a given range of the generated distribution and shows that there is a single maxima. Overlaid is the estimate from the above calculations which shows they have provided an estimate at the maxima.

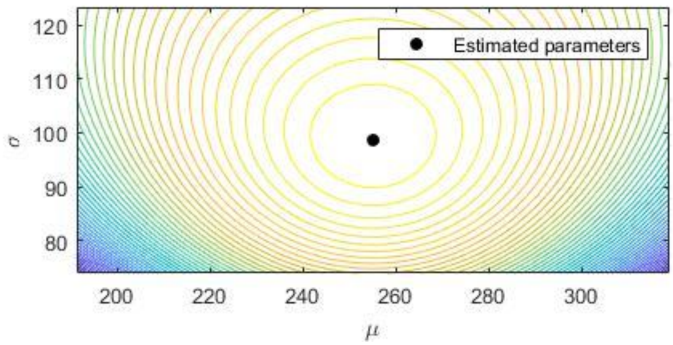


Figure 4-4 - Contour plot to show how estimated parameters of μ and σ fit the randomly generated distribution

With confidence it is now possible to show the estimated pdf over the normalised data which shows that the estimated distribution fits well and can be used in the model (see Figure 4-5).

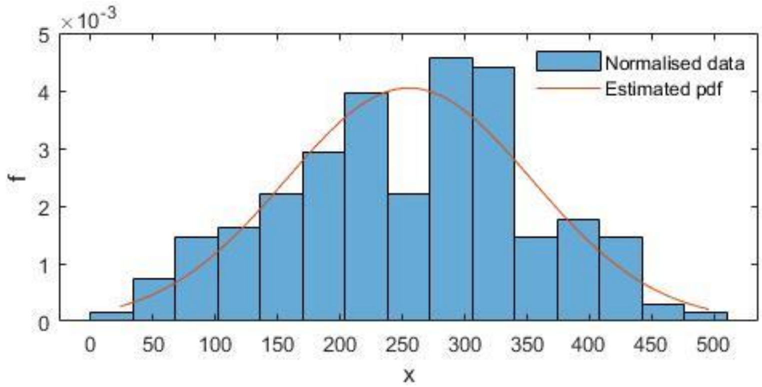


Figure 4-5 - Plot which shows the estimated pdf over the normalised data

The data here is assumed to come from a normal distribution. With no prior knowledge of the distribution the same method could be used to compare maximum likelihood estimates over a range of distributions to establish the best fit, the optimal solution can then be used in the model.

4.4.1.2 **Soft evidence**

As experts may not be able to give specific values of data the researcher needs a way to capture qualitative values and estimations. Bayesian methods have been chosen as a method to incorporate the expert opinion in the form of priors [171].

The priors elicited from experts must be converted into probability density functions to account for uncertainties (e.g. $Normal\ (\mu, \sigma), Exp\ (\lambda), Beta\ (\alpha, \beta), Gamma\ (\alpha, \beta)$).

Using probability distribution functions to represent expert opinions

Expert opinions can be more accurately represented if elicited as an uncertain judgement. An example of an elicitation for defect rates is sketched below.

In this simple example, the likelihood is assumed to be in the form of a Beta distribution.

Eliciting the prior (without observed data)

A beta prior is used for representing the uncertainty of experts about non-conformance rates ϕ.

$$\phi \sim Beta(a, b)$$

Equation 4.5

So

$$f(\phi) \propto \phi^{a-1}(1-\phi)^{b-1}$$

Equation 4.6

Assume that an expert is able to make a judgment about this parameter based on their median, 5th percentile and 95th percentile estimates of the number of non-conforming parts out of a total of 100 parts.

i.e the probabilities $\phi_{0.5}$, $\phi_{0.05}$, $\phi_{0.95}$

A judgement could be made that the number of non-conforming parts per 100 $\phi_{0.5} = 15$, $\phi_{0.05} = 3$, $\phi_{0.95} = 30$

$$P\left(\phi < \frac{15}{100}\right) = 0.5$$

Equation 4.7

$$0.15 \; is \; the \; median \; for \; \phi$$

$$P\left(\phi < \frac{3}{100}\right) = 0.05$$

Equation 4.8

$$0.03 \; is \; the \; 5th \; percentile \; of \; \phi$$

$$P\left(\phi < \frac{30}{100}\right) = 0.95$$

Equation 4. 9

$$0.3 \; is \; the \; 95th \; percentile \; of \; \phi$$

These elicited values are then expressed as a cumulative density function (CDF) and a beta distribution is then identified that is closest to this CDF in a least-squares sense. An optimization algorithm in specialist statistical software (e.g. SHELF) can be used to identify these parameters. In this case, SHELF identified the shape and rate parameters for the beta distribution of $a = 2.99$ and $b = 15.66$ respectively (see Appendix B).

So the prior distribution corresponding to the expert belief in the mean value of the defect rate parameter is given by:

$$Prior \; f(\phi) \propto \; \phi^{2.99-1}(1-\phi)^{15.66-1}$$

Equation 4.10

$$Beta \; (2.99, 15.66)$$

Equation 4.11

4.4.2 **Evidence synthesis**

Chapter 2 and Chapter 3 establish that Bayesian Networks have been chosen to model and analyse the decision problem in this research.

There are a range of considerations needed to build up a BN structure. The outputs need to represent drivers which can influence decision making (e.g. cost, productivity, waste, return on investment (ROI)) and the nodes that contain the outputs need to contain the mathematical relationships between the parameters which are contained in their child nodes. The child nodes can be numerical (parent) nodes with mathematical relationships to further numerical child nodes or input nodes containing continuous or constant data.

The process of building the example (simplified) BN shown in Figure 4-6 is:

1. Begin by defining the output parameter– for example;
   a. $Total\ Costs.$
2. Define a node for Total costs and describe the mathematical model for Total costs.
   a. $Total\ costs\ =\ Labour\ costs\ +\ Quality\ costs$
3. Define child nodes for each of Labour costs and quality costs and link them to the parent node Total costs.
4. Describe the mathematical relationship for each of the proceeding child nodes until an *input node* is reached and define the connections for each child node to its parent within its Node Probability Table (NPT).
   a. $Labour\ costs\ =\ Operator\ cost\ rate\ (£/hr)\ *\ Annual\ machining\ hours\ (hr)$
   b. $Quality\ costs\ =\ (non-conformance\ rate\ (per\ 100\ parts)\ *$
   $Annual\ output\ *\ (Rework\ cost\ (£)\ +\ Downtime\ cost\ (£)))$
      i. $Annual\ output\ =\ Annual\ machining\ hours\ (hr)\ /$
      $Part\ cycle\ time\ (hr)$
      ii. $Rework\ cost\ (£)\ =\ (Rework\ cell\ cost\ rate\ (£/hr)\ +$
      $Operator\ cost\ rate\ (£/hr))\ *\ rework\ time\ (hr)$
      iii. $Downtime\ cost\ (£)\ =\ machine\ cell\ cost\ rate\ (£/hr)\ +$
      $Operator\ cost\ rate\ (£/hr)\ *\ rework\ time\ (hr)$
5. Define which input nodes are composed of continuous data, i.e. uncertainty (from data or expert elicitation) and which are composed of constant data i.e. certainty.
   a. $Continuous\ data\ -$
   $Defect\ rate\ (\%), Part\ cycle\ time\ (hr), Annual\ machining\ hours\ (hr), rework\ time\ (hr)$
   b. $Constant\ input\ nodes\ -\ Operator\ cost\ rate\ (£/hr), rework\ cell\ cost\ rate\ (£/$
   $hr)$
6. Elicit judgements for continuous nodes – for example;
   a. $Defect\ rate\ =\ Beta(1.75,2.53):$
   b. $Part\ cycle\ time\ =\ TNorm\ (\ 30,0.2,0,40):$
   c. $Annual\ machining\ hours\ =\ TNorm\ (1000,0.4,0,1500):$
   d. $Rework\ time\ =\ TNorm\ (80,0.4,0,100).$
7. Elicit data for constant nodes – for example;
   a. $Operator\ cost\ rate\ =\ 40£/hr:$
   b. $Rework\ cell\ cost\ rate\ =\ 100£/hr:$
   c. $Machining\ cell\ cost\ rate\ =\ 80£/hr.$
8. Build the model structure (see Figure 4-5 for an example).
9. Create a Bayesian network, using the above.

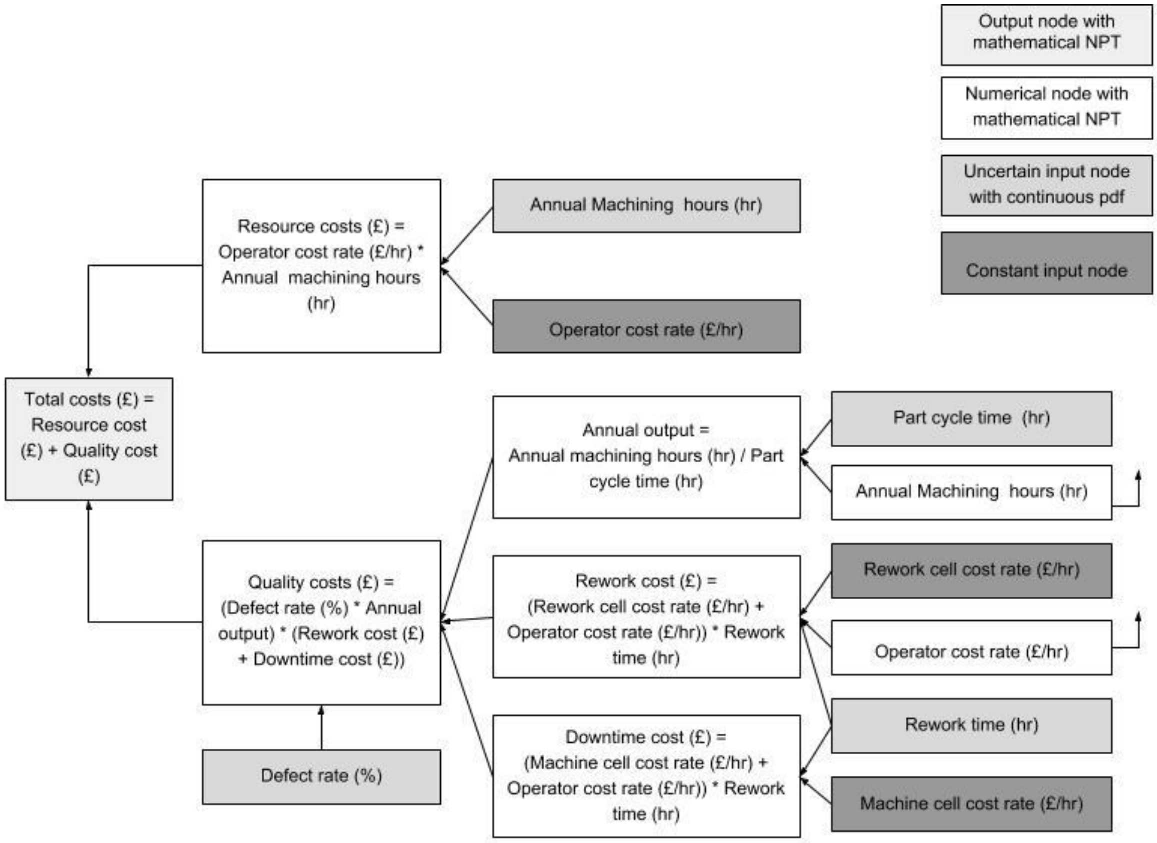


Figure 4-6 - Example structure for building a Bayesian network

Bayesian Networks work with discrete distributions. When uncertainty is propagated through continuous distributions this can cause errors in the shapes so continuous nodes need to be converted. To prevent this you can use dynamic discretisation [78], [172].

4.4.3 Decision support and visualisation/communication

This research is using multi-outcome decision support methods. Outputs such as return on investment (ROI) are typically used for business case decisions, but this research has shown that it is more powerful to include outputs which are required for cross stakeholder decision making. These are particularly useful for decision making earlier in the MCRL stage than ROI which does not show the full value proposition of a technology once adopted in industry. For example the results in Chapter 5 demonstrate that when ROI is clearly achieved (e.g. new filtration technology offers 4 months return) the technologies are still not adopted. The approach is also able to generate the high-level metrics required by stakeholders such as cost of quality. The ability to provide learning and evidence updating enables the impact of different cost drivers to be demonstrated and shows how they are affected by learning.

The simple example of a BN is built in AgenaRisk using the structure in Figure 4-6 to demonstrate how the results can aid decision making.

The BN allows multiple outputs to be displayed as pdfs which provide a wider picture of the value proposition with a level of confidence (see Figure 4-7).

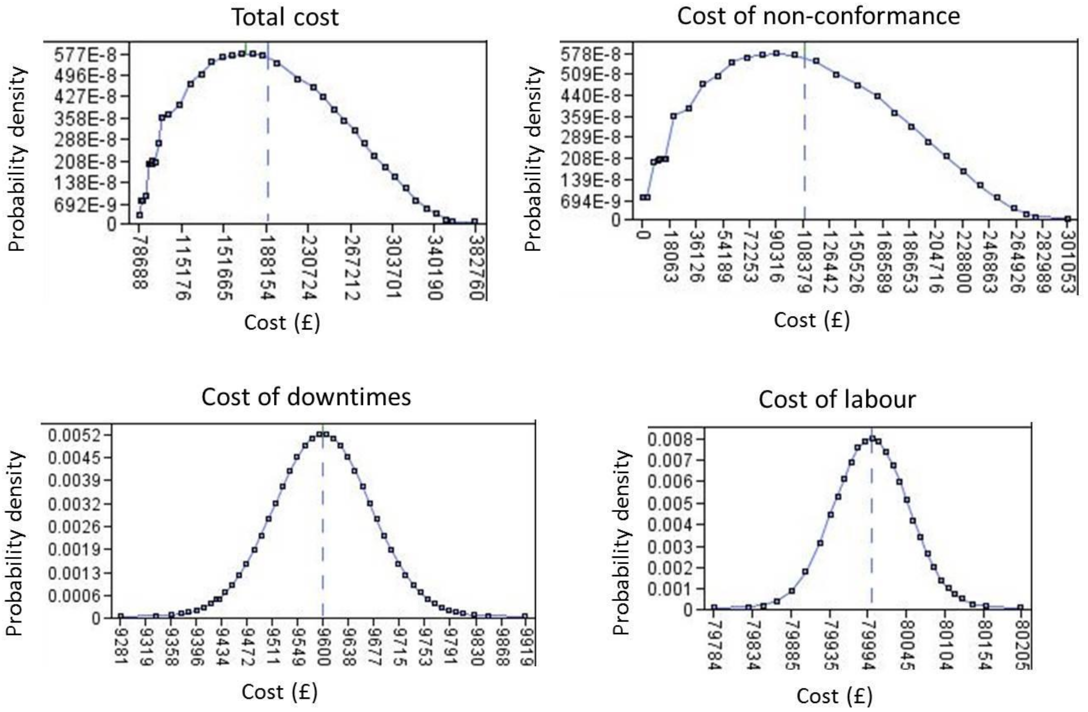


Figure 4-7- Multiple BN output nodes displayed as PDFs

The scenario capability enables alternative technologies to be compared and a toy example has been used to demonstrate this. The example includes two scenarios, new technology and exiting technology. Two operators are required to run the existing machine and one operator is required to run the new machine, and the effect on total costs can be shown in the output graph (see Figure 4-8).

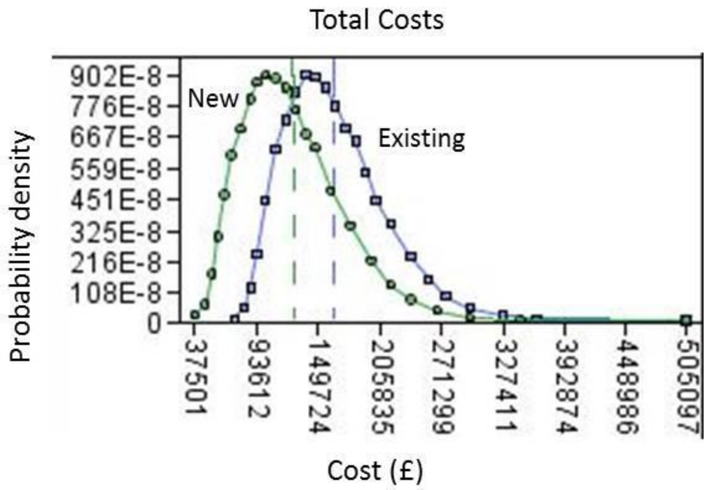


Figure 4-8 - Output graph showing total costs for two scenarios, existing and new machines

Sensitivity analysis can be used to determine cost drivers and their impact on certain output metrics. The sensitivity analysis in Figure 4.11 shows the total cost of varying the values of non-conformance (defects per 100 parts), part cycle time and rework time.

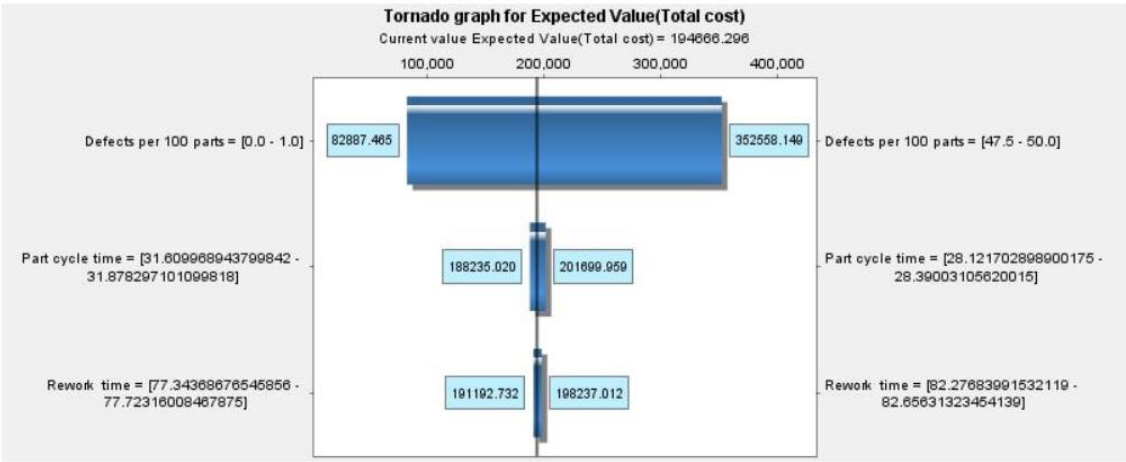


Figure 4-9 - Tornado diagram showing a Sensitivity analysis in a BN model

4.4.4 **Learning**

This research has highlighted the need to build learning into the process for decision making, gate reviews provide an appropriate opportunity for this as stakeholders can be asked to identify where additional evidence is available.

As explained in 4.4.1, expert judgement can be more accurately represented if elicited and as an uncertain prior judgement which is later transformed using Bayes theorem to a posterior value as evidence arrives [173].

The elicitation in 4.4.2 is reapplied to demonstrate the way that Bayes theorem is used in BNs to update the model when evidence arrives;

Updating with new evidence

In section 4.4.2, a beta prior is used for representing the uncertainty of experts about non-conformance rates ϕ.

$$\phi \sim Beta(a, b)$$

Equation 4.12

Giving a prior of:

$$f(\phi) \propto \phi^{a-1}(1-\phi)^{b-1}$$

Equation 4.13

The formula for the binomial likelihood is:

$$Likelihood = P^{x}(1-P)^{n-x}$$

Equation 4.14

We now observed some evidence that the number of non-conforming parts is 5 per 100, $x = 5$, $n = 100$.

And from Bayes theorem:

$$Posterior \propto Likelihood\ x\ Prior$$

Equation 4.15

$$Posterior = P^{x}(1-P)^{n-x}P^{a-1}(1-P)^{b-1}$$

Equation 4.16

$$Posterior = P^{a-1+x}(1-P)^{b-1+n-x}$$

Equation 4.17

This is a "conjugate distribution family" since the prior times the likelihood is also the same distribution as the prior. So the posterior function is also the beta distribution:

$$(\phi|x) \sim Beta\ (a+x, b+n-x)$$

Equation 4.18

$$Beta(2.99+x, 15.66+n-x)$$

Equation 4.19

Inserting vales for x and n gives a new distribution of:

$$Beta\ (2.99+5, 15.66+100-5)$$

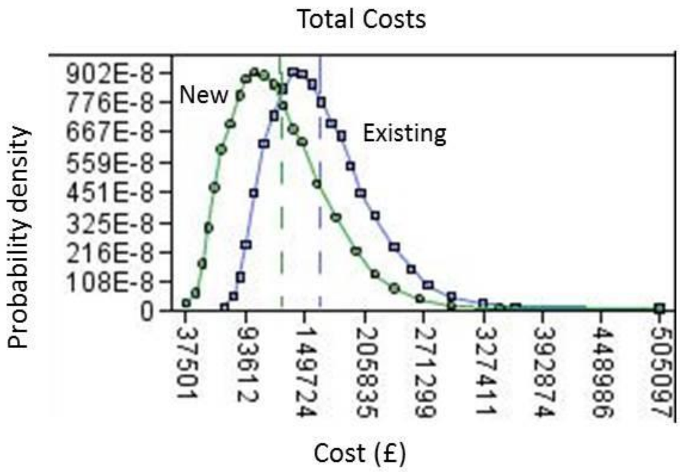
Equation 4.20

$$Beta\ (12.99, 105.66)$$

Equation 4.21

As the model can represent data as a distribution function, the new distribution can be placed in the relevant node and for updating to occur.

The BN software does this calculation automatically. Figure 4-10 shows the output from a BN model before and after this evidence has been incorporated. In this example the non-conformance rate of 10% has been observed for the scenario with the new machine. This evidence has reduced the average cost of the new machine from £130380 to £101440 and has also narrowed the uncertainty around the total cost estimation.



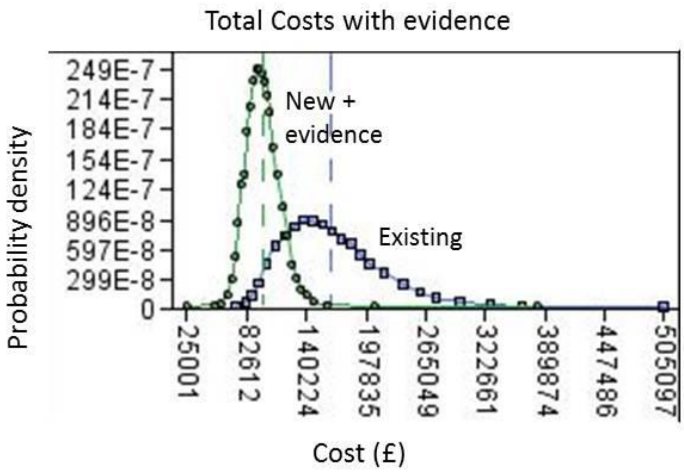


Figure 4-10 - BN output before and after new evidence is incorporated of 10% non-conformance rate for the new machine

Evidence and learning from all stakeholders should be captured and used to develop research proposals to ensure that the elements of technology that are invested in are the ones that give most value to the customer.

4.5 Tool sets

The requirement to evaluate the business case for a novel technology against an existing technology can be described as a decision problem with two or more alternatives, the current technology and alternative technologies with a high level of uncertainty. This can be mapped to a graphical model by creating scenarios, output parameters and variables with causality and interrelationships that are defined mathematically.

A standard cost modelling tree architecture was first used to build a graphical model of the decision problem and representation of all the cost related variables and interrelationships that are affected by the integration of the new technology. Using scenarios the baseline and alternative technology opportunities can be compared across output metrics. Vanguard Studio ™ is the preferred cost modelling tool used at Rolls-Royce and the AMRC and so was used in Chapter 3.

During framework development the model is mapped onto a BN to enable qualitative and quantitative data to be combined and forward propagation to occur. This also offers the opportunity to represent the output data as a dashboard of value across stakeholder key performance indicators. AgenaRisk ™ was chosen to model the BN due to its relative ease of use, functionality and affordability and was used in Chapters 5 and 6.

This section gives an overview of how these models were used throughout the research.

4.5.1 **Standard cost model for technology selection**

The Vanguard Studio™ architecture provides a visual representation of the relationships between variables. Each node in the model represents a variable which has a value. The nodes propagate from right to left with a mathematical representation of the relationship clearly visible in the dialogue box, input and values can be entered directly or read in from external spreadsheets. The model calculates total costs based on the mathematical relationships within the model, this is described as activity based costing (see Figure 4-11).

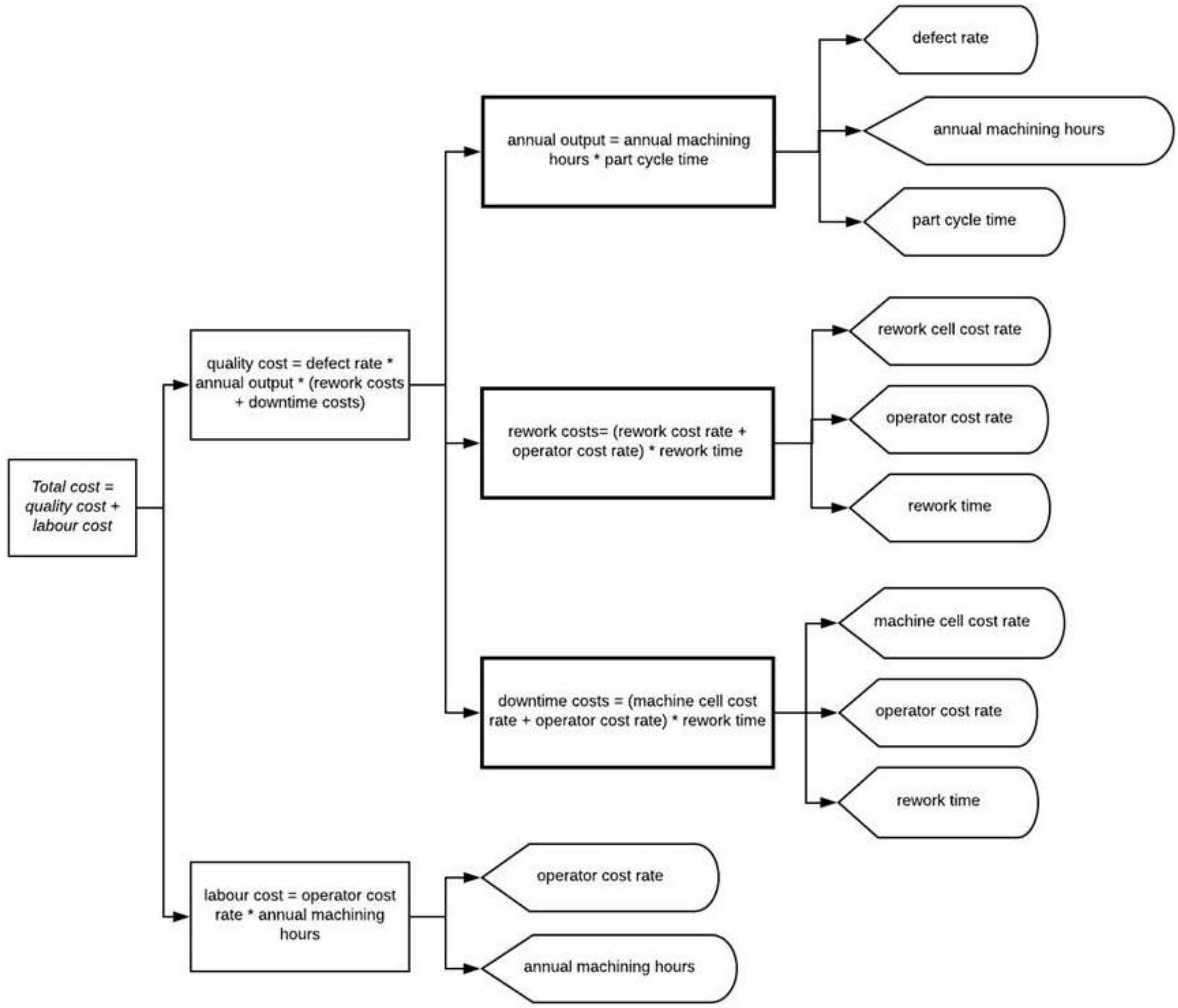


Figure 4-11 – Standard cost model architecture

The tool has the capability to model uncertainty by representing nodes as random variables using a three point estimate and Monte Carlo methods (see Figure 4-12). A sensitivity analysis can subsequently be performed to identify cost drivers by observing the effects on an output by varying a range of inputs for a given sample size of random variables (see Figure 4-13).

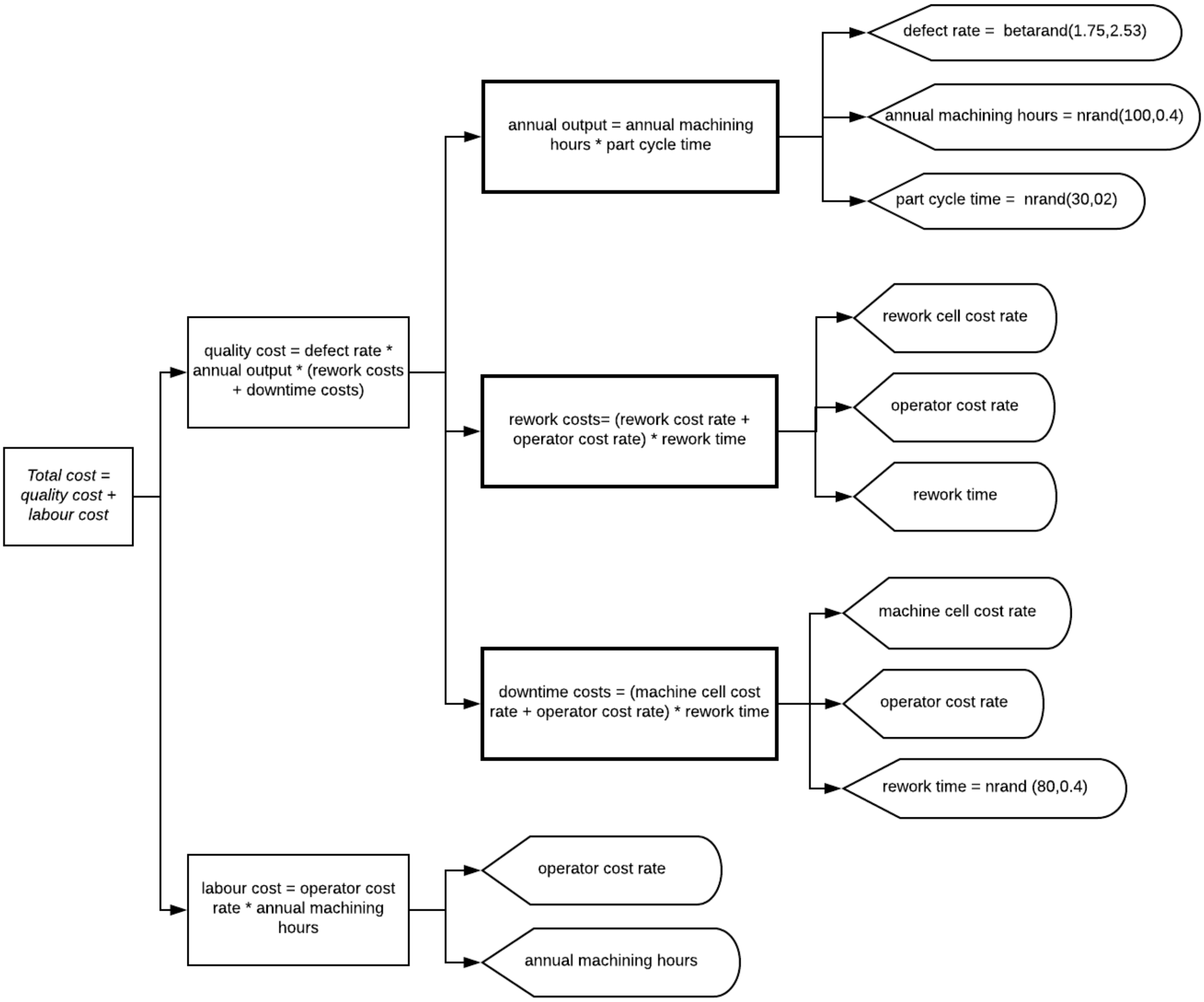


Figure 4-12 – Cost model with uncertain values

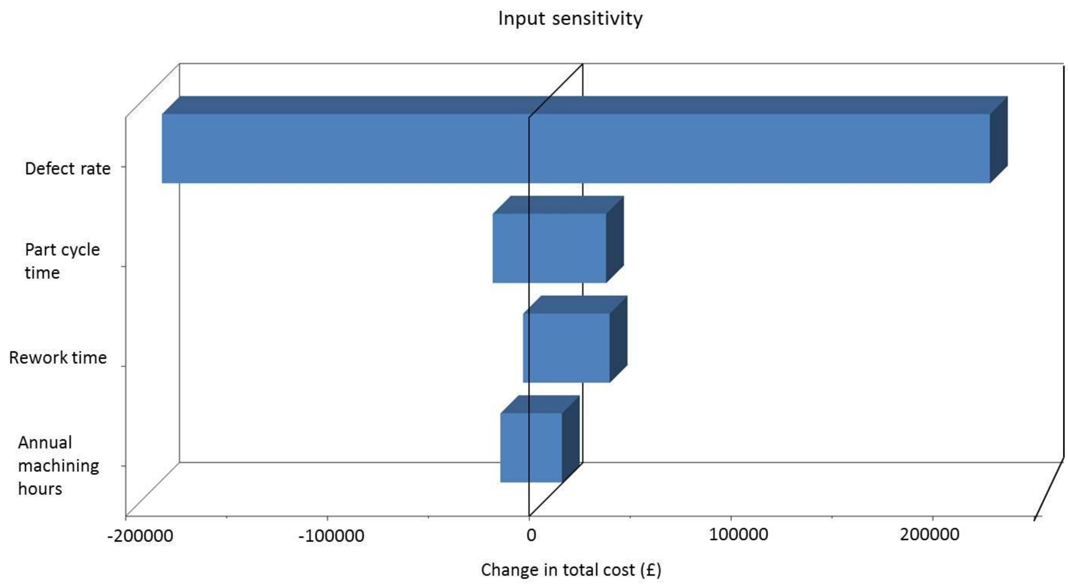


Figure 4-13 - Sensitivity analysis using Monte Carlo simulation

The modelling method described in this section provides a comprehensive graphical representation of the interrelated variables, cost drivers and mathematical relationships which can be used to support a business case for technology selection.

At this stage there are still some complexities highlighted in the framework that have not been included in this method. The model is somewhat static, evidence can be incorporated however propagation of continuous distributions is not possible and a level of confidence is required around the outputs. Uncertainty is significant in terms of lack of data and high levels of subjective judgement, furthermore the outputs are expressed for each output separately and if scenarios are run then comparisons are difficult to visualise.

The next stage of development includes the use of BNs. This provides a method to incorporate expert judgement with dynamic propagation of uncertainty. A level of confidence can be displayed for a range of outputs that are visible to multiple stakeholders. The aim is to provide support for more strategic decision making that has the potential to leverage interdepartmental buy-in of a business case for investment.

4.5.2 **BN models for technology selection**

Bayes Networks (in this research AgenaRisk™ software is used) are different from the Vanguard model as the mathematical or statistical relationships between the variables are determined in the arc between the nodes and a node probability table which represents the joint probability between parent and child nodes. When using numeric nodes, which will mainly be the case for novel technology selection, a range of pre-defined mathematical and statistical functions can be used, and an algorithm enables efficient dynamic discretisation for a large range of continuous distributions [78].

The nodes can represent constants, continuous distributions, Boolean or ranked variables. Each continuous node can be displayed as a distribution (see Figure 4-14). The interrelationships can be built as simple arithmetic expressions or probability distributions and can be built as partitioned expressions which separate data for each scenario. These can be displayed on the same graph as demonstrated in 4.4.1 Figure 4-6.

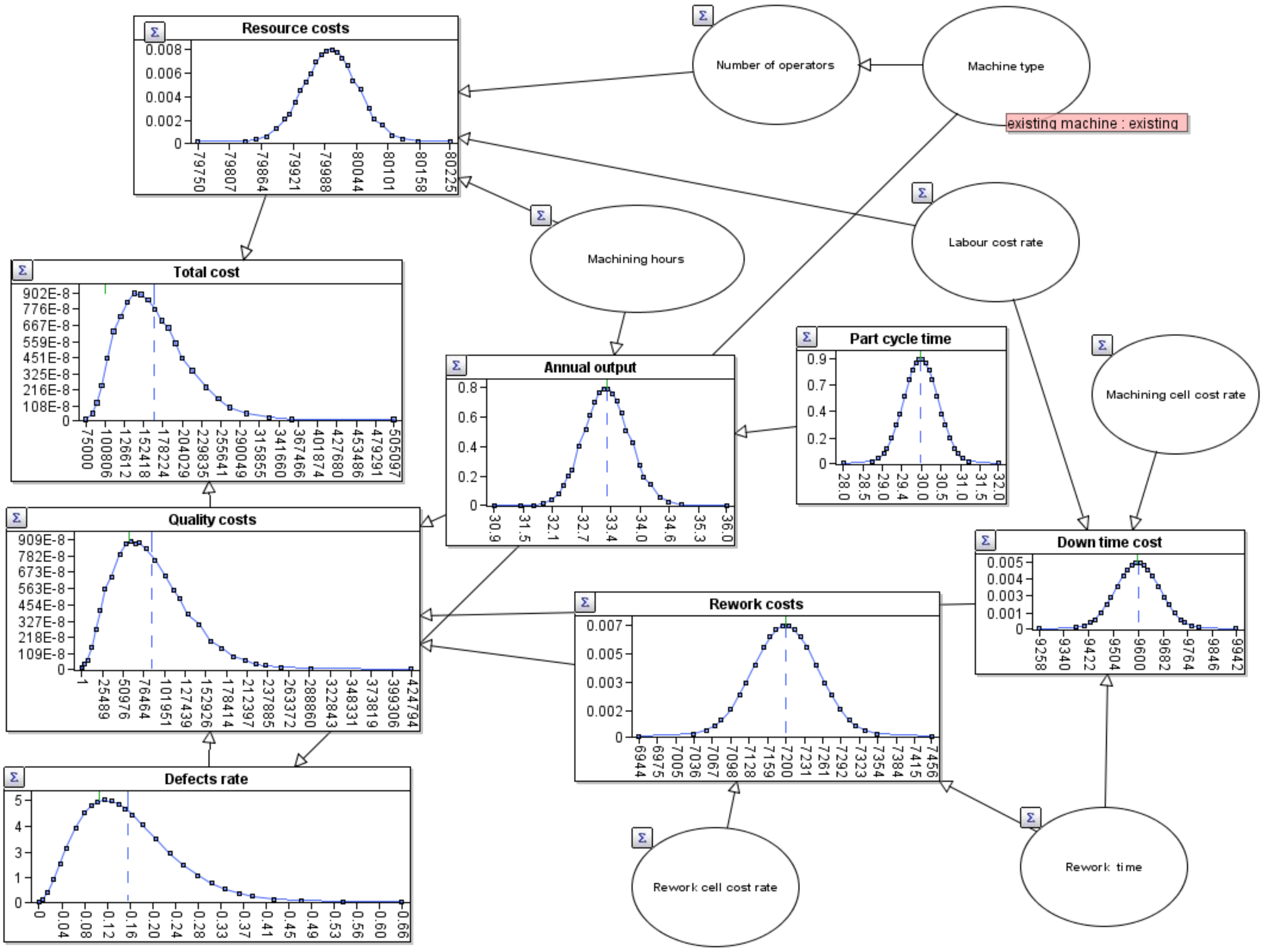


Figure 4-14 – A simple BN model example

Sensitivity analysis can be performed for each scenario on all of node types. The target node is selected and a range of nodes are used to perform the analysis, this enables cost drivers to be identified. The results can be displayed as a table, response curve or tornado diagram (see Figure 4-13).

When evidence is entered in the model, via a risk table or directly into a node, propagation occurs and the effects on the entire system can be represented graphically which is a powerful communication tool (see Section 4.4.2, Figure 4-8). Another advantage of BN representation is that it also allows hypothetical new evidence to be entered into the model enabling the value of the technology to be seen, assuming a trial provides a particular result. This can support decisions on whether the trial is worthwhile (and actually consider the trade-off that includes the extra investment in the trial). This is what is known as pre-posterior analysis.

4.5.3 **Summary**

To test the framework effectively, a range of complex capabilities are required in a model. This research has shown that a number of these capabilities are outside of the scope of the cost estimation software typically used in manufacturing and so a solution has been demonstrated using probability density functions and BNs to encompass the full suite of requirements set out below:

Elicitation – Include expert opinion and the uncertainties in judgement.

Elicitation techniques have been researched and furthermore an example has been given of eliciting a prior judgement as a probability distribution that can be used in the model and updated as new evidence arrives.

Consolidation - Combine both qualitative and quantitative data and map their interrelationships.

The causal relationships between variables can be mapped. The capability of the model to combine and propagate different types of data has been demonstrated.

Analysis – Perform sensitivity analysis to identify cost drivers and their dependencies.

Sensitivity analysis can be performed on any target node against a number of sensitivity nodes for each scenario.

Communication - Display outputs as key performance indicators relevant to a range of stakeholders.

The outputs are displayed as probability distribution functions with the mean and spread visible for multiple scenarios.

Feedback – Representation of uncertainties in data, updating and propagation to aid learning.

The model is capable of updating the level of confidence as new evidence appears using propagation.

4.6 Final framework to be developed using case studies

The framework has evolved to include elements that enable the AMRC to elicit, consolidate, analyse and communicate the multiple outputs required for decision making. The framework will be developed using two case studies to ensure that it is applicable across the MCRL phases (see Figure 4-15).

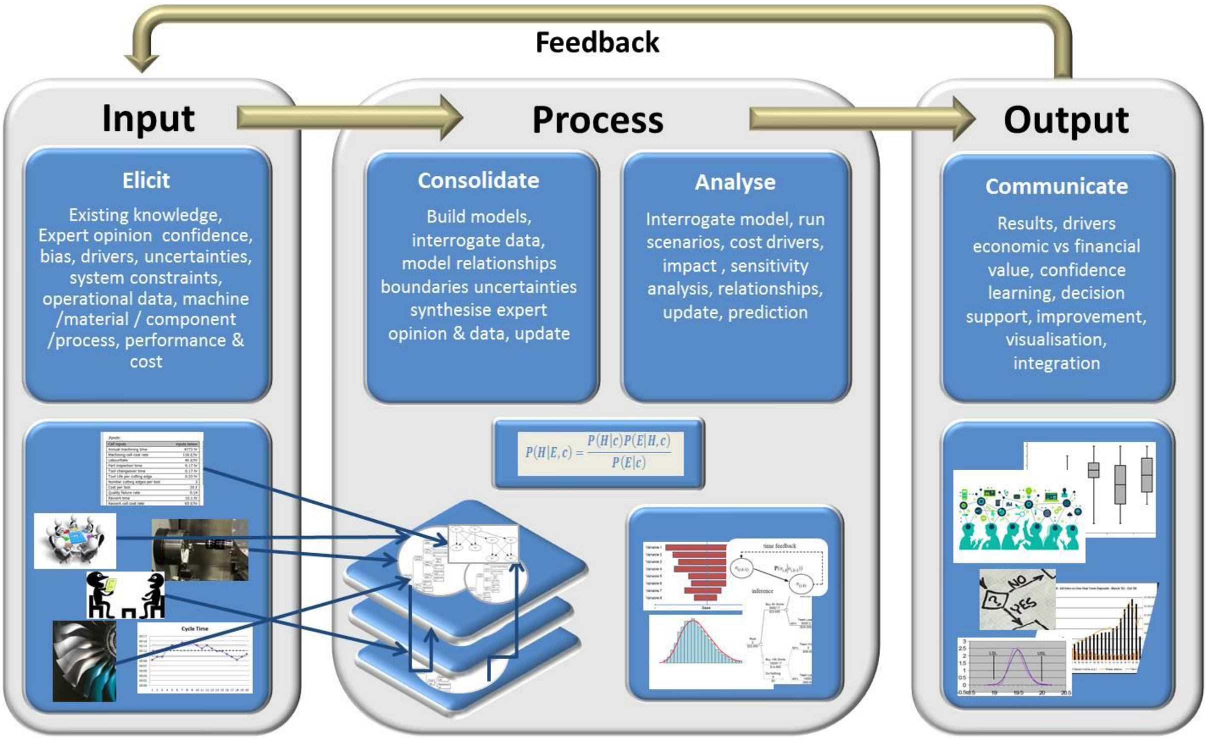


Figure 4-15 - Final framework to be developed using case studies

Recommendations for implementing of the framework fully will involve the methods described in Section 4.4. and the following:

Elicit

Ensure that cost related drivers and input parameters are identified as early as possible in road mapping sessions and at the scoping phase of all projects.

Capture both hard and soft evidence including uncertainties using expert elicitation where necessary.

Consolidate

Map all cost and value related parameters, uncertainties and their interrelationships, using existing cost models as a basis where available.

Ensure that continuous nodes represent the data appropriately, identifying parameters using Maximum likelihood where necessary.

Analyse

Identify sensitivities to cost of parameters using the built in sensitivity analysis and scenario capability.

Communicate

Results must be communicated as multi-objective outputs required by a range of stakeholders. This will ensure that the value proposition is communicated widely and provides an opportunity to validate the model as it is being built.

Feedback

Ensure that when new evidence emerges during road mapping sessions or at gate reviews that this is incorporated into the knowledge base and added to any relevant models. This will ensure that throughout the research project the most up to date information is available for decision making.

4.7 Chapter summary

The framework is built to provide a means of sharing cost and value related information across the MRCL phases and so improving the value of decision making. The intention is for early research and development in novel technologies to be directed toward those parameters that offer the best value proposition to industry, and likewise that industry describe their requirements clearly to research and development. The framework must be embedded into the quality gate procedures at the AMRC to provide consistency of use and to ensure that learning and feedback is incorporated as new evidence emerges.

The motivation for the framework comes from a request from Rolls-Royce to investigate an approach which reduces the risk of investing in novel technologies, ensuring that those investments are directed to aspects of technologies that provide the best value proposition. The Baseline evaluation helped to understand current practices within the AMRC, to capture complexities, requirements, suggestions and opportunities and to identify where the framework could be embedded into existing procedures. Framing the problem as a BN model provides a way to represent the variables and their interrelationships as well as a mechanism for providing decision support. Methods to elicit and synthesize the various forms of data are essential and best practices from the literature have provided an approach that decision makers can follow. Communication is crucial. The research uses multi-objective decision support to enable a range of stakeholders to see the impact of directing research to the various parameters of the technology.

The next chapters describe the two case studies selected to test the framework.

The first Case Study investigates how a novel technology is moved from pre-production to industry and provides recommendations for identifying the most useful outputs required by manufacturing research and development in support of multi-criteria decision making.

The second Case Study is within the research and development arena, with research into emerging coolant formulations and understanding how the framework can support early stage research to better align with industry requirements. The aim is to help ensure that investment in early stage technology development is directed at elements of technology which have the greatest impact.

5 Case Study 1 – Coolant management technology selection

5.1 Introduction

This chapter describes a Case Study which resides at interface 2 (see Figure 5-1) and investigates how a novel technology is moved from pre-production to industry. It provides recommendations for identifying the most useful outputs required by manufacturing research and development in support of multi-criteria decision making.

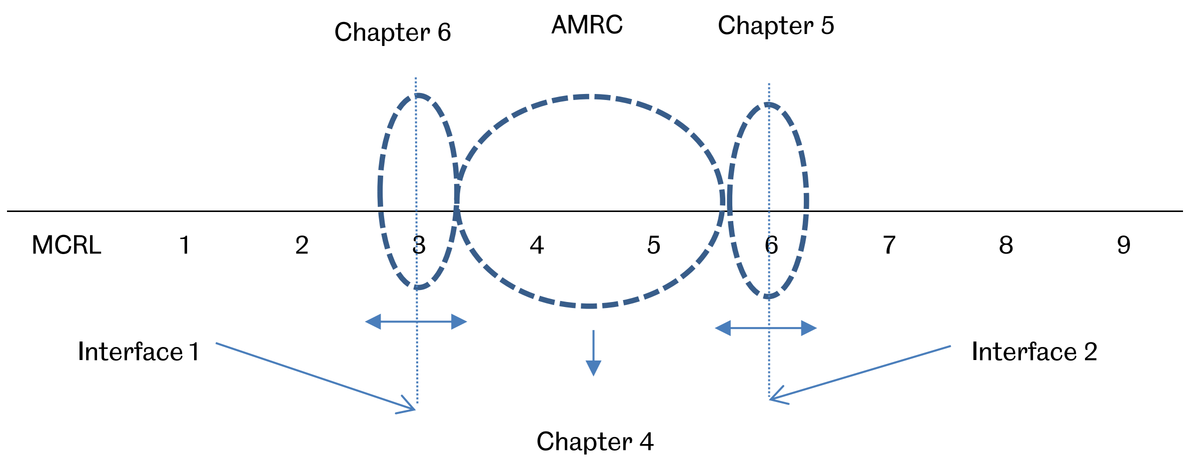


Figure 5-1 -Image showing how the thesis relates to the MCRL phases

5.2 Developing a new cutting fluid cost model

5.2.1 Stakeholder parameter validation

To ensure that these parameters are a reflection of current manufacturing practices and to identify any further requirements from stakeholders, a range of experts and working documents were consulted, representing suppliers, partners and departments from an advanced manufacturing research facility in the UK. Following ethical protocols for the research, details that could identify the experts have been removed and the results are combined in Table 3.6.

Each of the stakeholders was interviewed separately in a short face to face meeting. The first are cutting fluid technology suppliers, then three technical engineers were asked from different companies, who were partners at the AMRC. They sell their products to a range of high value manufacturing companies by developing fluids and fluid management systems which can compete in terms of fluid cost, sump life and improved machining performance. Next were two manufacturing engineers from Rolls-Royce, who are responsible for operational decisions in the production environment and have productivity, quality, waste reduction and process improvement targets. Next were two manufacturing research engineers from the AMRC, who are responsible for developing and testing state of the art technologies for high value industrial partners. Finally a sustainability manager was consulted from Rolls-Royce, who is responsible for companywide hazardous waste elimination and environmental impact reduction. All experts were asked to list the parameters that industrial decision makers should consider when selecting a coolant technology, the results of which are consolidated in Table 5-1. All stakeholders confirmed the lack of consolidated knowledge and need for a method to confidently determine the true cost and benefit of cutting fluid use.

Parameters to consider	Cost elements
Product type	Disposal costs
Material type & composition	Hazardous waste disposal quantity
Concentration and fluid stability	Waste water quantity
Lubricity Index/tool life and performance	Consumables disposal quantity
Surface quality	Water costs & treatment
Cooling ability/temperature	Coolant changeover labour cost
Pressure and flow capability and impact	Coolant changeover frequency
Filtration type/capability	Coolant changeover machine downtime costs
Nozzle shape and position	Maintenance time and cost
Influence and type machine (tramp) oil	Cost of additives
Maintenance additives and treatments	Maintenance and inspection costs (tank side)
Health and safety data	Maintenance and inspection labour costs
Waste management/handling requirement	Coolant sump and machine volume
Material compatibility	Cost of sampling/ testing
Coolant farm compatibility	Cost of inventory / storage
Swarf formation, management and recycling	Cost of non-conformance
Trigger for coolant change	Unplanned intervention time and cost
Root cause of coolant related failure	Set-up costs (foam settling/turnover costs)

Table 5-1 - Stakeholder coolant parameter and cost considerations

5.3 Requirements for a cutting fluid cost model

After consolidating insights from previous research and stakeholders the requirements for a more comprehensive cost model could be considered. A cutting fluid model needs to provide a map of the manufacturing process, capturing existing data, uncertainties in knowledge, and interrelationships between production parameters that are influenced by the use of cutting fluids. To achieve this map, the system can be decomposed into constituent cost elements, giving the benefit of re-using data and logic. Stakeholders identified that transparency of data is beneficial for communication and validation. To support these requirements, an object–oriented tree architecture (see Figure 5-2. for an example) would be very useful. Cost models of this kind have been effective in research into manufacturing processes by the cost and knowledge engineering community [49], [174], [175].

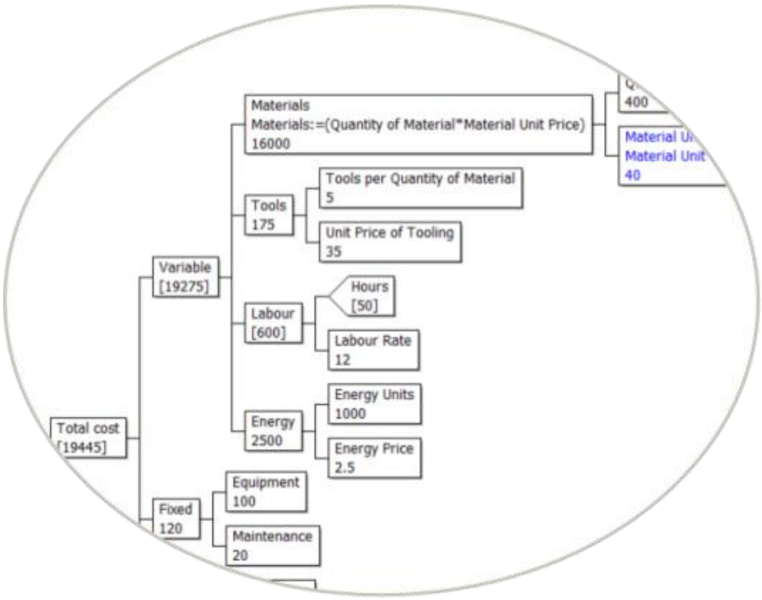


Figure 5-2 - Example of cost modelling tree architecture

The overall modelling framework should take input parameters from the machining process that are related to coolant usage, enable a cost model to be built that incorporates the interrelationships of those cost parameters and has the capability to run sensitivity analysis on those parameters. Outputs must demonstrate to a range of stakeholders the current cost of cutting fluid use as well as the cost of machining parameters that could be influenced by management and maintenance decisions. Such a framework is shown in Figure 5-3 and has been adopted for the cost modelling in this chapter.

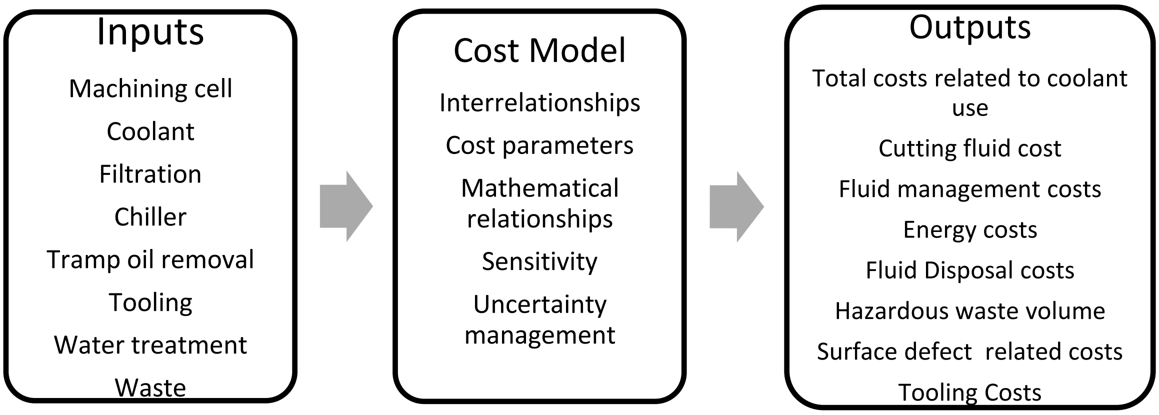


Figure 5-3 - Approach used to build the cutting fluid cost model

5.4 Cost model development

A range of input process parameters must be captured, relating to: (1) machining cell; (2) cutting fluid; (3) filtration; (4) chilling; (5) tramp oil removal; (6) tooling; (7) water treatment; and (8) waste. The chosen cost modelling methodology establishes the relationships between the input and output parameters and enables a systematic analysis to be performed to determine cost drivers and their sensitivities. The output parameters are: (1) total costs related to cutting fluid use; (2) cutting fluid cost; (3) fluid management costs; (4) energy costs; (5) fluid disposal costs; (6) hazardous waste volume; (7) surface non-conformance related costs; and (8) tooling costs. These parameters have been selected to demonstrate a breakdown of direct cutting fluid usage costs and also to identify potential cost reduction strategies – for example surface non-conformance and tool life can be influenced by improved coolant management, as discussed earlier.

A cost model of cutting fluid use has been created by mapping parameters identified in Table 5-1 and Figure 5-3 to a milling process in a high value manufacturing environment. The real system was used to identify the feasibility of collecting information related to each parameter; the numbers in the model have been altered due to confidentiality constraints. From this model certain aspects of coolant use can be analysed to see their impact on output metrics and to determine which areas are important to focus on when attempting to reduce the negative impacts of cutting fluid use.

5.4.1 **Software selection**

Vanguard Studio™ software was used to build the cost model as it is the software of choice at Rolls-Royce and the AMRC. Other commercially used systems are available such as SEER [176] and Apriori [177], and these systems are able to construct cost estimations from CAD features but rely on a manufacturing knowledge database which is stored by the software company and Rolls-Royce are not comfortable with a third party storing detailed cost information, so insist on the use of Vanguard to enable the security of cost information. As this research relies on sensitive cost information to provide a solution to Rolls-Royce the Vanguard was the software of choice.

The useful features of Vanguard include; the availability of data analysis tools such as Monte Carlo simulation and sensitivity analysis; clear visualisation of data/calculations; a logical tree structure, ease of use; an object oriented approach so that templates and generic models can be used and its ability to read from excel.

The modelling environment is a simple tree structure using parametric cost estimation; the relationships are built up systematically between variables using cost calculations that were chosen based on existing cost calculations used at Rolls-Royce PLC during in-house training of Vanguard software and through the review of cost calculations used in Chapter 2.

The inputs and outputs declared in Figure 5-3 have been used to build up the cost relationships in the form of sequences of equations. As discussed earlier, cutting fluid use and management has been shown to reduce tool life, improve surface finish and increase the speed of machining operations. This in mind, the cost associated with reduced non-conformity due to surface anomalies has been incorporated in the total annual fluid related cost so that a reduction in non-conformance can be simulated. The lack of knowledge in the effects of cutting fluid management leads to sump life holding less importance than surface non-conformance so the model calculates sump-life from non-conformance rate not vice versa. Since the annual tooling cost is not directly attributed to the cutting fluid, the tooling costs have been included as a separate output. However, when analysing the cost model, an increased tool life can be simulated to see the sensitivity to cost in terms of total tooling cost and the reduction in fluid related costs simultaneously. Similarly, with the potential for increased cutting speed, the production output variable is embedded into the cost model so that when an increased production output is simulated, the economic impact can be studied. The nature of the model tree allows the output display to include specific requirements for alternative stakeholders – for example hazardous waste volume is required by environmental managers, cutting fluid costs by procurement and the overall fluid related costs by operational decision makers.

5.4.2 **Fluid related costs**

The total annual fluid related cost is the sum of the annual variable costs and the annual fixed costs per machine, related to fluid use Equation 3.4:

$$TAC_{fr} = AVC_{fr} + AFC_{fr}$$

Equation 5-1

Where TAC_{fr} is total annual fluid-related costs per machine (£), AVR_{fr} are the annual variable costs per machine related to fluid use (£) and AFC_{fr} are the annual fixed costs per machine related to fluid use (£).

5.4.2.1 **Variable cost calculations**

The annual variable costs are calculated as:

$$AVC_{fr} = AC_c + AC_{fi} + AC_{sm} + AC_{fd} + AC_e + AC_{qfr}$$

Equation 5-2

where AC_c is annual cost of coolant (£), AC_{fi} is annual cost of fluid inspection and maintenance (£), AC_{sm} is annual cost of swarf management (£), AC_{fd} is annual cost of fluid disposal (£), AC_{qfr} is annual cost of fluid related quality (£), AC_{ce} is annual cost of energy (£) and AC_{fc} is annual cost of filtration consumables (£).

Breaking the costs down further:

5.4.2.2 **Annual cost of coolant**

The annual cost of coolant AC_ccan be estimated from:

$$AC_c = AC_{cf} + AC_w + AC_{tu}$$

Equation 5-3

Where AC_{cf} is annual cost of cutting fluid per sump change (£), AC_w is annual cost of water per sump change (£) and AC_{tu} is annual cost of top-up (£),

and:

$$AC_{cf} = (12/LS_c) \times (CU_{cf} \times V_s \times FC)$$

Equation 5-4

Where LS_c is life span of coolant (months), CU_{cf} is unit cost of cutting fluid (£/$m3$), V_s is sump volume (m^3) and FC is fluid concentration (%),

and:

$$AC_w = (12/LS_{cf}) \times (WR \times V_s \times (1 - FC))$$

Equation 5-5

Where WR is water rate (£/l),

$$AC_{tu} = V_{tu} \times \left(CU_{cf} \times TU_c\right) + (WR \times (1 - TU_c))$$

Equation 5-6

Where TU_c is top-up fluid concentration(%).

5.4.2.3 **Fluid inspection**

The annual cost of fluid inspection AC_{qfi} can be estimated from:

$$AC_{fi} = AC_{ic} + AC_{il} + AC_{sc}$$

Equation 5-7

Where AC_{ic} is annual cost of inspection consumables (£), $AC_i l$ is annual cost of inspection labour (£) and AC_{qsc} is annual cost of sump change (£).

where:

$$AC_{ic} = AC_{tc} + AC_{ttc}$$

Equation 5-8

Where AC_{tc} is annual cost of testing consumables (£) and AC_{ttc} is annual cost of treatment consumables(£).

$$AC_{il} = I_f \times T_i \times LR$$

Equation 5-9

Where T_i is inspection time (hr), I_f is inspection frequency $(/yr)$ and LR is labour rate $(£/hr)$,

and:

$$AC_{sc} = (12/LS_c) \times T_{sc} \times LR$$

Equation 5-10

Where T_{sc} is time taken for a sump change(hr).

5.4.2.4 Fluid disposal

The annual cost of fluid disposal AC_{fd}can be estimated from:

$$AC_{fd} = DR_c \times \left((12/LS_c) \times V_s\right) + V_{tu}$$

Equation 5-11

Where DR_c is disposal cost rate $(£/l)$.

The annual cost for energy AC_e is the sum of energy cost rate for the coolant delivery system ECR_{cd}, chiller ECR_{ch}, filtration system ECR_{fs} and conveyors ECR_{con} multiplied by the annual machining time AT_m.

$$AC_e = AT_m \times \left(ECR_{cd} + ECR_{ch} + ECR_{fs} + ECR_{con}\right)$$

Equation 5-12

5.4.2.5 Cost of quality

The annual cost of quality related to surface non-conformance AC_{ncr} can be estimated from

$$AC_{ncr} = (APO \times QNCR_{sd}) \times \left(AC_{mq} + AC_{lm} + AC_{rw}\right)$$

Equation 5-13

Where APO is annual production output (units), $QNCR_{sd}$ is annual surface non-conformance rate (%), AC_{mq} is annual cost of maintaining quality (£), AC_{lm} is annual cost of lost machining time (£) and AC_{rw} is annual cost of rework (£),

and:

$$AC_{mq} = T_i \times LR$$

Equation 5-14

Where T_i is part inspection time (hr),

and:

$$AC_{lm} = D_{rw} \times CR$$

Equation 5-15

Where D_{rw} is delay time for rework (hr) and CR is machining cell cost rate $(£/hr)$,

and:

$$AC_{rw} = LR \times T_{rw}$$

Equation 5-16

Where T_{rw} is rework time (hrs).

The trigger for a sump change in this example is a non-conformance due to surface non-conformance, so simulated improvements to quality non-conformance rate will be reflected in the sump life variable and will propagate through the model.

5.4.2.6 **Tooling Costs**

The annual tooling cost AC_t (£) is estimated as:

$$AC_t = (C_t + C_{tco}) \times \left(AT_m/(L_{tce} \times N_{tce})\right)$$

Equation 5-17

where C_{tco} is cost per tool change over $(£)$, AT_m is annual machining time (hr), L_{tce} is tool life per cutting edge (hr) and N_{tce} is the number of cutting edges per tool.

The cost per tool change is calculated as:

$$C_{tco} = T_{tco} \times RL$$

Equation 5-18

Where T_{tco} is time for a tool changeover (hr) and RL is labour rate $(£/hr)$.

Tool life can be increased by improving cutting fluid management. Changes to tool life could therefore be simulated in the model and used in the sensitivity analysis.

5.4.2.7 Fixed cost calculations

The annual fixed costs related to cutting fluid AFC_{fr} are the sum of all the annual costs of machinery required to deliver and manage the coolant. These are coolant delivery AC_{cds}, tramp oil removal AC_{tors}, filtration AC_{fs} and water treatment AC_{wts}.

$$AFC_{fr} = AC_{cds} + AC_{tors} + AC_{fs} + AC_{wts}$$

Equation 5-19

These annual fixed costs per machinery item break down to the sum of purchasing C_p, installation C_i, and disposal costs of each machine C_d, divided by the number of years that machine is likely to be in service (depreciation, D):

$$AC_{(each\ machine)} = (C_p + C_i + C_d)/D$$

Equation 5-20

5.4.3 Model implementation

The model is constructed using the cost calculations described in the previous section. In this example there are two higher level output parameters: total annual fluid related costs and annual tooling costs. Once the mathematical equations are written into a node in the Vanguard software, the tree structure is automatically constructed. Figure 5-4 is a partially constructed tree demonstrating how each branch can be populated. Once declared as an input each parameter is displayed in the table on the left and can be easily validated and altered by the user, similarly the declared output values are highlighted.

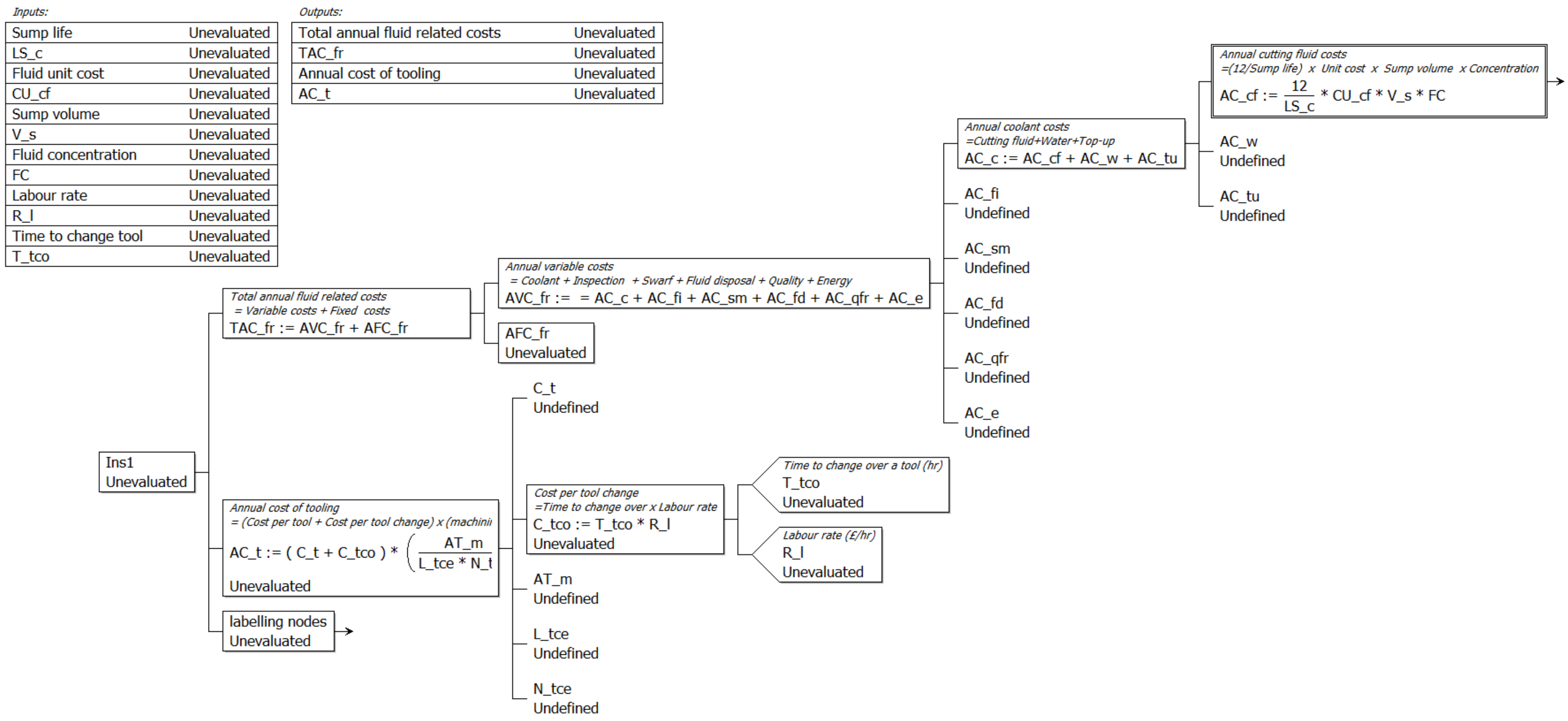


Figure 5-4 – Partial cost model tree construction

As discussed in previous sections, modelling uncertainty in a cost model improves the accuracy and validity of a cost model. Monte Carlo methods provide a simulation-based means of modelling uncertainty. In this approach, uncertain inputs are modelled using a range of probability density functions – the point estimates typically used in cost estimation can then be replaced with probability distributions which reflect uncertainty. The Monte Carlo method then involves sampling from the uncertain inputs and running the simulation for each set of input samples. In this way, the input uncertainties are propagated to the model outputs. The results can be displayed using various types of probability plot (e.g. cumulative distributions, box plots, or histograms) that demonstrate the range and likelihood of reaching potential outcomes in the simulation. Figure 5-5 shows uncertain variables used for top up quantity and concentration. Top-up is the result of evaporation, drag out, machinery leaks, as well as the efficiency of filtration, tramp oil removal and conveyor systems and so volumes can vary significantly and the concentration varies by the quantity lost due to evaporation. The distribution can be estimated by expert judgment, in this example a triangular 3 point estimate was elicited for top-up concentration TU_c, with min, mode and max estimates of 1%, 2% and 4% respectively. Alternatively, the distribution can be determined by observing existing data, in this example the top-up volumes V_tu for the previous year were found to fit a normal distribution, with a mean of $400l$ and standard deviation of$150l$.

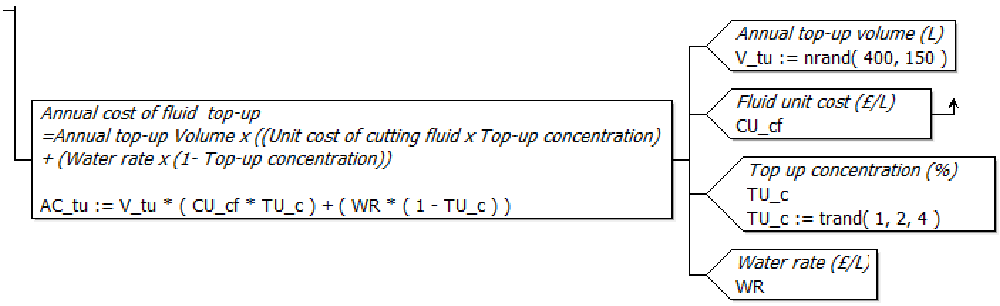


Figure 5-5 – Cost model branch showing uncertain inputs

Different scenarios can be represented to meet the requirements of each stakeholder and can reflect the level of granularity in data for a particular process. The use of logical statements (e.g. IF THEN) in the model enable outputs to be based on a range of pre-determined input data. Figure 5-6 shows how such a statement can be used to switch on or off the requirement of a chiller.

```
Energy rate for chiller (£/hr)
ECR_ch := ( _IFELSE( ( Is chiller required == "Yes" ), ( ( ECR_ch ) ), ( ( 0 ) ) ) )
```

Figure 5-6 - Logical statement in model construction

5.5 Findings

The model uses real data but this has been sanitised due to its commercially confidential nature. The relationships shown in this section are, however, indicative of the relationships and findings in the true real-world problem.

The model is developed with an interface that can be easily manipulated by the user, Figure 5-7 shows the user interface for the fully populated model, with input parameters selected based on data that is typically available for the machining cell. The model determines the total annual fluid related cost, and a breakdown of these into the cost of cutting fluid, the costs associated with surface quality non-conformance that had been linked to fluid contamination, the energy costs of fluid management machinery, and the fluid disposal costs. The total tooling costs are included as an output to demonstrate where coolant based decisions can have a significant impact on the cost of running a machining cell. The model shows that the majority of cost related to cutting fluid use is linked to surface non-conformance quality costs, namely sump changes and rework. As a result this model can be used to highlight the importance of fluid management, which is known to improve surface quality and extend sump life.

Inputs:

Cell inputs	inputs below
Machining type	Milling
Annual machining time	5000 hr
Annual cell production output	50
Machining cell cost rate	100 £/hr
LabourRate	50 £/hr
Part inspection time	0.25 hr
Surface quality failure rate at machine	15%
Rework time	10 hr
Rework cell cost rate	40 £/hr
Length of rework delay	84 hr
Sump changeover time	5 hr
Cutting Fluid inputs	inputs below
CuttingFluidUnitCost	6667 £/m^3
WaterRate	5 £/m^3
Cutting fluid concentration min	6%
Cutting fluid concentration max	10%
Inspection consumables cost	4 £
Likelihood of coolant treatment	50%
Inspection frequency per year	52
Inspection time	0.17 hr
Treatment consumables cost	20 £
Tramp oil removal system inputs	inputs below
TORS Purchase price	1200 £
TORS Depreciation years	10
Water treatment system inputs	inputs below
WTS Depreciation years	10
WTS Purchase price	8000 £
Filtration system inputs	inputs below
FS Purchase price	20000 £
FS Energy cost rate	0.85 £/hr
FS Depreciation years	10
Annual cost of FS consumables	300 £
Fluid waste inputs	inputs below
Cost per litre disposal	130 £/m^3
Chiller inputs	inputs below
Is a chiller installed	Yes
Chiller Purchase price	10000 £
Chiller Depreciation years	10
Chiller Energy cost rate	0.85 £/hr
Tool inputs	inputs below
Cost per tool	30 £
Number cutting edges per tool	2
Tool Life per cutting edge	0.5 hr
Tool Changover time	0.1 hr

Outputs:

Total annual fluid related cost	101190 £
Annual cutting fluid cost	12656 £
Annual cost due to quality defects	66094 £
Annual fluid disposal cost	2925 £
Annual Energy costs	8500 £
Annual tooling cost	225000 £

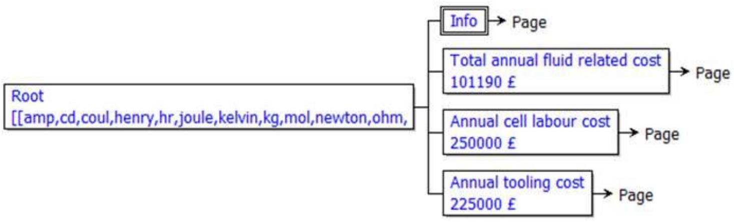


Figure 5-7 - Cost model diagram showing input parameters and outputs with no uncertainty

The model provides single point output values without any confidence levels. The addition of the stochastic parameters quality non-conformance rate, concentration, and top-up rate(%), enable a Monte Carlo simulation to be run that demonstrates the variability in the outputs. Figure 5-8 shows the probability density distribution of the total fluid related costs. The software is able to fit the most likely distribution, in this case normal distribution to the data. The actual cost values cannot be shown, however the probability distributions in the model are based on estimations from actual data and so the shape and spread relate to representative manufacturing conditions and demonstrate the confidence in output cost values.

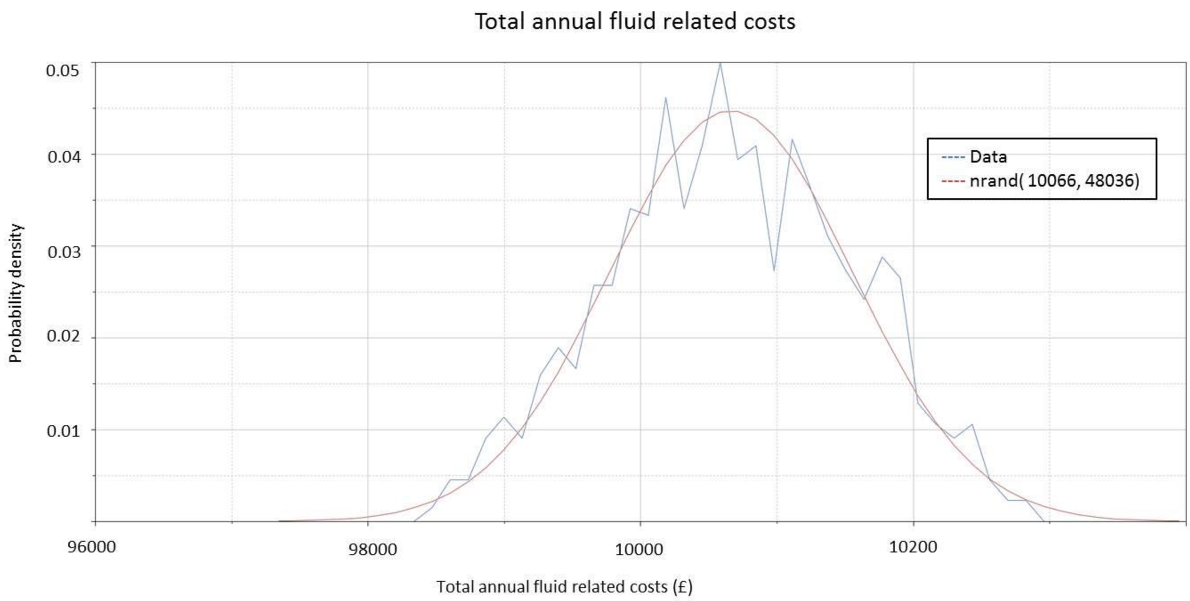


Figure 5-8 - Pdf graph showing uncertainty related to total annual fluid related costs

Next a scenario was run to investigate the impact of improving non-conformance rates. Figure 5-9 demonstrates that reducing non-conformance by 10% reduces total coolant related costs by around 60%, which would provide a strong business case for investment in improved fluid management practices and technology. Furthermore due to the relationship mapping in the model, additional information can be added in terms of waste fluid volume which reduces again by over 60% per year in this scenario, linking directly to a cross stakeholder driver adding weight to the investment decision.

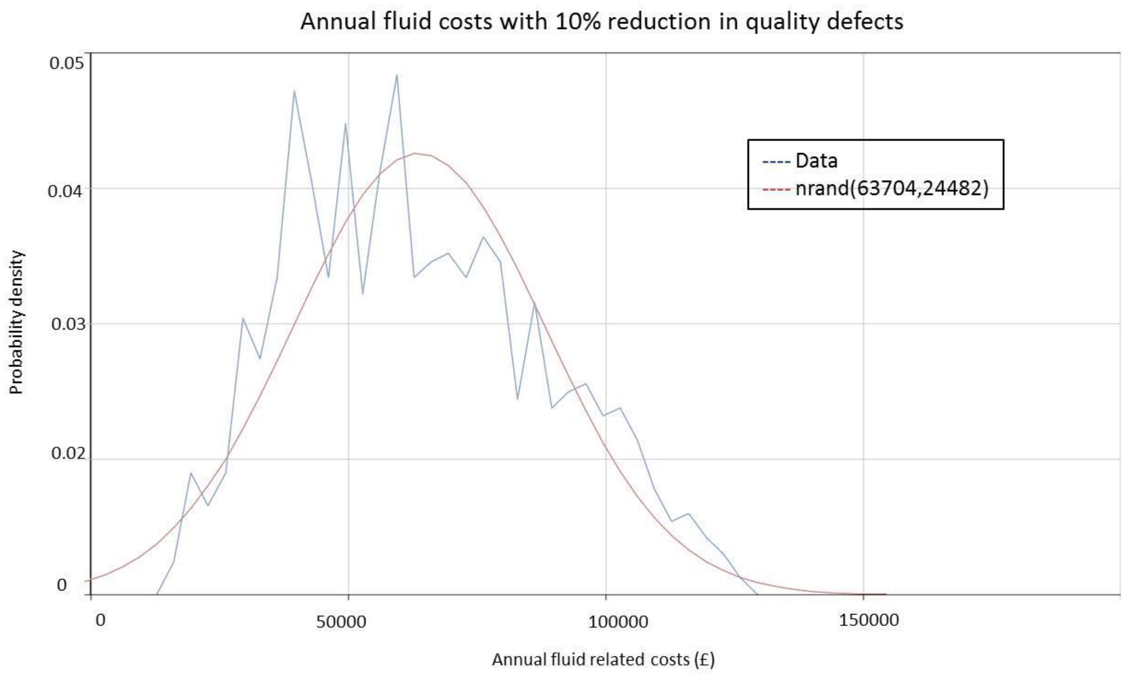


Figure 5-9 - Frequency distribution showing total annual fluid related costs with 10% reduction in quality defect rate

5.6 Discussion and recommendations

Difficulty of machining high value materials causes significant operational costs and disruption. Improved cutting fluid formulations and management practices offer the potential to machine faster with reduced surface non-conformance, increased tool life and enhanced machinability whilst reducing environmental impacts. Development in this area offers a potential step change in capability and cost in advanced manufacturing environments with the emergence of technologies such cryogenic machining. To better understand the value of using these new capabilities, decision makers have communicated the need for a model that demonstrates the current total cost of coolant use.

There are many hidden costs in the use of coolant. Cost models used in industry rarely include the majority of them. The largest costs in a machining process are related to machining time and tool wear and this is in turn related to coolant performance, yet less emphasis is put on coolant management practices than cutting fluid formulations [146]. Even the most elaborate models (e.g. [132], [146]) do not include all of the costs identified in this research – for example consumables, cost of quality, and integration

– and very few analyse cost sensitivity or simulate uncertainty in data. Cutting fluid usage costs are often combined with maintenance or running costs and it is reasonable to suggest that many of these costs are assumed as being insignificant or out of scope and are not accurately planned into the business case of a new cutting fluid or coolant system. The impact of cutting fluid use is far reaching and so offers a potential area for research into cost methods which could influence technology decisions that have a significant impact on quality, tool-life, machining performance, productivity, maintenance, health and safety, and environment amongst others.

This chapter has highlighted production parameters that are significantly affected by coolant use and management in an advanced manufacturing environment, and exposure to the model will support stakeholder understanding of this area. The model has shown that there are many costs related to cutting fluids use and management and that often these are not fully captured in cost models. Cutting fluid related variables interact with critical machining performance indicators. The model has been developed from requirements of stakeholders including coolant technology suppliers as well as operational, strategic and environmental experts to help ensure that it is useful for decision making for operational procedures, environmental policy and technology development. The causal relationships included in the model enable a cross-stakeholder understanding of the impact of specific changes. The capability of modelling uncertain variables will aid understanding of sensitivities in the system and strengthen the confidence in decision making.

The scenario presented demonstrates the benefit of the model for supporting business case decision-making investment in improved fluid management. It provides an estimate of cost reduction and the impact on fluid waste reduction enables cross-stakeholder input and support for the investment decision. In a data rich environment, parameters such as consumables and tooling cost reduction can also be included, providing further insight on the cost implications of fluid management.

The environmental aspect, particularly in relation to hazardous waste disposal due to coolant sump life and contaminated filtration consumables is an aspect which is growing in strategic importance and cross-departmental collaboration will help to identify opportunities to reduce waste whilst improving operational performance.

Further development of this cost modelling approach is essential. A particular challenge is the modelling of uncertainty and more accurate relationship mapping with other machining process parameters where data is scarce. The framework must be applicable across the MCRL phases of technology development and enable the alignment of technology research and development decisions with industry requirements. Both industrial environments and technology development are dynamic and new evidence will often appear and so an alternative method of representing uncertainty in a model that can dynamically propagate this uncertainty is an area for further research.

The next chapter introduces a new value-focussed approach for manufacturing capability decision making and a resulting framework which will later be developed in two case studies.

5.7 Background to the Case Study

High temperature nickel based super alloys are used extensively in the aerospace sector due to their ability to maintain outstanding mechanical performance and corrosion resistance when subjected to extreme temperatures in the gas turbine. For a number of reasons these materials are regarded by both academics and industry as 'difficult to machine' and as many of the components produced in this material are safety critical, they are also subject to stringent quality control procedures [133].

The machining process under consideration uses standard industry computer numerically controlled (CNC) milling equipment in the finishing cell. Non-conformance problems have arisen with the introduction of next generation powder based metal alloys, leading to undesirable levels of rework and inspection, causing disruption to operational performance.

Coolant management has been proven to provide benefits to machining feeds and speeds and tool life alongside quality improvements [127], [146]. A previous investigation carried out at a Rolls-Royce facility suggested coolant contamination as a potential factor, providing evidence that improving coolant cleanliness could offer significant improvements to the surface finish of components. The technology used for this investigation is the Integrated Fluid Delivery and Recycling (IFDR) system provided by a tier two partner, Fluid Maintenance Solutions (FMS), at the AMRC. The IFDR is a hydro cyclone filtration technology capable of filtering dirty coolant from the machine sump down to < 10μ particle size, removing residual machining oils using a weir system and delivering clean coolant directly back to the cut. This technology may offer a solution – however, the technology has not been substantively evaluated in Rolls-Royce facilities. The uncertainty over effectiveness, together with the capital cost required to test the technology, creates a barrier to its introduction.

Understanding the full value of any technology requires a detailed examination and comparison against existing technologies across multiple production variables [178]. When the business case for technology introduction is, as here, the requirement to provide a solution to a particular problem, then the direct financial cost of purchasing and installing the technology must be balanced against the impact of solving the problem. This comparison may not provide a large net benefit and so accounting for a range of outputs in the selection or comparison of a technology could provide a stronger case for investment and is investigated here.

Chapter 3 suggests a lack of understanding of all of the costs and value associated with coolant management and usage in Rolls-Royce as a business. A better understanding of the underlying cost drivers is required which link cost to quality and productivity. The main cost drivers associated with the initial business case are non-conformance rates and sump life; once the problems appear the coolant is changed, so these two factors are directly related. Although these parameters enabled the adoption of the system for a trial to commence it takes a long time to do so, inclusion of the waste streams and environmental factors identify further value opportunities (e.g. reducing hazardous waste disposal by extending sump life, reducing fluid treatment by stabilizing coolant chemistry, eliminating consumables such as paper media and filter cartridges along with the associated maintenance and downtime costs).

This Case Study provides a deeper insight into the value streams of cutting fluid use and demonstrates how this value may be greater than anticipated in the initial business case.

The aim of the Case Study and ultimately the thesis is to test, reflect on, and further develop the framework introduced in Chapter 4 against decisions involving the introduction of novel technology in manufacturing R&D.

The objectives were to:

1. Collect and collate operational parameters associated with coolant use.
2. Construct the cost model developed in Chapter 3.
3. Interview process experts to elicit qualitative evidence and decision making processes.
4. Provide evidence of changes to non-conformance rate, costs, and sump life to support the business case for a trial of the technology.
5. Populate and develop the model by iteratively applying the framework from Chapter 4.
6. Reflect on the ability of the framework to support manufacturing decision making.

5.8 Applying the framework

There are four main parts to the framework in Figure 5-10: input, process, output and feedback. The application of the framework was iterative, first identifying key variables and drivers and then re-visiting these in three loops when more information was needed to support decision making.

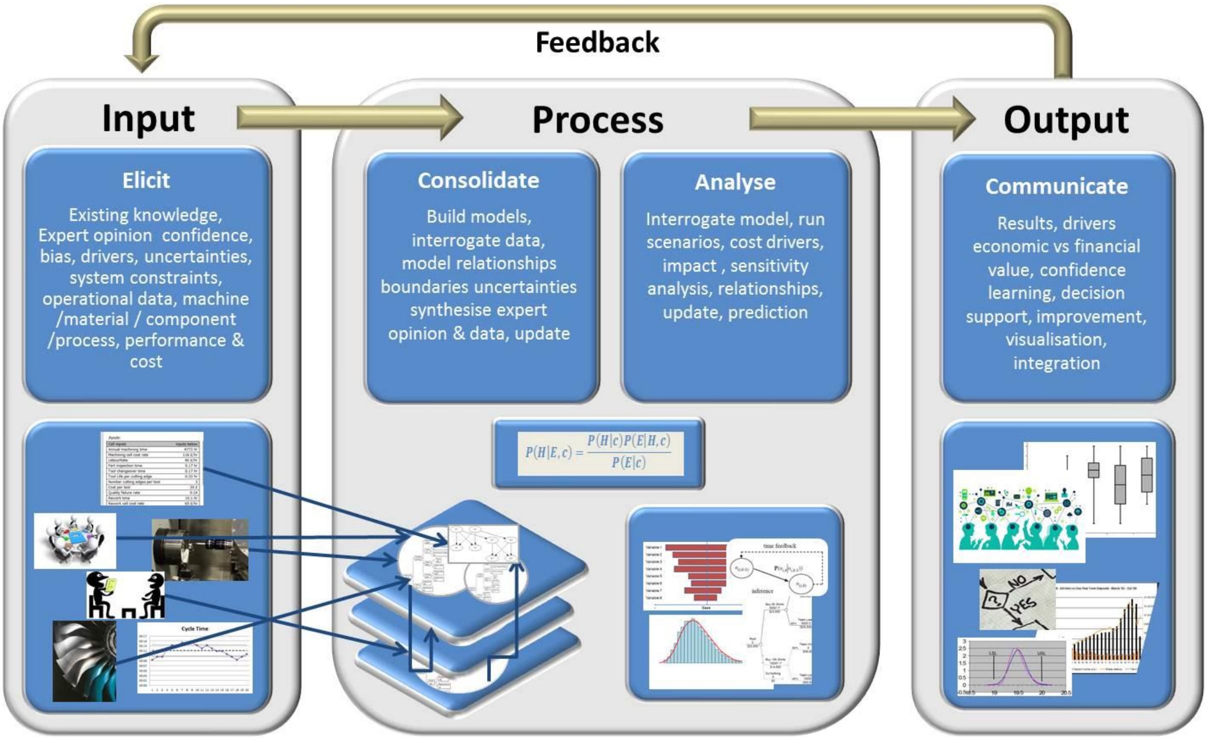


Figure 5-10 - A framework for enhanced decision making in manufacturing R&D

5.8.1 **Loop 1**

The focus of the first loop is on identifying and quantifying variables, their relationships and degrees of uncertainty.

The model in Chapter 3 is a total cutting fluid use model on a typical manufacturing process; the model is parameterized to reflect the specific machining cell under study and structured so that it provides a comparison of the current system with the novel technology, the IFDR.

First the original business case is studied to understand how the adoption of the new technology is justified, including an indication of the metrics and parameters that should be used in the cost model. Next the model is adapted to include variables for both the current system and the new technology, including financial and management costs of each scenario. The manufacturing engineer responsible for creating the business case is consulted on the content during the early and final stages of the model development to decide what should and should not be excluded from the model. The model is then run providing output values for sump life, total cost of coolant use and cost of non-conformance.

5.8.1.1 **Input**

The first step was to understand the process and variables related to coolant use, together with associated uncertainties. The model from Chapter 3 was used as the baseline model, providing a mathematical description of most of the process, along with a set of coolant related variables. A data capture sheet was created which included 34 variables, agreed in consultation with the manufacturing engineer (ME). This data includes financial cost, machining, materials, coolant and waste data (see Table 5-2). The data was captured through observation of the process, contextual interviews and documentation study along with email communication with operators, manufacturing engineers, fluid maintenance contractors, filtration suppliers and maintenance staff at the site. Access to these stakeholders was critical to the success of the Case Study. Each variable was checked by the ME. There were no inconsistencies as the information was taken from documentation.

Variable	**Value**	**Uncertainty**
Cell Inputs		
Machining type		
Material type		
Annual machining hours	hr	
Machining cell cost rate	£/hr	
Labour rate	£/hr	
Part inspection time	hr	(+/-%)
Quality failure rate	%	(+/- %)
Rework time	hr	(+/-%)
Rework cell cost rate	£/hr	
Length of rework delay	hr	(+/- %)
Annual cutting fluid inputs		
Fluid type		
Fluid unit cost	£/l	
Concentration	%	(+/-%)
Coolant life span	months	(ave, min, max)
Water rate	£/m^3	Not applicable
Fluid management contract cost	£	Not applicable
Inspection consumables cost	£	Not available
Probability of inspection failure	%	(+/- %)

Inspection frequency	/year	Not available
Inspection time	hr	(+/-%)
Top-up quantity	ltr	(+/-%)
Top-up frequency	wks	Not available
Top-up concentration	%	Not applicable
Treatment consumables cost	20£	(+/-%)
Tramp oil removal system (TORS)		
TORS purchase price	£	Not applicable
TORS maintenance costs	£	Not available
TORS depreciation	yrs.	Not applicable
Water Treatment system (WTS)		
Is treatment required?	Yes/no	Not applicable
WTS cost rate	50£/hr	Not applicable
Filtration system (FS)		
FS purchase price	£	Not applicable
FS consumables	£	Not applicable
FS cost rate	£/hr	Not applicable
FS depreciation	yrs.	Not applicable
IFDR system		
IFDR sump life	months	(min, ave, max)
Quality improvement with IFDR	%	(+/-%)
IFDR purchase price	£	Not applicable
IFDR depreciation	yrs.	Not applicable
IFDR installation cost	£	Not applicable
Waste		
Cost per litre waste	£/m^3	Not applicable
Down time per fill	hr	(+hr , - hr)

Table 5-2 – Cost model data capture sheet (confidential data redacted)

The performance objectives and constraints were next determined; a sample of this is shown in Table 5-3. As the IFDR is previously untested on the same equipment, estimations are agreed by the technology supplier and the manufacturing engineer responsible for the machining cell. The non-conformance rate is estimated to be reduced by 80%, the previous investigation removed non-conformance completely but a conservative 80% was chosen. The sump life is set to two years (the original sump life is sensitive information but was significantly less than this); fluid suppliers state that with effective management the coolant sump life can be reasonably expected to reach this value.

Potential benefits	Quantification	Clarification
Particulates		
> potential non-conformance reduction -80%	Remaining parts from previous business case plus error	previous experience, spec of < 10μ
Extension of coolant life		
> *** months to minimum of 2 years	From fluid supplier	
Consumables		
> Removal of consumables - *** pa	Current filter media costs	None on IFDR

Table 5-3 - IFDR benefits capture sheet - confidential data redacted

5.8.1.2 **Process**

Vanguard Studio™ was used as the implementation tool as it is a recognised industrial cost modelling tool and is the preferred software for cost estimation at the AMRC and RR. Total costs are calculated from mathematical relationships within the model (a method known as activity based costing).

The relationships were defined using a tree hierarchy structure and the manufacturing engineer studied the tree to ensure that the model reflected the process. To include the IFDR option, some modifications were made to the model. Table 5.4 shows how the input table in Vanguard has been updated to include the scenario of using IFDR along with a number of IFDR system variables.

Inputs:
Cell inputs
Material type
Is IFDR fitted
Machining cell cost rate
Part inspection time
Non-conformance rate
Rework time
Rework cell cost rate
Length of rework delay
Maintenance consumables average unit cost
Cell downtime
Cell breakdowns
Cutting fluid inputs
Fluid type
Water rate
Is a Fluid Care contract in place?
Coolant lifespan max
Coolant lifespan min
Concentration max
Concentration min
Annual tramp oil removal system (TORS) inputs
TORS purchase price
TORS maintenance cost
TORS depreciation cost
Water treatment system inputs
Is water treatment required?
WTS cost rate
Filtration system (FS) inputs
FS purchase price
FS consumables
FS cost rate
FS depreciation
IFDR system inputs
IFDR sump life
Quality improvement with IFDR
IFDR purchase price
IFDR depreciation
IFDR installation
Waste inputs
Cost per litre waste
Down time per fill
Labour rate

Table 5-4 - Vanguard studio cost model inputs

The tree structure was altered so that the model could be run with or without IFDR and the outputs compared. Figure 5.11, Figure 5.12 and Figure 5.13 show first, second and third level examples of the architecture for this adaption.

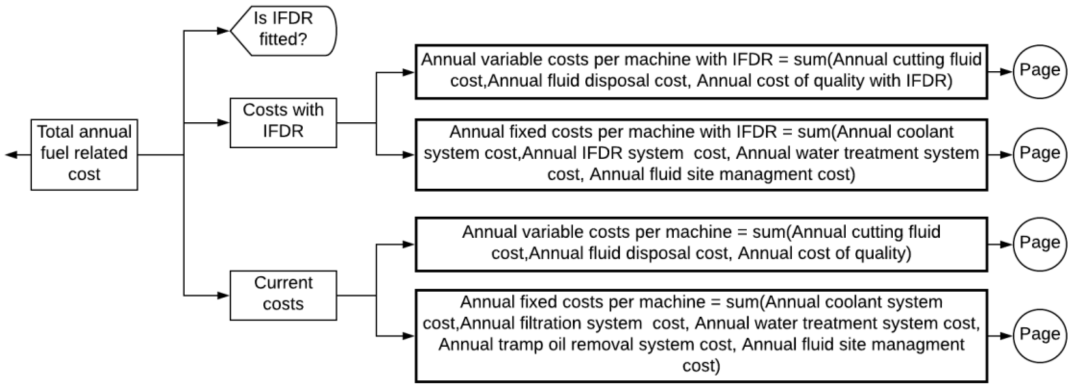


Figure 5-11 - First level cost model architecture that shows the mathematical relationships with and without IFDR

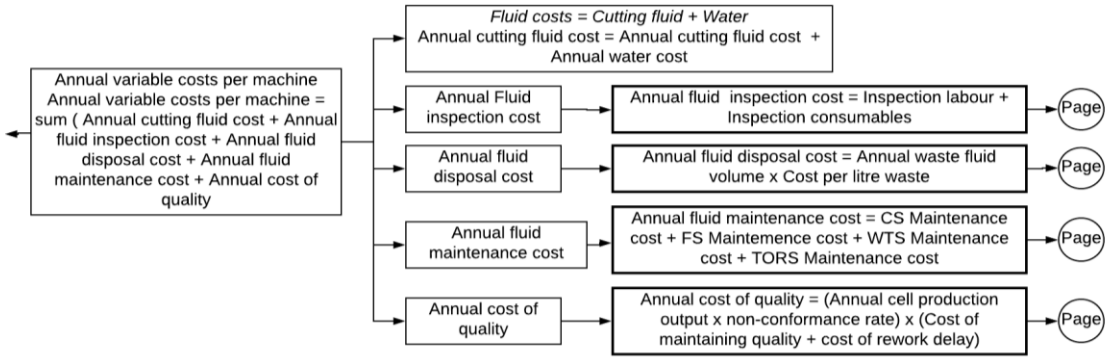


Figure 5-12 - Second level cost model architecture that shows mathematical relationships between variables

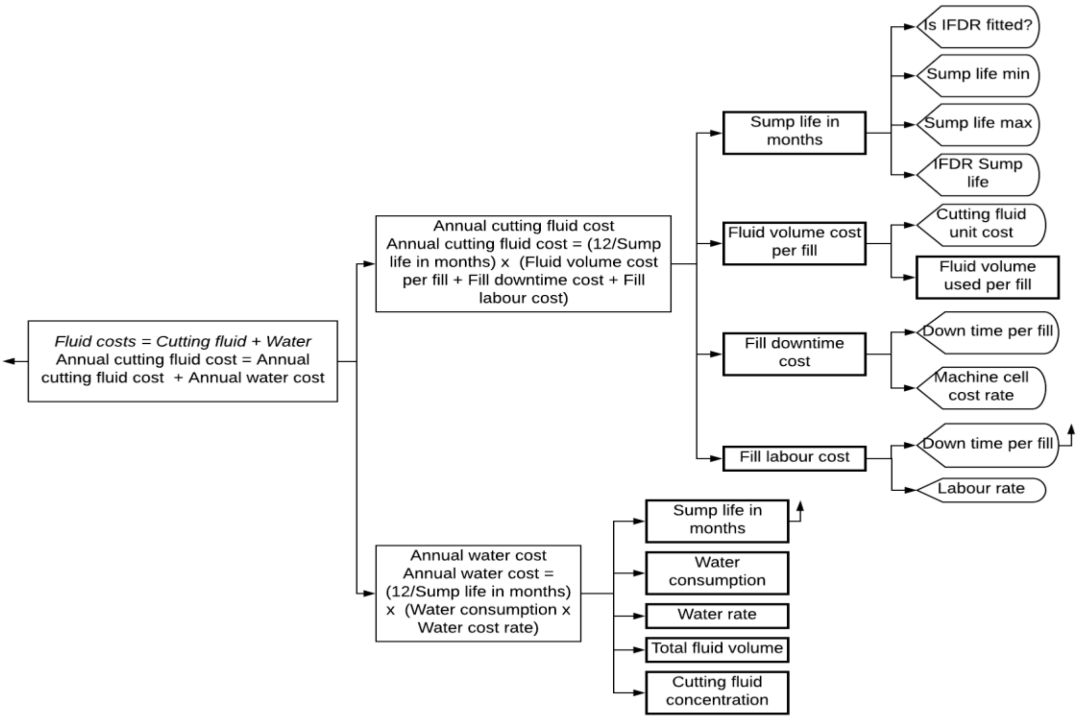


Figure 5-13 – Third level cost model architecture that shows mathematical relationships between variables

Uncertainty has been elicited in the form of three-point estimates, representing expert beliefs for equally likely minimum and maximum values for each variable. This uncertainty was then modelled using a parametrically-defined random variate between the lower and upper bounds – a triangle distribution was chosen in all cases as this is standard practice by cost modelers. In the Vanguard system, the distribution is represented non-parametrically using samples drawn using a pseudo-random number generator for each sample in the simulation; a new number is randomly selected for each stochastic input and a different result is calculated. An example of how these distributions are incorporated is shown in Figure 5-14.

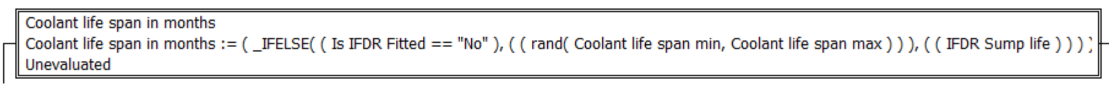


Figure 5-14 - Cost model branch showing how uncertainty is represented

Once stochastic variables are included in the model, Monte Carlo simulation is used to determine the variables which have the greatest sensitivity in terms of the impact on total cost. The simulation helps visualize the effects of all inputs on the results simultaneously; the model is then run to determine how sensitive the results are to input assumptions. Figure 5-15 shows that in this case sump life, quality and concentration are the most sensitive. Of immediate interest is that, although the main driver is for non-conformance to be reduced, increasing sump life in the process offers the most substantial cost benefits which was a surprise to both the ME and researcher.

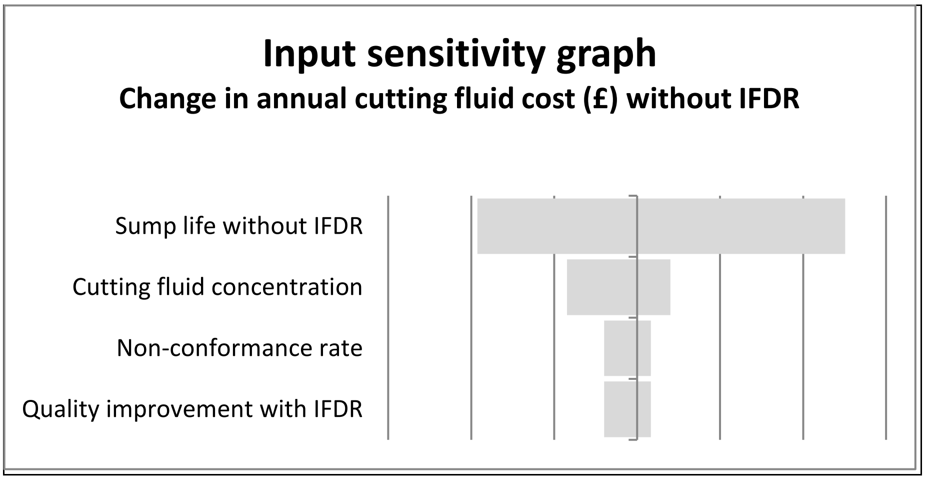


Figure 5-15 -Tornado diagram showing the most sensitive variables to total cost of fluid use in the model

5.8.1.3 **Output**

Two scenarios were run. The first with variables for the current system and the second for the system with an IFDR system fitted. Three outputs were captured for each scenario. Output one was the total fluid related costs. This encompassed direct and indirect costs. The direct costs (including capital cost and depreciation) included cost of filtration, tramp oil removal, and water treatment machinery. The indirect costs included inspection, maintenance, fluid use, water use and consumables cost as well as cost of non-conformance. The next output was cutting fluid costs, including the annual cost of fluid influenced by sump size, sump life, fluid concentration, top-up and the subsequent cost of water. Finally the cost of non-conformance was captured, including the cost of maintaining quality as well as the cost of non-conformance including rework and downtime. A comparison between the two scenarios was calculated. For purposes of information sensitivity these are displayed in Table 5-5 as percentages however monetary values were reported to Rolls-Royce.

The output metrics in Table 5-5 were provided at the request of the manufacturing engineer to enhance the justification for trialing the new system alongside the business case. The results were compelling to the manufacturing engineer, with a 76% reduction overall in fluid related costs, including 85% reduction in coolant costs and 65% reduction in non-conformance costs, resulting in a return on investment (ROI) of less than 4 months. However the trial and the business case were not accepted by more senior signatories immediately, perhaps due to a lack of confidence in the technology, it took a further eighteen months to launch a 12 month trial of the system and the researcher was unable to clarify the reason for this.

Output variable	**Value (units used for data sensitivity)**
Total annual fluid related cost current	
Total annual fluid related cost with IFDR	-76%
Annual coolant cost current	
Annual coolant cost with IFDR	-85%
Annual cost of quality current	
Annual cost of quality with IFDR	-65%
Return on investment	< 4 months

Table 5-5 - Output results from loop 1

Once the trial commenced, data for particle content, non-conformance and sump life were collected over a period of 10 months. The particle content was maintained well below 10µ as predicted. The quality defect rate reduced to zero, the coolant concentration remained stable with no treatment required and the sump life extended to 10 months. Unfortunately at 10 months, although no detrimental production issues were reported, the sump was changed. This was due to opportunistic maintenance of the sump tank which had not been communicated to the researcher and was not at the request of an operator or the ME involved in the trial. The trial was deemed a success by the ME and on the back of the results a business case for three further systems for the remaining three identical machining platforms experiencing quality issues was produced by the ME and accepted by senior decision makers.

5.8.1.4 **Reflection**

This modelling method was effective in representing the interrelated variables in a way useful to support a business case for technology selection. However, a number of areas were also identified where the modelling could be enhanced to increase the speed and confidence of decision making surrounding novel technology implementation. Although the results of the first loop showed a clear opportunity for cost reduction, uncertainty could be modelled more accurately and also updated dynamically as new evidence is generated. Widening the stakeholder group could also identify output variables which could modify the findings – although the current system and business case is based mainly on non-conformance, there is potential for the technology to have a wider impact on the business.

Loop 1 gives an existing understanding of the costs related to coolant use and Loop 2 moves the study towards an improved understanding of the challenges in measuring data and in reflecting the uncertainty and impact across the business.

5.8.2 **Loop 2**

For this loop the focus is on representation, propagation and updating of variables and data and communication to a wider stakeholder group. A Bayesian Network model (BN), described in Chapter 2, was selected as the modelling mechanism due to their ability to: (1) incorporate uncertainty as a probability density function (pdf); (2) propagate uncertainty through the model; (3) visualize uncertainty. In terms of decision making support, the difference between the cost model and BN is predominantly in terms of visualization. Changes to the model are propagated through the model; the evidence can be easily incorporated and is visualized by the changes in the location and shape of the pdf. A key benefit of using BN in a trial scenario is that the method progressively attenuates the effect of uninformative prior information as observations appear – providing a more confident visual representation of the most likely outcomes, given empirical observations.

The cost model from Loop 1 was used as a baseline for the development of a modelling methodology capable of handling the more complex aspects of the framework.

5.8.2.1 **Input**

A group meeting was held with a wide group of stakeholders to present the outcome of the trial and to determine the requirements each stakeholder held in relation to the use of cutting fluids. The stakeholders were brought together as a group, as opposed to individually to improve the effectiveness of information gathering while reducing the likelihood of bias a method described in qualitative research literature [179], [180]. This environment provided an opportunity for individuals to express to each other the importance of their business drivers. The discussions across stakeholders helped to align motivations and created a more collaborative environment for establishing common ground. This would not have been possible with individual interviews with the researcher. During the meeting the researcher acted as a facilitator to provide the opportunity for open discussion allowing the stakeholders to steer the discussions and to mitigate the likelihood of the meeting being dominated by the researcher. The stakeholders were: (a) the Rolls-Royce manufacturing engineer (ME) involved in the trial; (b) a Rolls-Royce global environment manager; (c) a Rolls-Royce sustainability manager; (d) a Rolls-Royce coolant specialist; (e) a Rolls-Royce machining platform lead; (f) a Rolls-Royce machining specialist in milling and turning; (g) the IFDR supplier. Each stakeholder discussed their interest in coolant use and described how outputs from an enhanced modelling methodology could enable them to make more informed decisions related to their specific drivers. Table 5-6 provides verbatim results of this discussion.

Job title	Coolant management interest	Requirements
Machining platform lead	Identification of technology with the potential to generate improvements across the platform, standardising best practice with evidence from the trial to support the business case for initial trial and then roll-out. With new machine tool purchases, how best to alter filtration system purchasing.	Impact on non-conformance (particle size reduction) Cost of coolant Sump life Disruption to productivity Business case support Return on investment
ME involved in the trial	Offering evidence, advice, lessons learned and recommendations for rolling out the technology.	
Global environment manager	Cross-cutting initiatives which can target waste reduction. Chemical and coolant waste is high and sump life extension can greatly reduce this. The move away from paper media filtration systems is of great interest.	Reduction in consumables Fluid waste volume Water consumption and waste
Sustainability manager	Developing a cleaner waste stream, environmental improvements and opportunities for recycling.	Reduction in consumables Fluid waste Water consumption and waste
Machining specialist in milling and turning	Improving part quality and machining performance.	Non-conformance costs Reduction fluid related costs to production Opportunities for retro-fit
IFDR supplier	Supply and technical advice for installation queries.	
Coolant specialist	Coolant stability improvements with the use of filtration technology.	Sump life

Table 5-6 - Stakeholder requirements for coolant management

The annual waste fluid volume, work in progress (WiP) and return on investment (ROI) were included in the model the results are shown in Table 5-7. These were significant improvements and could make a compelling case for investment. However these are still single point outputs and the stakeholder may still lack confidence of the model.

Outputs	Difference
Total annual fluid related cost current	
Total annual fluid related cost with IFDR	-76%
Annual cutting fluid cost current	
Annual cutting fluid cost with IFDR	-85%
Annual cost of quality current	
Annual cost of quality with IFDR	-65%
Annual waste fluid volume current	
Annual waste fluid volume IFDR	-49%
WiP current	
WiP with IFDR	-80%
ROI for IFDR	<6months

Table 5-7 - Outputs of cost model including metrics identified by wider stakeholder group

During the stakeholder meeting a discussion was held about uncertainty quantification and visualization. The consensus was that uncertainty is best demonstrated visually in the form of probability density, where an average value and spread can be communicated (e.g. normal distribution). When data is analyzed in machining trials or any other data analysis, confidence is represented in the range and shape of the data. The stakeholders were able to estimate uncertainties for a number of key variables in the model. It was agreed that current machining variables would most likely be in the form of a normal distribution so using the range method, $variance = (max - min/4)^2$, enabled the representation of these stochastic variables in the network. The max and min values were given by the ME as; in this case, the ME was the only representative with access to data. For the IFDR sump life the distribution is more complex – similar to the example described in Chapter 4, a beta distribution best describes the likely shape of sump life with the IFDR, so when eliciting priors from the IFDR supplier a median of 24 months was given, with 5th percentile estimated at 12 months and 95th percentile estimated at 60 months. A statistical package called The SHeffield ELicitation Framework (SHELF) was used to translate these into the shape and range parameters needed to represent a beta distribution. The method uses parameters of the fitted distributions for each expert and sums the squared errors from the elicited distributions and the original elicited judgements. SHELF is software designed to enable the elicitation of probability distributions for uncertain quantities from a group of experts and is described in detail in [90], [173]. The authors of the software have confirmed that to their knowledge they are not aware of any use of the software/SHELF elicitation process in a similar application. This further reinforces how the selection of tools and methods in this research approach represent novelty in regards to this area of application.

Table 5-8 includes a number of the variables discussed using sanitized data for the purpose of demonstration. These were included as prior distributions for nodes in the BN.

Variable	**Distribution**	**Mean**	**Min**	**Max**	**Variance (Max-Min/4)^2**	**alpha**	**beta**
Current Sump life	Normal	4	2	6	1		
Sump life with IFDR	Beta	24 (50th %)	12 (5th %)	60 (95th %)		6.17	18.8
Rework time	Normal	84	64	104	100		

Table 5-8 – Uncertain variables elicited during group discussions with stakeholders

5.8.2.2 **Process**

The modelling software used to define and implement the BN was AgenaRisk, selected for its availability, cost and ease of use. The network was defined using the structure of the cost model, where each variable is represented as a node and the relationships between the nodes are represented by arcs (see Figure 5-16). Each child node includes an equation defining how the variable is calculating from incoming arcs (from parent nodes). Nodes can contain constant values or uncertain distributions (see Figure 5-17). The child node contains a node probability table with an expression which describes its relationship with its parent nodes and so enables the propagation of uncertainty throughout the network (see Figure 5-18).

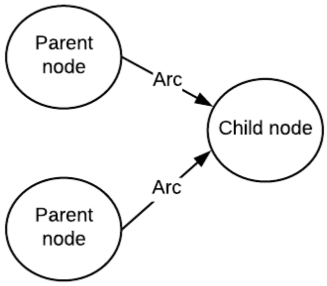


Figure 5-16 - Bayesian Network diagram

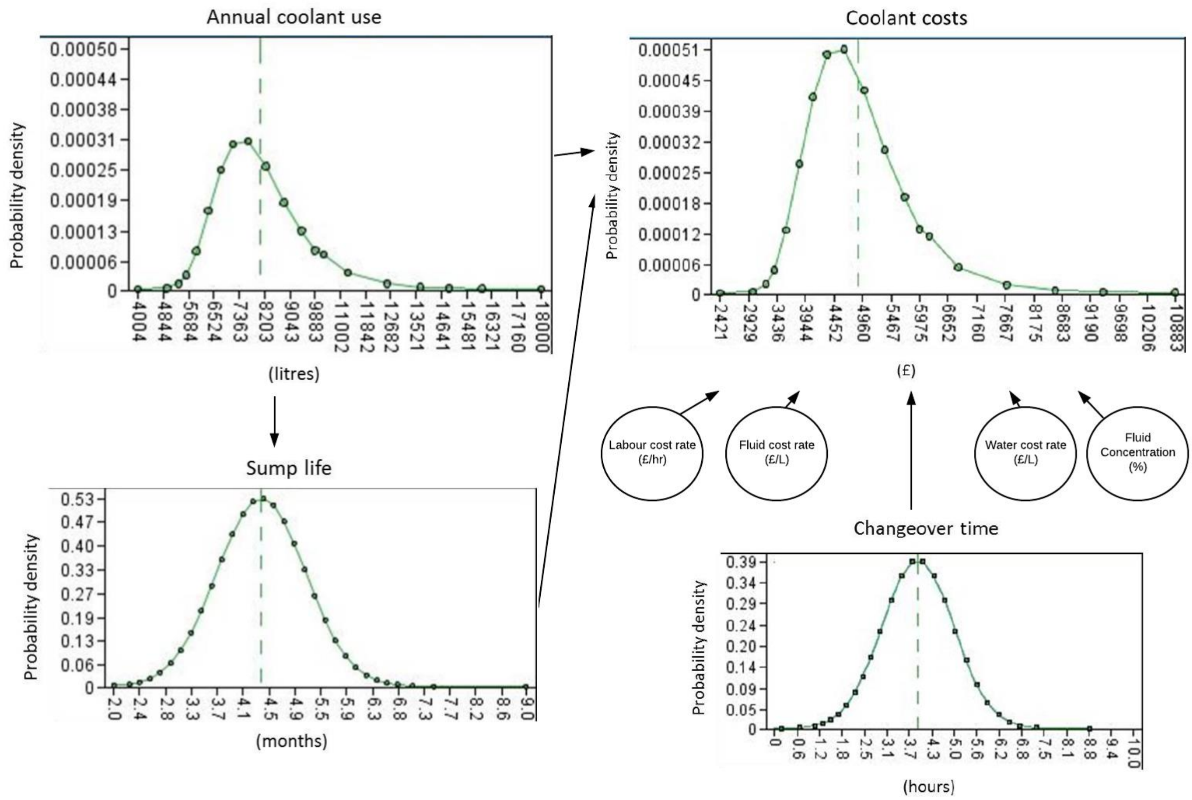


Figure 5-17 - Bayesian network showing uncertainty propagation from parent to child node

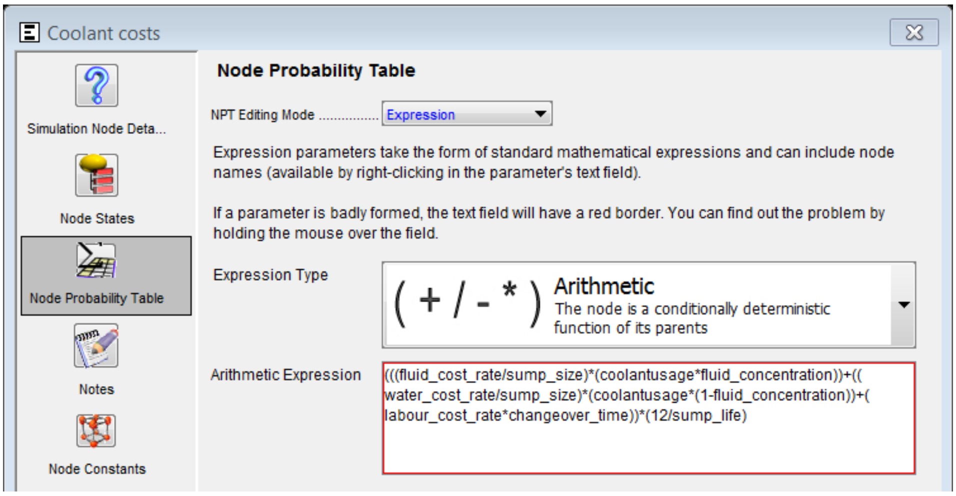


Figure 5-18 - Node probability table for coolant cost showing the node probability table with mathematical relationships between and from parent nodes

5.8.2.3 Output

The BN is run and the outputs are shown graphically in Figure 5-19, Figure 5-20 and Figure 5-21. The two scenarios IFDR and no IFDR are represented with different colours, blue and green respectively on each graph enabling comparisons of the value and uncertainty of the variables for each scenario. The values are representative but have been altered for data sensitivity reasons. The graphs are indicative of the type of data that a Bayesian network could provide to the decision maker.

Total annual coolant related costs

Figure 5-19 are the results for total annual coolant related costs. For the scenario representing the current system with no IFDR on the right, the mean cost is around £9500 with a large spread of uncertainty showing a small probability of costs exceeding £12000. For the scenario with an IFDR the distribution has a mean of around £2500 with tighter distribution and a small probability of costs exceeding £4000.

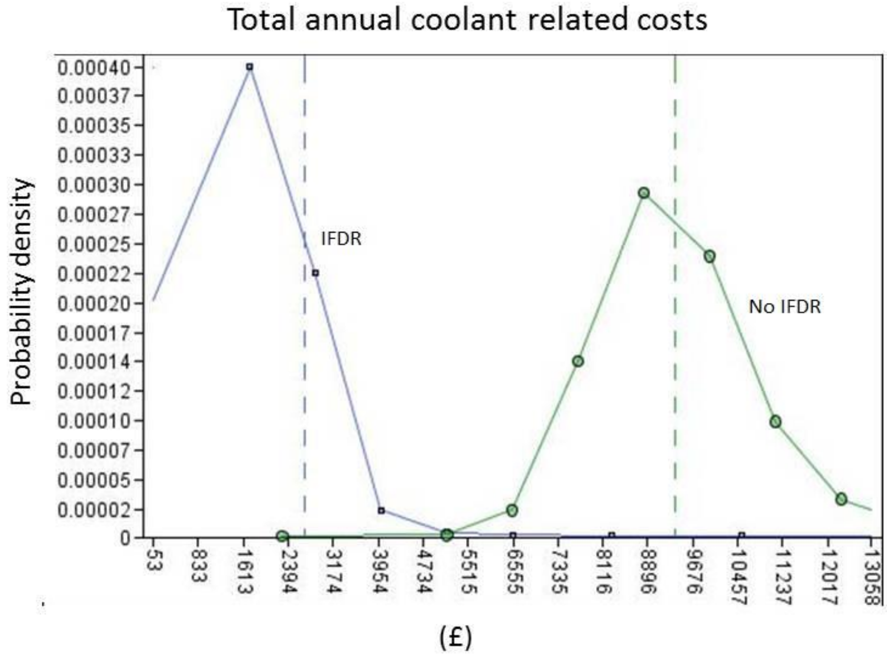


Figure 5-19 - Output graph from Bayesian Network showing probability distributions of Total annual coolant related costs for the current system (Right) and with an IFDR fitted (Left)

Return on investment

The original estimations from the ME presented in the business case lead to a calculated return on investment (ROI) of 0.75 years. The more detailed model described in Loop 1 estimate a return on investment of 0.34 years based on the inputs collected in Table 5.1 and the estimations of IFDR benefits in Table 5-3. This difference can be attributed to the introduction of additional factors in the model. The second Loop involved a wider stakeholder group and the introduction of the Bayesian network, where uncertainties were defined as probability density functions which are propagated through the network to the outputs. The total annual fluid related costs (TC) distribution displayed in the outputs for the scenario without the IFDR has a mean of £9510, with lower percentile £8510 and upper percentile £10392 and for the scenario with the IFDR, the distribution has a mean of £2781, lower percentile £1242 and upper percentile £2595. Using Equation 5-21 we can estimate the mean (Equation 5-22), best (Equation 5-23) and worst (Equation 5-24) cases for the ROI of an IFDR.

$$ROI = \frac{Purchase\ price\ of\ IFDR}{TC\ without\ IFDR - TC\ with\ IFDR} / 12$$

Equation 5-21

$$Mean\ ROI = \frac{20000}{9510 - 2781} / 12$$

$$= 0.25\ years$$

Equation 5-22

$$Worst\ case\ ROI\ = \frac{20000}{8510 - 2595} / 12$$

$$= 0.28\ years$$

Equation 5-23

$$Best\ case\ ROI\ = \frac{20000}{10392 - 1242} / 12$$

$$= 0.18\ years$$

Equation 5-24

The average ROI results are similar to the results of Loop 2. Having a best case and worst case adds a level of confidence to the estimate.

Annual cost of process performance

Figure 5-21 are the results for the annual cost of non-conformance. For the scenario representing the current system with no IFDR on the right, the mean cost is around £3000 with a large spread of uncertainty showing a small probability of costs exceeding £4000. For the scenario with an IFDR the distribution has a mean of around £600 with a tighter distribution and a small probability of costs exceeding £900.

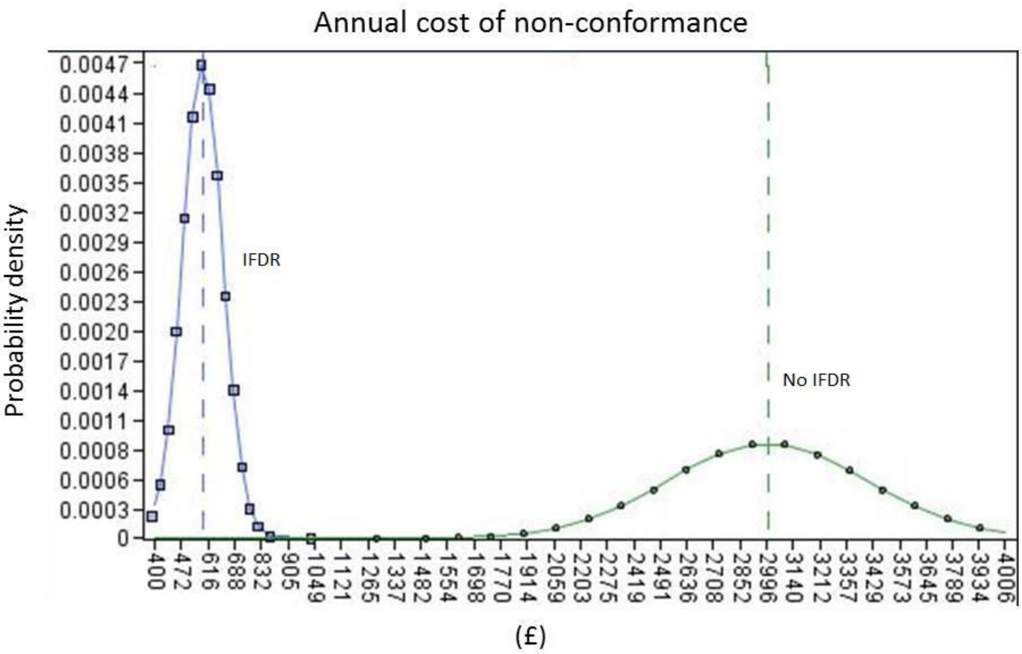


Figure 5-20 - Output graph from Bayesian Network showing probability distributions of Annual non-conformance costs for the current system and with an IFDR fitted

Figure 5-21 are the results for the annual coolant use which represents hazardous waste volume. For the scenario representing the current system with no IFDR on the right, the mean volume used is 8252 litres with a large spread of uncertainty showing a small probability of volumes exceeding 12000 litres. For the scenario with an IFDR the distribution has a mean of 1701 litres with a tighter distribution and a small probability of costs exceeding 3500 litres.

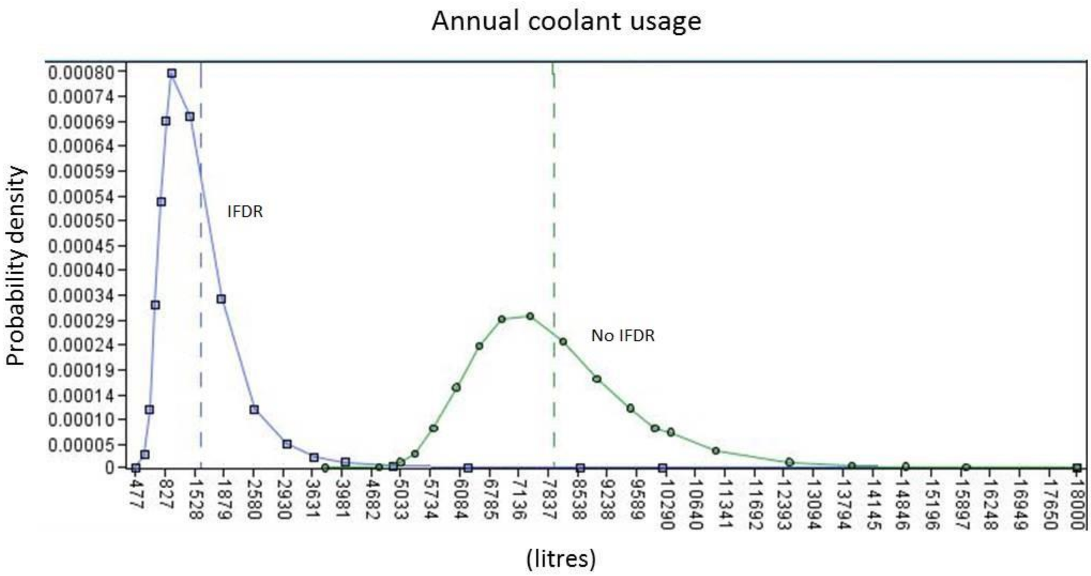


Figure 5-21 - Output graph from BN showing pdfs of annual coolant usage with and without the IFDR

Feedback

The current method of capturing learning with novel technologies is qualitative; evidence is collected in lessons learned logs alongside subjective discussions with researchers and industrial partners who have had experience with specific trials of a technology.

The benefit of the learning mechanism in Bayesian networks is that it is quantitative; the evidence propagates through the network and provides an incentive for individuals to provide new evidence, thus promoting an effective feedback loop. Evidence can be incorporated by adding direct observations to a node (Figure 5-22 shows how evidence is added to the current system scenario). This information propagates through the model and the outcomes change to reflect this new evidence. Figure 5-23 shows the graphical outputs of total annual coolant related costs before and after an observation of 4 months sump life entered. The distribution representing the IFDR output demonstrates how uncertainty narrows with the additional information.

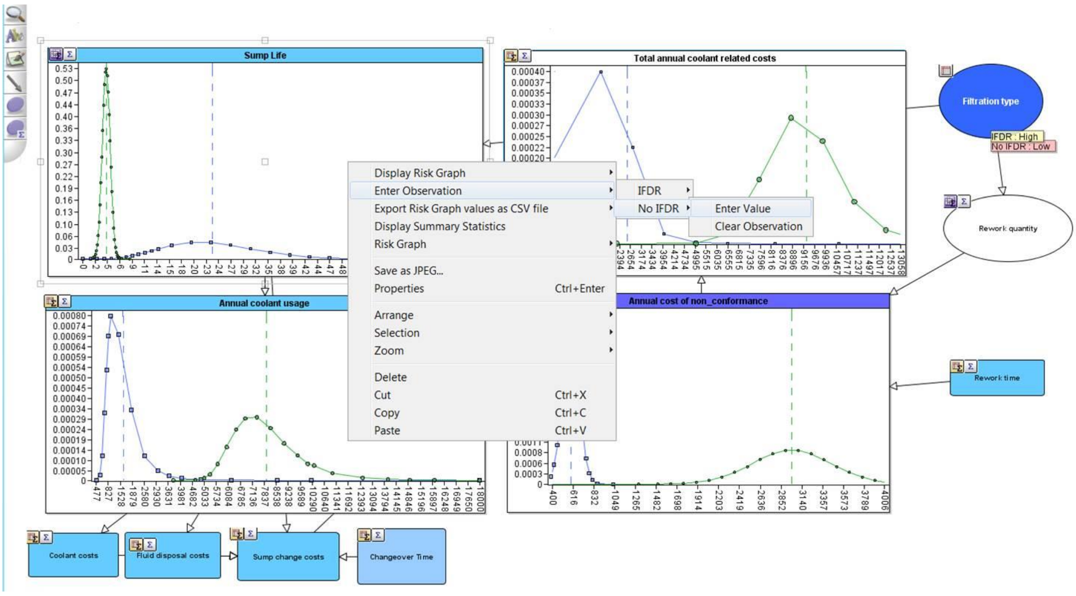


Figure 5-22 - Example of how new hard evidence is entered into the Bayesian network

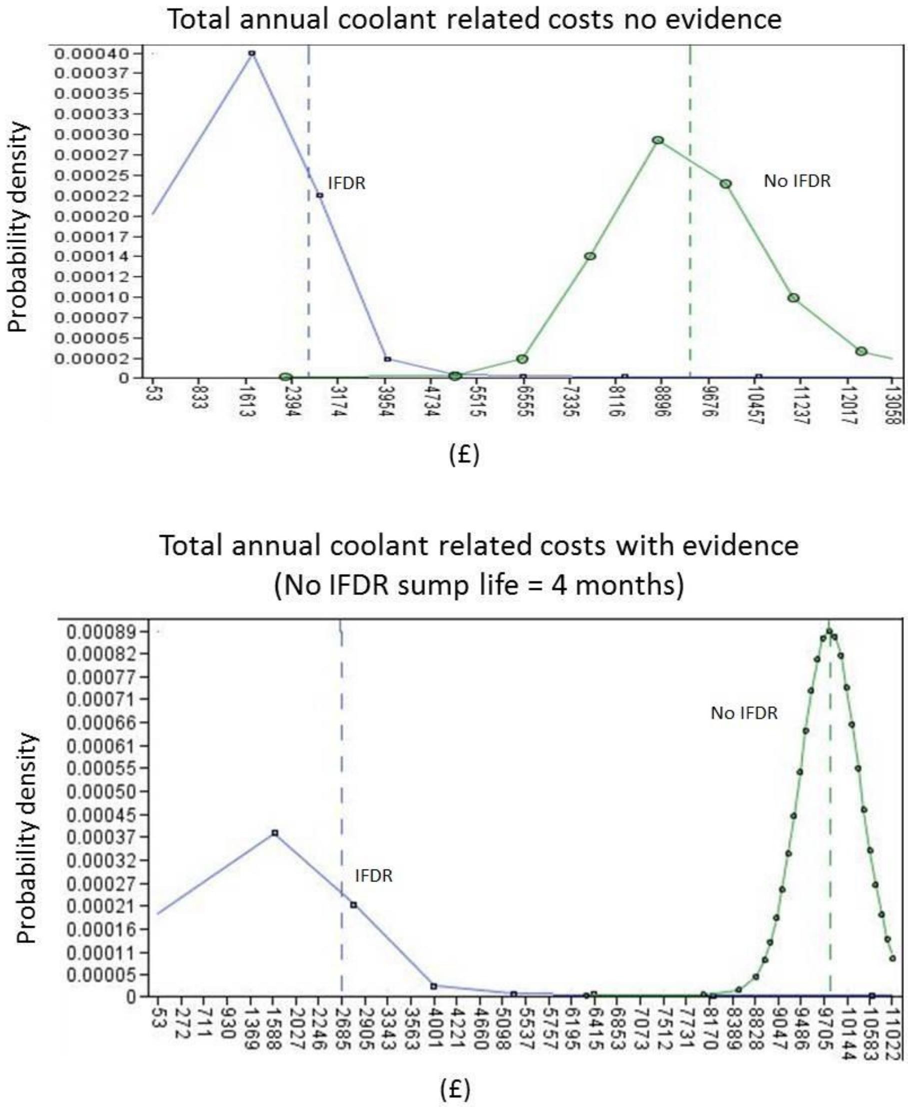


Figure 5-23 -Showing the effect of evidence propagation both prior and posterior with evidence of 4 months sump life observed for the current system

The BN software enables decision makers (or their analysts) to run scenarios in real time, seeing the impact of changing or challenging variables and assumptions. They can also visualize the impact on a relevant range of business drivers. This enhances decision making as there may be value streams associated with technologies which are not captured in business cases, such as fluid waste volume not being included in the original business case described above.

5.8.3 **Loop 3**

5.8.3.1 **Input**

Having produced a model that is able to propagate uncertainty and visualize confidence in the outputs, a further round of evidence collection was undertaken. A series of visits was made to five companies based in Italy who used the IFDR technology across a range of applications and platforms. Each visit included a site tour and semi-structured discussions via an interpreter with the manufacturing manager and operators to record their experience of using the technology. Each was asked a list of the following questions to capture: 1. industrial context; 2. application context; 3. quantity of IFDRs on site; 4. previous filtration system; 5. nature of problems reported using the original filtration system; 6. post IFDR benefits reported; 7. sump life extension achieved. Findings from these visits are shown in Table 5-9Table 5-9.

Company	**Valentini**	**InGlass**	**Elmann**	**Uster**	**MVO**
Industry	Aerospace and automotive	Injection moulding	Automotive	Automotive, aerospace, medical and food	Automotive (large components)
Application	Grinding, milling turning	Deep hole drilling & boring of carbon graphite and hard alloy steels	Drilling	Precision machining	Grinding
Quantity of IFDRS	4 (2 retrofit + 2 on new machine tools) IFDR with each new machine tool purchase	3 (1 retrofit + 2 on new machine tools) IFDR with each new machine tool purchase	2 retrofit + 1 on order IFDR with each new machine tool purchase	4 (2 retrofit + 2 POD) IFDR with each new machine tool purchase	1 retrofit IFDR with each new machine tool purchase
Original problems caused by OEM supplied system	Bacteria/foul smells 6 months life Corrosion in tank Low productivity due to low pressure Slow material/fluid changeovers	6 months life, paper media change every 6 days (250kg of dust per fortnight) Surface defects H&S issues Maintenance	Uncertainties in tool life and surface finish Large consumables spend maintenance and downtime for sump cleanouts too high	Not capable of achieving surface finish on deep hole drilling Through hole blockages Monthly cartridge change	Slow production and not achieving acceptable tolerances 2 week life High maintenance cost

				Yearly fluid change	
Previous filtration	Paper media supplied by original machine equipment manufacturer(OEM)	Paper media +bag filter (OEM supplied)	Paper media (OEM supplied)	Cartridge system (OEM supplied)	Two paper media (OEM supplied)
POST IFDR Benefits reported	Increased sump life Stability & no smell Productivity increase (HP capability) Extended tool life Quick changeover Small footprint No maintenance or consumables for 5 yrs.	Increased sump life No H&S issues No defects, rework or inspection Extended tool life No maintenance (suction pump after 4 yrs.)	Increased confidence in coolant Stability No defects Sump & tool life increased No consumables or maintenance Recycling of coolant drag out back through secondary IFDR solution Small footprint	Surface finish achieved No cleanouts No consumables Doubled tool life Cutting speed increase 30-40%	No fluid cleanouts required 100% quality 100% Capable on required tolerances 4kg per hour recovery for recycling
Sump life extension	18months (alternate fluid types but re-use fluid)	5, 4 and 3 years so far	3 years so far	3 years so far	7 years so far

Table 5-9 - IFDR system user data capture from Italian companies

The results provide further evidence for the cost, productivity and environmental outcomes of interest to decision makers. For example, in the case of sump life, evidence has been collected for sump lives exceeding ten months and two years specified by suppliers, in cases where coolant cleanliness and filtration is managed properly.

5.8.3.2 **Process**

In this case there is uncertainty around evidence, we have sump life evidence of 18 months, 3, 4, 5 and 7 years so a distribution must be fitted to the data. The method described in Section 4.4.1 for updating with soft evidence will be used. In this example the expert judgment is that of a beta distribution with 5^{th} percentile 18 months, 50% percentile 3 years (36 months) and 95^{th} percentile of 7 years (84 months). The SHELF software returned parameters for the distribution of 2.04 and 4.21. This evidence requires an additional ranked node to be added to the BN; called Sump life observations (see Figure 5-24).

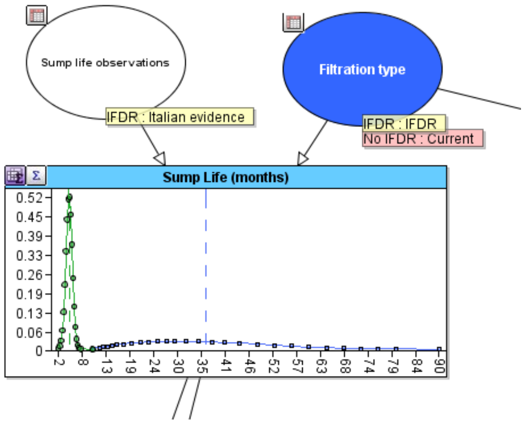


Figure 5-24 - Image showing the new node for sump life observations

The Sump life observations node contains two states, the first is UK evidence, representing the initial judgement of IFDR sump life and the second is Italian evidence. This extra node provides an additional scenario to the partitioned expression in the NPT of the sump life node of $Beta\,(2.04, 4.21)$ for the IFDR scenario and $Beta\,(2.57, 3.57)$ for the Italian evidence scenario (see Figure 5-25).

Filtration type	Current		IFDR	
Sump life observations	UK evidence	Italian evidence	UK evidence	Italian evidence
Expressions	TNormal(4.5,0.56,2,24)	TNormal(4.5,0.56,2,24)	Beta(2.57,3.56,10,30.0)	Beta(2.04,4.21,10,90.0)

Figure 5-25 - NPT for Sump life node with additional scenario

The software also enables a level of confidence around this new evidence. Instead of changing the sump life distribution entirely to reflect the new evidence, it is possible to enter a subjective estimate, for example 80% confidence in the Italian evidence, 20% confidence in the UK evidence (see Figure 5-26).

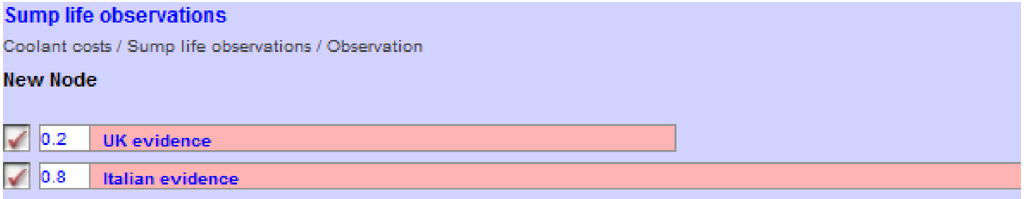


Figure 5-26 - Confidence level estimate for new evidence

5.8.3.3 **Output**

Figure 5-27 shows how the addition of the Italian evidence of extended sump life affects the fluid usage, and coolant related costs compared to the current system. The total annual coolant related cost graph shows how with the original system the average cost is over 80% higher with a greater level of uncertainty than the IFDR result. The figure also shows the average annual coolant usage and annual cost of non-conformance for the current system is over 80% higher with a wider uncertainty distribution than with the IFDR and Italian evidence.

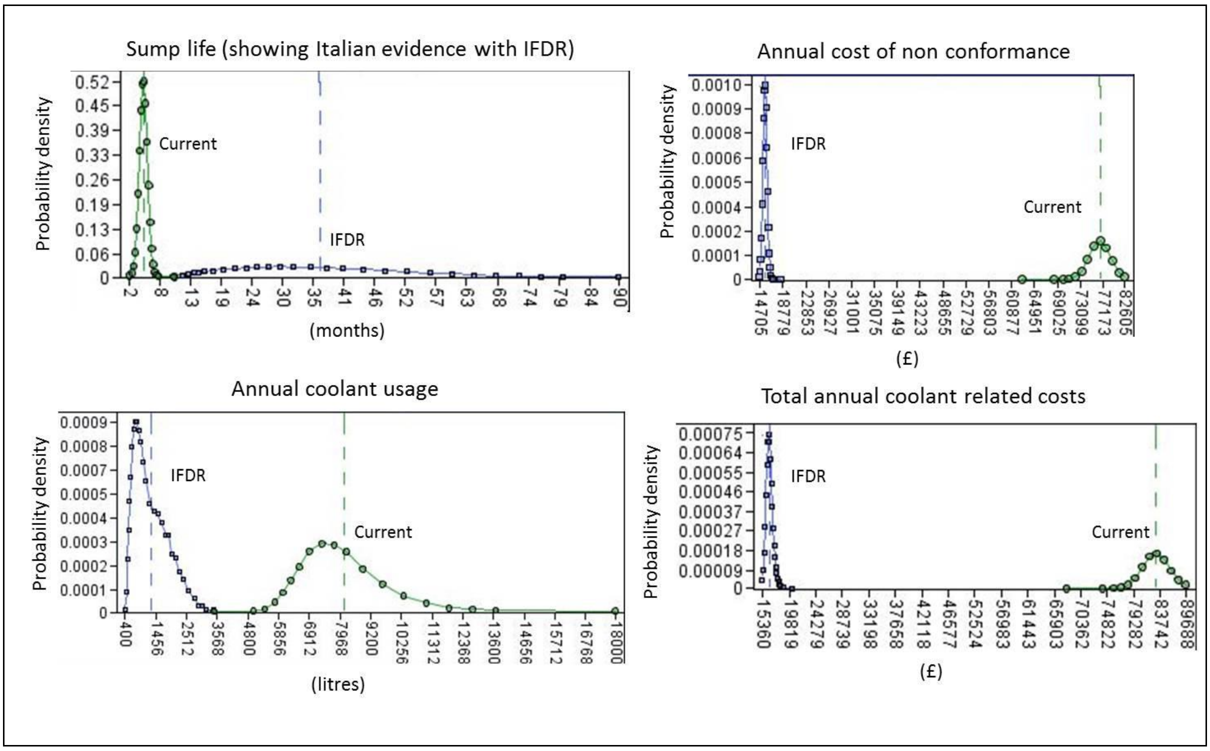


Figure 5-27 – Output results for Annual coolant use, Annual cost of non-conformance and Total annual coolant related costs after evidence of extended sump life is incorporated for the IFDR in the Sump life input node

5.9 Findings from the application of the framework

As discussed in section 2.4.2 the aim of this research is to provide stakeholders with a range of outputs to aid multi-criteria decision making. The original business case metric of return on investment can be calculated by comparing total costs before and after the IFDR is installed. The annual cost of non-conformance, annual coolant usage and total annual coolant related costs are visually demonstrated. Next the confidence is described for each using probability densities. Then the impact of new evidence is demonstrated.

The results of the sensitivity analysis (conducted in loop 1) show that the main drivers of cost in the manufacturing process are sump life, non-conformance rate and coolant concentration. For the novel IFDR technology, the largest uncertainties (elicited in Loop 2) relate to sump life and predicted impact on non-conformance. Clearly, reducing the uncertainties on these variables is important for decision makers' confidence around the impact of the technology on total cost and associated business case metrics. The impact of new (uncertain) evidence on these outcomes has been demonstrated in Loop 3.

5.10 Reflections on the effectiveness of the framework

The Bayesian model could help decision making by enabling different variables to be communicated at the same time, where the business model is hard to justify on one variable alone, the model now shows how other drivers are impacted and where larger stakeholder groups are involved, these tend to be the decisions and drivers that more senior decision makers are aware of. When a manufacturing engineer requires sign off from a senior manager, this manager may be more receptive to the business case in terms of 'companywide' drivers and this may aid decision making. A person tends to be risk averse [181] and so taking the decision to invest in an expensive novel technology based on one driver is more difficult.

The outputs from the Vanguard model show the difference for a range of variables. Outputs from the Bayesian model show the difference, in terms of cost and confidence, for a range of output variables and have the mechanism to display the impact of incorporating evidence into the model along with a confidence interval so the decision maker can see the output and variance for the range of outputs across the different drivers.

Prior to the introduction of the framework, the decision to adopt the IFDR technology was based on a particular issue or requirement for an improvement, i.e. non-conformance and the main decision driver was return on investment. The framework provides a means of expanding the range of considerations for investment by bringing into play the following additional aspects: management, waste streams, effect on quality and stability, longevity of coolant, maintenance, productivity, and reduction in hazardous waste. Although waste was not a factor for consideration in the original business case, a production plant manager will have full factory targets and so will see that, although the cost of introducing the technology may increase, reduction in maintenance, health and safety issues, coolant delivery, mixing, waste removal, environmental impact, management time and fluid management services could justify the investment. Instead of just concentrating on return of investment, decisions can be influenced by a range of output drivers.

Each iteration of the framework provided increased benefits: initially there was an improved model which includes the full impact of coolant; subsequently uncertainty was added (e.g. sump life and concentration); next the Bayesian network was constructed to enable the impact of uncertainty in the main cost drivers to be communicated in graphical form; finally additional evidence from Italy could be incorporated to improve the estimates of the key drivers (e.g. savings in terms of both cost and hazardous waste disposal).

The Vanguard studio cost modelling approach is currently used at both the research centre and within Rolls-Royce and so little or no training would be needed to incorporate the approach in Loop 2; however the introduction of cost modelling into the gate process as standard would require a change to quality procedures and this remains a barrier to uptake, as discussed in Chapter 2. Bayesian networks are not currently used at the research centre and so the adoption of Loop 3 would require training along with investment in software licenses.

The framework widens understanding of important drivers and enables propagation of evidence and uncertainty to key decision making metrics (e.g. return on investment) in a way that is understandable for decision makers. The additional information can help to support deliberative decisions over new trials to inform some of the important, uncertain drivers (such as sump life). So this improved procedure can not only direct industrial decision making but can also be directed back to early stage research and development of technologies, defining decisions for new trials and ensuring that technology research parameters of interest are also aligned to industrial needs.

The case study 1 activity identified the value of robust coolant cleanliness and control to current production practice, through further consultation with the central manufacturing team this inspired a farther reaching evaluation plant to plant of coolant management and helped to initiative an intensive investigation of coolant filtration technologies to enable improved coolant life and quality. Focus on this matter which is now yielding significant cost reduction and improved life and sustainability to coolant practices across the company was therefore a direct result of the initial; case study 1 findings and the models ability to identify significant near-term mature, technology leverage.

The next chapter describes Case Study 2, the creation of an improved assessment process for novel cutting fluid technologies within the lower MCRL phases at the AMRC. The ideal scenario would have been to use the results of Case Study 1 to provide the foundation and influence the direction of Case Study 2. However due to the nature of industrial trials delays to Case Study 1 meant that case studies overlapped (see Figure 5-28). This changed the research approach in that the researcher played a less active role in Case Study 2, acting primarily as an observer but was able to draw on the knowledge, experience and developing framework from Case Study 1 to provide support and direction when unexpected complications arose. An assessment of the project described in Case Study 2 was carried out using the improved framework and ultimately provided recommendations for an alternative approach to decision making during technology development R&D that would provide maximum benefit of investment with the highest confidence.

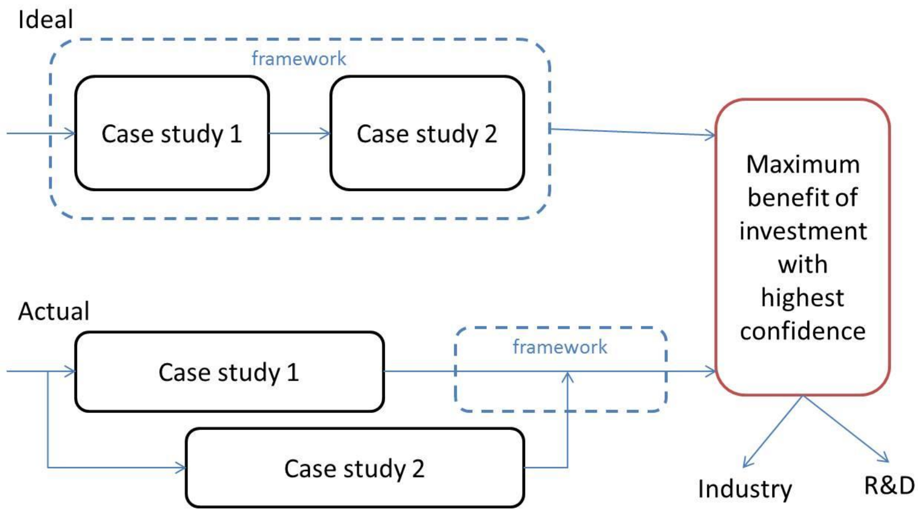


Figure 5-28 - Image showing the ideal Case Study progression and the actual situation

The requirement to alter the way in which the research was carried out in itself emphasises the real disconnect between production and technology development drivers. The framework aims to try and bridge this gap, whilst dealing with the reality of two very different environments. The power of the eventual framework synthesis is to direct and infer what the benefits could have been if the ideal scenario of directed research had taken place.

6 Case Study 2 – Cutting fluid technology selection

6.1 Introduction

This chapter describes a second Case Study which resides at interface 1 (see Figure 6-1) and follows the development of an improved assessment procedure for new cutting fluid formulations. The procedure from the start was being driven by the historical context that maximum benefit would be delivered by evaluating new coolant technology for impact on machining performance e.g. productivity and consumable life and assuming that cuttings fluid controls used in production were established and effectively applied.

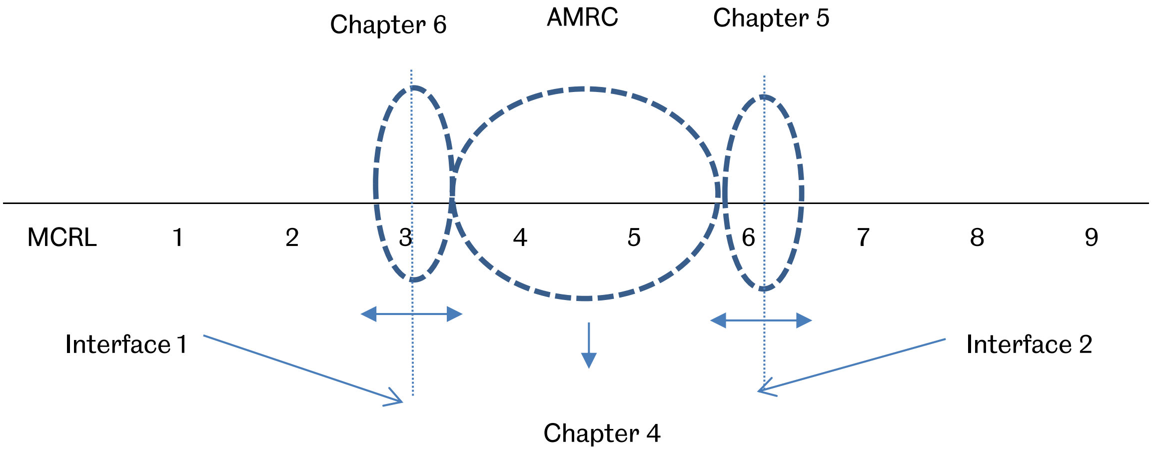


Figure 6-1 - Image showing how the case studies and chapters relate to the MCRL phases

As described in earlier chapters, the manufacturing industry faces challenges in perceiving the value of emerging technologies. In this instance the emerging technologies are novel fluid formulations provided by the cutting fluid supply chain. The challenges could arise because:

1. Suppliers are not providing compelling evidence;
2. Industry is not defining what evidence is required;
3. There is a lack of a test environment to synchronise 1 and 2, or a lack of clear direction for the test environment to take.

6.2 Details of the Case Study 2 problem

Cutting fluid supply chains aim to develop new formulations for improved machining performance. Improvements in coolant performance are desirable because of ongoing costs associated with fluid use, maintenance and ultimate disposal [182]. Health and safety requirements and increased environmental awareness also require new formulations to be developed [183]. These emerging novel technologies may offer significant improvements to industry in terms of tool life, cutting feeds and speeds and surface integrity; however the supply chain struggles to provide evidence that is compelling enough for industry to adopt these new formulations. Whilst the suppliers test the products, the machining processes, materials and standards do not adequately reflect that of the machining environment of the customer and this is why an independent approvals process is required. The risks involved in changing fluid are significant and so a rigorous test is needed.

Rolls-Royce had an historical process for cutting fluid approvals. This offered the suppliers a route through which new fluids could be tested against a benchmark fluid and those which appeared to give better performance in terms of tool life and productivity would be approved for use within the manufacturing environment.

Although many fluids met the approval standard, none were taken through this route into the production environment. This is because, although they showed improvement against the baseline, the value of implementation was not sufficiently quantified for a business proposition.

This chapter describes the approach taken to design a new coolant approvals process and a subsequent evaluation and set of recommendations for improvements with insight from Case Study 1 and by using the framework developed in the thesis.

6.3 Historical Rolls-Royce approvals process

The historical process used by Rolls-Royce to approve novel cutting fluid formulations for use in their production facilities included 14 different cutting fluids analysed from 1999 to 2015 and was carried out at a University Technical Centre (UTC). Each cutting fluid was tested on the same material in milling, tapping, grinding, drilling, and turning. The output metrics were tool wear (VB – time taken to exceed a pre-defined wear), CME 5043 (this is the RR company metallographic measurement specification for Ra roughness profile), surface micro hardness, and cutting parameters (feed, speed, depth of cut). Each fluid was given a pass or fail if the fluid performed above or below a baseline fluid used widely across Rolls-Royce. Each new fluid was ranked across the range of machining processes and the combined rank was used to screen the fluids that were performing the best. The data suggests there may be correlations but these are difficult to prove and indicates that some processes are independent from others.

Although a number of fluids passed the approvals process, none progressed through this route to be used in Rolls-Royce, suggesting that the process was not enabling novel formulations to enter the production environment regardless of any improved performance indication suggested by the test process.

Rolls-Royce and the supply chain require an improved approvals process be designed bringing together stakeholders to agree a test regime as a level playing field for suppliers to develop and test their fluids in a way which provides compelling evidence of their value proposition to their customer.

6.4 New cutting fluid approvals approach

The Case Study resides in a research and development project at the AMRC which aims to design and develop a new procedure based on the historical Rolls-Royce approvals process to verify and screen novel cutting fluids to reduce machining costs while maintaining process quality. The researcher plays the part of an observer in the project team, capturing details of the approach in order to identify how the framework developed in previous chapters could enhance the value proposition of these types of projects for industrial applications.

Several requirements were defined by Rolls-Royce for the new process:

1. Merge the supplier and customer test regimes and bridge the gap;
2. Bring the two parties together in a transparent way to align research development and industrial metrics;
3. Make sure all suppliers meet customers' needs on a level playing field using a standardised approach;

4. Identify the basic mode of value proposition for the supply chain to develop new products against the performance improvement metrics of tool life and cost of production;
5. Ensure that industry are defining and therefore seeing or recognising the value proposition, hence describing what evidence needs to be collected and met by the supplier;
6. Identifying the basic elements of cost and value that are not currently present in the development of coolant technologies;
7. Design an agreed approach and test that approach which answers either the lack of test or the test environment then synchronise these;
8. Ensuring that the test provides a clear comparison of fluid performance compared to the baseline fluid across a range of applications and against a range of data by a set of production metrics that are useful for decision making in terms of support for the business proposition;
9. Provide evidence from an approved source.

A multi stage / process specific / value specific test was designed and developed to provide a sequential process of verification. The fluids may pass through each stage by demonstrating their ability to provide benefits to Rolls-Royce. Stage 1, the initial screening phase, is carried out using the widely accepted industry standard tap torque test with results supplied by the fluid supplier. Stage 2 involves a multi-process machining trial at the AMRC. Stage 3, although not yet fully defined, involves an end application test of the fluids, successfully demonstrating cost benefit from stage 2 on a machining process within a Rolls-Royce production environment. Provided that fluid offers improved cost benefit to the default coolant used, the fluid is approved for use.

These stages and complications encountered are described further in the following sections. Due to data sensitivity some details are sanitised.

6.4.1 **The project team**

An integrated project team (IPT) was set up by the AMRC as shown in Table 6-1.

Rolls-Royce	AMRC
Project owner (Customer)	Project manager
Machining specialist	Technical lead researcher
	Machine operator
	Technical fellow

Table 6-1 - Cutting fluid approvals IPT members

6.4.2 Pre-defined Coolant Approvals assessment

6.4.2.1 Stage 1

The first stage of the process is to screen fluids which have the potential to achieve a clear demonstration of improvement in tool life against the baseline fluid - thus providing Rolls-Royce with a significant cost justification for adopting novel fluid formulations in their machining processes.

Ten fluid suppliers had approached Rolls-Royce with novel formulations for the approvals process. The aim of the new process is to provide a cost effective route for suppliers to approval.

The suppliers were consulted to agree on the most appropriate test available in house to pre-screen the coolants and the tap torque test was chosen. A current industry standard test is the tap torque test and while there is a lot of existing ambiguity in this area all agreed that this was appropriate in this case due to the availability of the testing equipment for use in-house by the coolant suppliers and because the equipment existed at the AMRC.

A standardised procedure was developed for this screening phase, including the material and machining set-up, cleaning procedures and standardised reporting [184].

The test measures the effectiveness of the lubricity of the fluid for two material specifications. The level of torque is measured during tapping process. Low torque readings indicate low friction and so better lubricity. The test was either carried out by the suppliers, with in house capability, or at an agreed neutral laboratory. In each case the test must adhere to the agreed standard tooling parameters, experimental method, data collection requirements and standardised operating procedure. Reporting documents were provided by the AMRC.

The intention is for suppliers to provide the raw data and summary sheet and pay for test. The University technical college provides an independent environment to process the data and provide Rolls-Royce with the results.

On provision of two aerospace grade material samples, the suppliers are required to conduct a tap torque test study, report back results, and return all test samples to an independent lab. The test is conducted on a number of 'blind' coolant samples of pre-defined concentration and preparation. These samples include the benchmark fluid, the samples put forward in the test and further samples provided by Rolls-Royce.

Water, fluid and test block preparation are standardised along with experimental methods and procedures for all suppliers. Template matrices are provided for the reporting of fluid application and experimental data, including entry, exit and relative torque between entry and exit of each tool.

The trial structure is briefly:

- For each alloy, coolant samples produce a number of tapped holes using the tooling specifications and parameters defined for each alloy for each tap. This is repeated a number of times;
- The output measures of torque as a function of time for each test are captured using an experimental data capture form.

On completion of the test regime a further meeting takes place with all parties to review the outputs results, which are:

- A complete experimental data capture form;
- A summary presentation giving an analysis and conclusions for these results.

The outputs requirements of a successful test are:

- Differentiation against the baseline fluid;
- Consistency and stability of the supplier entries;
- Better lubricity than the baseline fluid.

On successful screening, the best fluids can then be offered for a Stage 2 evaluation.

When working through the input section of the framework, the need is to establish how this phase is describing the value proposition to the end customer. At this stage other capabilities are uncertain, such as coolant life, cost per barrel or details of how the fluid will interact with other variables in the production system. The research in Case Study 1 provides knowledge about the real and effective value propositions and the approaches can be used in this situation. For example uncertain information could be captured using expert judgement techniques from the suppliers.

6.4.2.2 **Stage 2**

This stage follows on from the initial screening in phase 1 and is relevant to the process section of the framework, addressing the synthesis of what industry needs to know and identify gaps. It must demonstrate the performance of the fluid samples in three machining processes – drilling, milling and turning – on two representative aerospace grade materials. The machining is carried out at the AMRC who have identified suitable machining cells to carry out the test procedure, those that are representative of machining in Rolls-Royce.

The cutting performance, tool wear rates and integrity of machined surface and roughness to the minimum standard defined by CME5043 are tested for each sample fluid, to test for the following output metrics:

- Tool life (VB – from historical process).
- Co-ordinate measuring machine (CMM) surface integrity readings (Ra and microhardeness –from historical process).
- Cutting force measurements (from historical process).
- A clear demonstration of improvement – an increase of 20% in tool life determines the cut-off point, which is a generic target that represents the identification of a 'step change' over the existing or previous metric that should have a pay back within 3-5 years. An improvement of this magnitude is required for R&D activity since, as part of existing contracts, established suppliers and technology providers are expected to deliver a year on year improvement of around 5%. (This additional metric has been introduced by the IPT to demonstrate a clear improvement used to justify moving the technology onto the next stage)

A number of machining trials were carried out on milling and when the results were analysed a phenomenon was encountered: over time there was increased variability in tool-life indicating a lack of control over key process variables. This result was not expected and so required further investigation. Initially the water was investigated by the IPT – in some Rolls-Royce processes demineralised water is used so in this process the water was changed to demineralised water to potentially reduce variability from the trial. This was tested, and did not cure this symptom. On closer inspection it seemed that contaminants (tramp oil) were mixing with the coolant and changing its properties. A larger concentration of tramp oil was affecting the lubrication and causing variability in tool life. This compromised the integrity, repeatability and effectiveness of the test. Further investigations were carried out with high and low levels of oil to understand the effect on the results.

As stated by the machining specialist within the IPT, "If correlation and causation is demonstrated between levels of hydraulic oil contamination with coolant A but this same correlation and causation doesn't extend to coolant B then the trials are not valid, equally if the type of tramp oil changes across applications (which is likely) then the trials are not valid. There is also the risk of machine tool wear changing the rate of contaminate oil in the coolant (there is also a risk that the OEM updates the machine and changes flow settings)"

These concerns brought out a number of risks and questions raised by the IPT which were captured verbatim in Table 6-2 and Table 6-3.

If	The effects of contaminating coolant with excessive amounts of tramp oil (or other) is not identified, understood and eliminated (minimised).	Then	The base line coolant performance described by tool life and cutting force trials is invalid.
If	The volume of oil in the coolant is unknown.	Then	Machining trials could unknowingly be effected and comparing a coolant against the base line is invalid.
If	The condition of the coolant being tested is not stable and changes due to contamination.	Then	Machining trials could unknowingly be effected and comparing a coolant against the base line is invalid.
If	The effect on the machining process of mixing machine tramp oil with suppliers' product is unknown.	Then	Comparing suppliers' coolants against base line is not valid.

If	There are no monitors/controls of the coolant condition.	Then	Machining trials could unknowingly be effected and comparing a coolant against the base line is invalid.
If	The effects of other (than oil) coolant contaminants is unknown.	Then	Machining trials could unknowingly be effected and comparing a coolant against the base line is invalid.
If	Machine clean down at the time of a coolant change is not thorough.	Then	Contaminants could propagate across coolant trials and invalidate comparisons against base line.

Table 6-2- Risks to approvals process identified by the IPT

1	What are the design and actual dosing rates of slide way and spindle oil with respect to time and machine use?
2	What is the maximum particulate size in coolant and does it affect tool life?
3	Is there a local test that will show how oil contamination of the coolant changes over time?
4	What is the oil level at start and end of trial period?
5	How much tramp oil is contained in the coolant flowing from the coolant delivery nozzles?
6	What are the suppliers' views on effects of tramp oil on their product and on tool life?
7	Is filtration of 0.158mm particulate size too coarse?
8	Is the machine actually operating to specification regarding lube oil losses? (design specification is known)

Table 6-3 - Questions raised by the IPT when investigating oil contamination phenomena

Differentiation between cutting fluids was hindered by the effect of tramp oil. On closer inspection there was a design fault with the waste oil tank. The project was put on hold. The tank was modified to remove this issue. Based on experience from Case Study 1, an IFDR was fitted. Earlier trials had shown that an IFDR can remove tramp oil and contamination successfully as well as providing a stabilising effect on the machining process. The testing recommenced and the increase in tool life was removed, therefore stabilising the results. There was however the uncertainty around oil contamination and third party formulation testing of dirty fluid samples was inconclusive. Although the system was behaving in a stable manner; the identification of variables which can render the test invalid had caused too much risk to the project. On realisation that coolant contamination has a significant effect on coolant performance in the R&D environment; an additional supporting project was launched to return to the production environment to better understand the industrial position (and benefits case) for this moving forward. This additional project captured previous experience and lessons learned as well as an understanding of the latest technologies adopted by Rolls-Royce that provide coolant condition monitoring and management

Contamination was an issue highlighted in Case Study 1. The results clearly demonstrate that these parameters need to be investigated and mitigated. It is infeasible to effectively differentiate between fluids when a third-party contaminant is affecting results. This experience demonstrates that using information from the production environment can have a significant effect on experimental procedures in the AMRC and relates to the output / feedback stage of the framework. Best practice should read across from industry to AMRC and inform fluid suppliers of the effects of other oils/contaminants in the system.

6.4.3 **The AMRC-RR coolant management and waste control project**

Case Study 1 identified initial issues and opportunities associated with coolant management and control, the resulting comprehensive cost model suggested that the introduction of high performing coolants in the current production environment may include risks that the potential benefits of such coolants are not realised.

Case Study 2 reinforced this due to the identification that critical process controls not understood or in place at the R&D level. Coolant selection via this route without that understanding or control could therefore be flawed. Case Study 1 suggested where improved control can be achieved with improved filtration which is subsequently shown to stabilise the outputs.

So in order to improve the synthesis between Case Study 1 and 2 a mini-project was launched to more fully evaluate the benefits of good coolant management and control, identify the technology enablers and propose where the new focus would be driven and connected from both development and production areas.

The project aim was to bring together a range of Rolls-Royce stakeholders, capture current issues, experience and drivers for cutting fluid use, and process this information to identify opportunities, and define recommendations for further work in order to realise a range of opportunities in terms of economic benefit to the company.

The researcher used semi-structured interviews to engage with Rolls-Royce stakeholders to capture current issues, technologies, and practices related to coolant use. This information enabled an outline of potential opportunities in both the short and medium term for consideration, which align to business drivers (see Figure 6-2).

6.4.3.1 **Method**

The project consisted of:

- Visits to four Rolls-Royce manufacturing facilities;
- Interviews with sixteen key Rolls-Royce stakeholders with a previous interest in coolant contamination (identified by Rolls-Royce), see Table 6-4;
- Capture of existing processes and manufacturing data for assessment and analysis;
- Capture of coolant related issues across sites;
- List of recommendations to consider, regarding creation of a Statement of Requirements (SoR) for follow on work.

Site	Location	Role	Interview Method
Turbine Blade Facility	Derby	Manufacturing engineer	Site visit and joint semi-structured interview
		Maintenance team	
Assembly & Test	Derby	Staff manufacturing engineer	Site visit and semi-structured one to one interview
Experimental	Derby	Manufacturing engineer	Semi-structured interview
Manufacturing Technology	Derby	Engineering associate fellow in Manufacturing Technology	Group discussion
		Mill/drill global process owner	
		Machining specialist Rotatives	
		Sustainability manager	
		Manufacturing services leader	
		Manufacturing services	
		Civil aerospace HSE leader	
Civil aerospace blisk (bladed disk) machining	Annesley	Blisk adaptive machining process owner	Site visit and semi-structured interview
Rotatives	Derby	Equipment lead Rotatives	Semi-structured Interview
Compressor components	Barnoldswick	Manufacturing engineer	Site visit and semi-structured Interview

RRPS	Germany	Manufacturing engineering and machine tools specialist	Semi-structured phone interview
Submarines	Derby	HS&E lead Submarines infrastructure	Semi-structured phone interview

Table 6-4 -Details of Rolls-Royce stakeholders for coolant waste and management project

A requirements capture form was created and used as the structure for each interview and group discussion, the researcher facilitated as each section of the capture sheet was discussed (see Appendix C). The form aimed to capture information on current machining performance against coolant management (including filtration, condition monitoring and tramp oil removal) systems in order to identify which areas could benefit from a more detailed investigation/trial into improved solutions. Comments, observations and / or data were collected from each stakeholder to obtain their views on coolant related issues.

6.4.3.2 **Results**

Fortuitously the area of coolant management is also incorporated into the wider drive of waste reduction in the company. In fact, the results of Case Study 1 better identified the cost / benefit drivers from coolant management, many of which tackle waste control. The mini project was also timed to feed into this waste reduction drive and helped to direct the wider initiative which is reflected in the results.

The key economical drivers identified by the stakeholders revolved around two main themes: cost effectiveness and waste. The companywide internal waste target is to "Reduce total solid and liquid waste by 25%, normalised by revenue, by 2025 (includes hazardous and non-hazardous waste)". In addition, current fluid management provided by external services brings into question cost effectiveness and process intervention protocols, as there are gaps in knowledge and communication between what external services do and what Rolls-Royce have control over. Variables affecting cutting fluid waste and opportunities to improve practices were identified. All improvements which could reduce waste, reduce the cost of the fluid management package, and reduce manufacturing costs are key focus areas.

The key technical drivers identified by the stakeholders revolved around the following themes: waste reduction and recycling processes, filtration, process intervention, control of fluid delivery metrics (including cutting fluid condition monitoring), and contamination control. Cutting fluid waste measures identified a range of waste management and recycling activities which could be assessed to improve the method by which waste is treated before disposal. A number of novel filtration and cutting fluid management technologies were identified across Rolls-Royce sites, and several had been tested or are still under assessment. Although each of these technologies has delivered improvements in certain areas, the conclusion was that none of them provided a solution to cover all the issues regarding cutting fluid management across the business. Process intervention triggers for sump change and cutting fluid checking procedures were identified as target areas for immediate assessment. Several variables were identified as the most appropriate first stage for improvement, including a detailed assessment of the cutting fluid testing procedures and practice.

During the group discussion, stakeholders suggested that a useful initial study would be to determine the baseline, in terms of effectiveness of current testing regimes and decision making procedures, to help determine the next steps. Targeted collection of fluid samples to test for cutting fluid condition, pH, concentration, bacteria, and contamination, including particle analysis is required. It is then necessary to record details regarding the time since the last sump change and machining key performance indicators (KPIs) including material type, production quantities and conformance data. This would allow Rolls-Royce to create a site-wide map of cutting fluid condition as a key decision-making and process-monitoring tool, covering elements such as cutting fluid conditions and their effect on machining performance.

Further recommendations include the identification of the most cost effective technology adoption for waste, filtration, and cutting fluid monitoring to provide a minimum specification for all current and new machine tool purchases.

The findings from this mini-project confirmed that waste targets are key, stakeholders are all responsible for this overarching driver, and steps taken to reduce waste could have an effect on other drivers such as cutting fluid contamination, part non-conformance and production performance. Figure 6-2 represents the range of variables which affect the use of cutting fluids across multiple sites from the 16 stakeholders interviewed. Phase 1 – short term recommendations: investigating fluid condition checks, identification of sump change triggers and testing fluids before a changeover. Phase 2 – medium term recommendations: establishing the business case for cutting fluid management technologies, evaluating and improving fluid condition checking procedures, investigating the performance between central and stand alone filtration systems, investigating waste fluid recycling and treatment, investigating grinding specific cutting fluid issues and research into the effect of filtration on bacterial growth and tool wear. The opportunities identified included sump life extension, reduced downtime, reduction in consumables, and cost of the fluid management contract, fluid cost reduction, and reduction in non-conformance and improved cutting fluid cleanliness and fluid stability. Each of these opportunities provides improvements to the main business drivers of waste and cost reduction and quality improvement.

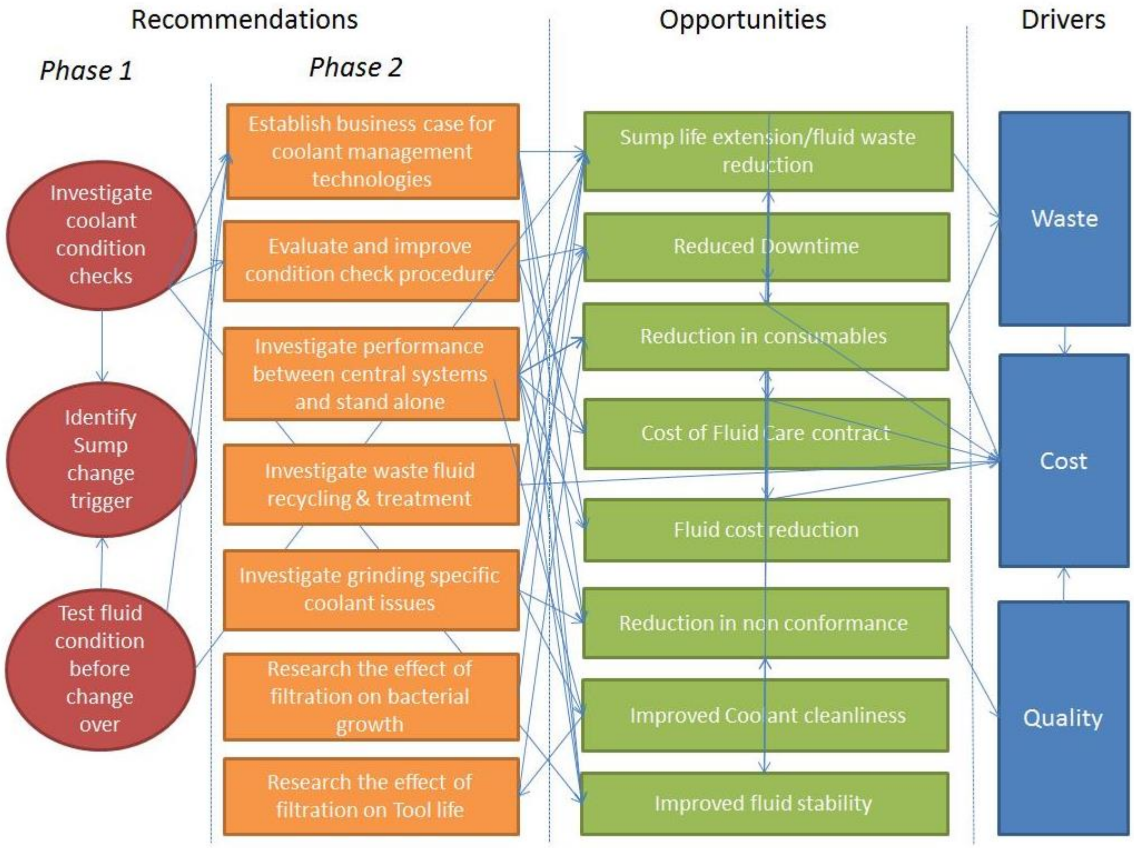


Figure 6-2 - Recommendations, opportunities and drivers identified in Rolls-Royce coolant waste and management project

The results of this mini project were presented to the waste reduction programme team at the company and have gone on to provide the foundation for future activities.

6.5 Project evaluation and framework application

Case Study 1 identified how other variables such as cutting fluid cleanliness can have an effect on performance variables with the use of cutting fluids and so further variables should be included such as sump life estimation and filtration technologies. The mini-project identified how cutting fluid cleanliness can have an indirect or direct impact on machine performance. In the example of a central cooling system, the impact on fluid pumps caused vibrations in the machine tool, resulting directly on machining performance. Case Study 2 reinforces the need to ensure process controls are fully in place at the R&D level to enable effective technology selection. This evidence needs to be directed back into the testing regime and drives the need for more fundamental research activity, not limited to the direction of industrial benefit such as tool life increase of 20% and improved cutting performance.

The framework and experience has identified that a model needs to include the underlying and unrecognised aspects of the technology that lower MCRL level testing and development currently do not address.

To evaluate the framework across the MCRL stages, experience from the two case studies must be aligned. There is a disconnect between parameters that have a significant effect on the production environment and the procedures which are developing technologies at a lower MCRL. The true value proposition and risks involved in the use of cutting fluid is not fully understood in the development phases and feedback from the production environment can enhance the development of technology evaluation.

The issues regarding tramp oil highlighted the need for detailed analysis and challenges to existing practices. The AMRC staff are highly experienced in performing tool wear trials however with cutting fluid technologies the risk to the trial was compromised due to an issue not previously experienced and many factors brought out in the cleanliness investigation describe the disconnect between industry and cutting fluid development. This Case Study has identified how the development of cutting fluid technologies for increased tool life does not necessarily offer the best solution when production factors are at play. Consumable reduction benefits may not outweigh the cost of approving a new fluid, the implications of poor cutting fluid filtration and management and the resulting short sump lives can be significant.

The next section describes how the framework can be used to align production with early technology development, including a demonstration of how the value proposition may be enhanced if experience from the production environment is included in earlier MCRL phases.

6.6 Application of the framework

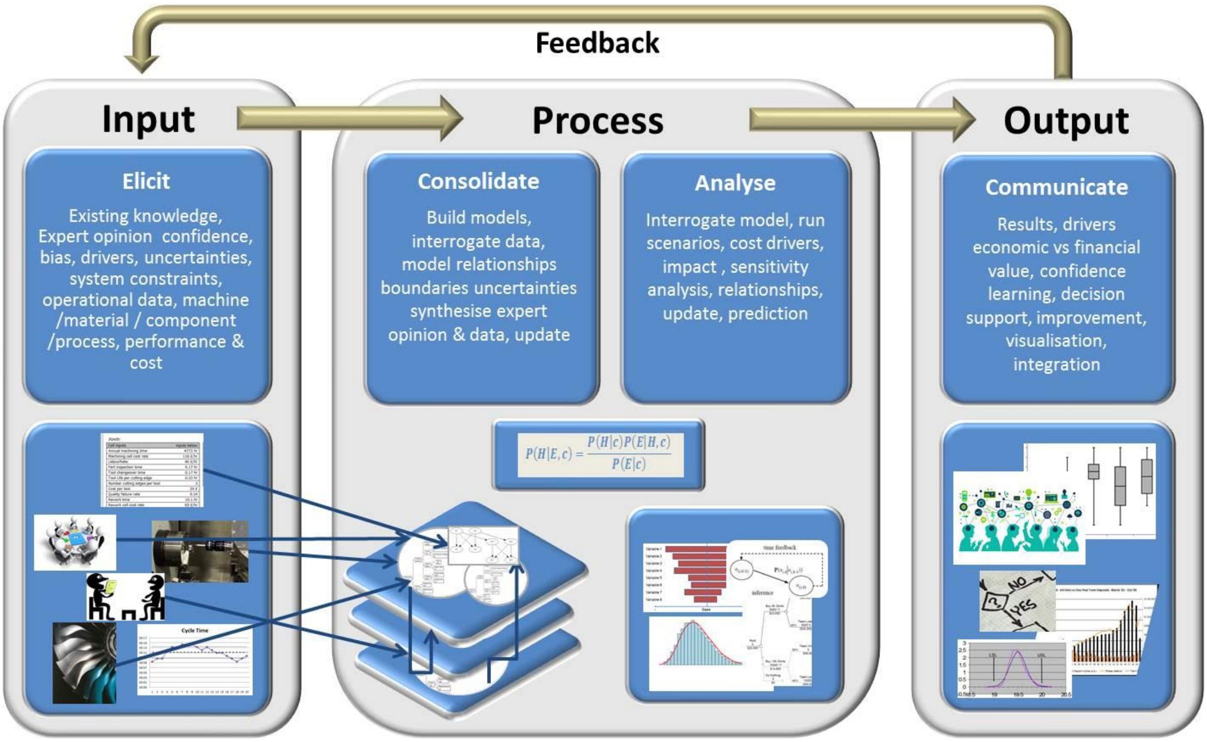


Figure 6-3 – A value – focussed framework for technology selection

The framework covers the main aspects of value related decision making and can be used to inform the new cutting fluid approvals process.

The framework would be used to enhance the value proposition by:

1. Bringing together stakeholders, including those currently using existing technology to provide information about production issues;
2. Clarifying the value proposition for both in terms of output metrics, and providing a clear definition of the input approach to ensure outputs align to industrial decision making metrics;
3. Simulating the production environment ensuring stability and repeatability, including integrated technology and management processes to give value to the customer in terms of read across;
4. Agreeing and developing a standardised test regime and data analysis approach which provides value for money for all parties;

5. Providing a detailed analysis of comparisons against these agreed approaches, including relationships between variables, differentiation between test fluids using expert opinion, by interrogating the data thoroughly to ensure a standardised and stable decision making tool;
6. Ensuring that uncertainties are mitigated or quantified and communicated including cost of implementation, management and approvals;
7. Ensuring that the outputs of the test provide a clear value proposition with compelling evidence to support the approval and subsequent adoption of the novel formulation inside the production environment;
8. Ensuring that previous experience is fed into the process and likewise lessons learned are captured.

6.6.1 **Model 1 – Tool life increase vs IFDR**

Input elicitation and stakeholder management is key to the effective development of any technology evaluation process. The gate review process aims to ensure that throughout a project the results are analysed by a range of stakeholders, questions are asked and results are challenged. While the existing process brought together the project team to test and design and lay down procedure inside the AMRC and worked with the supply chain to identify an appropriate screening test, the process was designed around metrics of tool life, and therefore consumables reduction, and the maintenance of current surface quality benchmark.

Case Study 1 and the subsequent tramp oil contamination issues highlighted the need to include fluid robustness to bacteria and cleanliness parameters to ensure the consistent behaviour of the cutting fluid in production. A broader knowledge of industrial complications and previous experience allows these unexpected outputs to be identified sooner and mitigated. The impact of these parameters can outweigh the benefits associated with increased tool life, based on a return on investment in development phases. The criteria highlighted in the production environment which have significant impacts in production can be used in the research environment for decision making.

To demonstrate the potential of including production experience in early MCRL testing, the model in Case Study 1 was adapted to describe three scenarios. The first is the original system with no IFDR; the second is the introduction of the IFDR; and the third with no change to the system but with a tool life increase of 20% (to simulate improved fluid technologies) (see Figure 6-4). Note that all data presented in this research is not real production data but is representative of the type and range of data used in production.

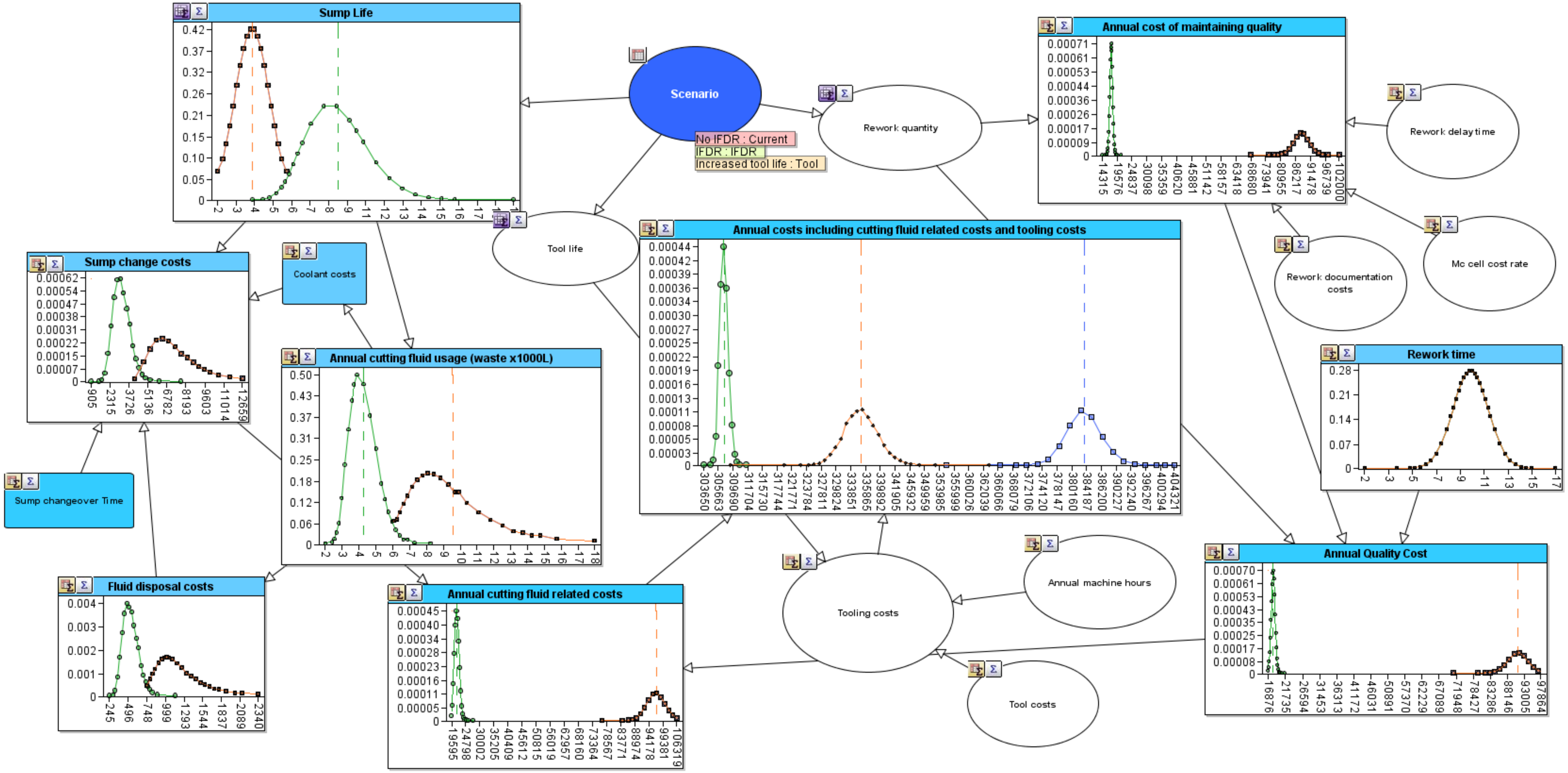


Figure 6-4 - Full BN model for CS2 including three scenarios and uncertain values

6.6.1.1 **Input**

The sump life priors in this case remained the same as in Chapter 5 (see Table 6-5 and Figure 6-), with the sump life of the increased tool life scenario the same as the current sump life.

Variable	Distribution	Mean	Min	Max	Variance	alpha	beta
Current Sump life	Normal	4	2	6	1		
Sump life with increased tool life	Normal	4	2	6	1		
Sump life with IFDR	Beta	24 (50th %)	12 (5th %)	60 (95th %)		6.17	18.8

Table 6-5 - Sump life priors used in chapter 5.

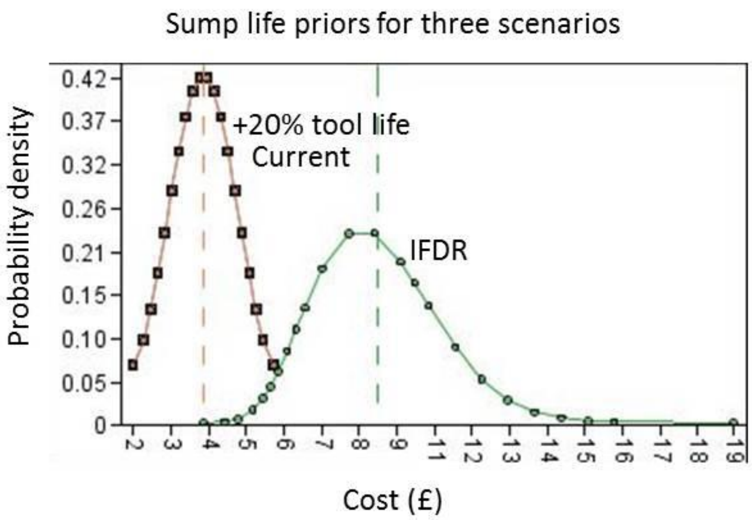


Figure 6-6 - Sump life prior distributions

6.6.1.2 **Process**

The requirement for tool life representation meant that additional nodes must be added to the Bayesian network from Case Study 1 (see Figure 6-5 and Figure 6-7), with associated node probability tables (Figure 6-6 and Figure.6-8).

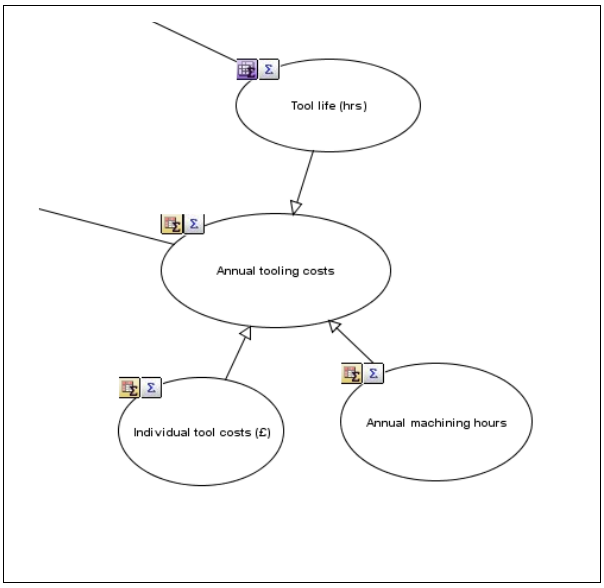


Figure 6-5 - Annual tooling costs added to BN

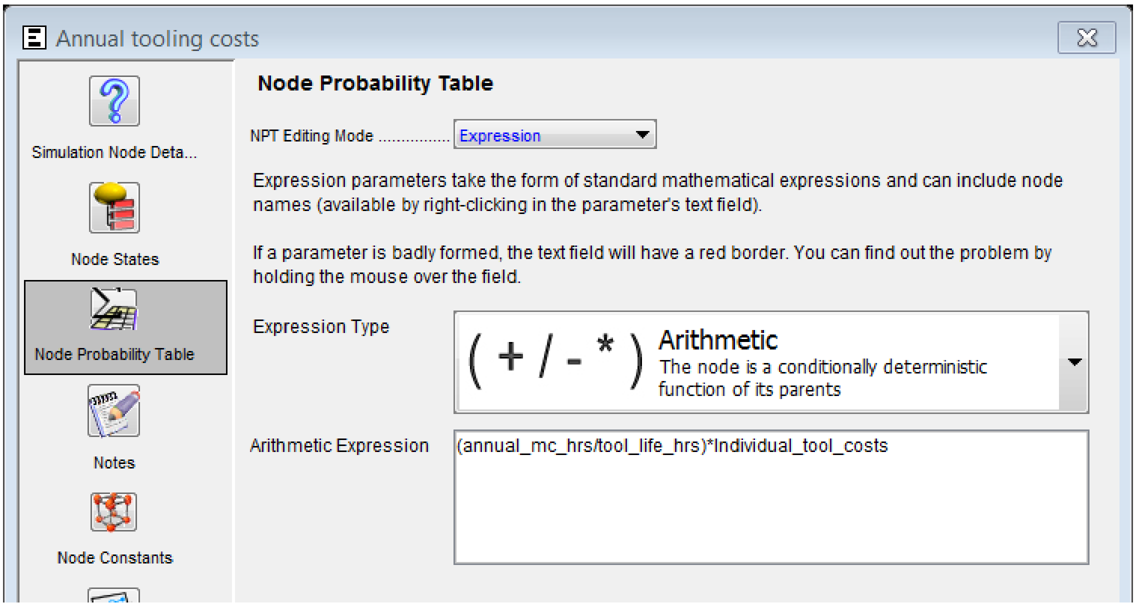


Figure 6-6 - Annual tooling cost - node probability table

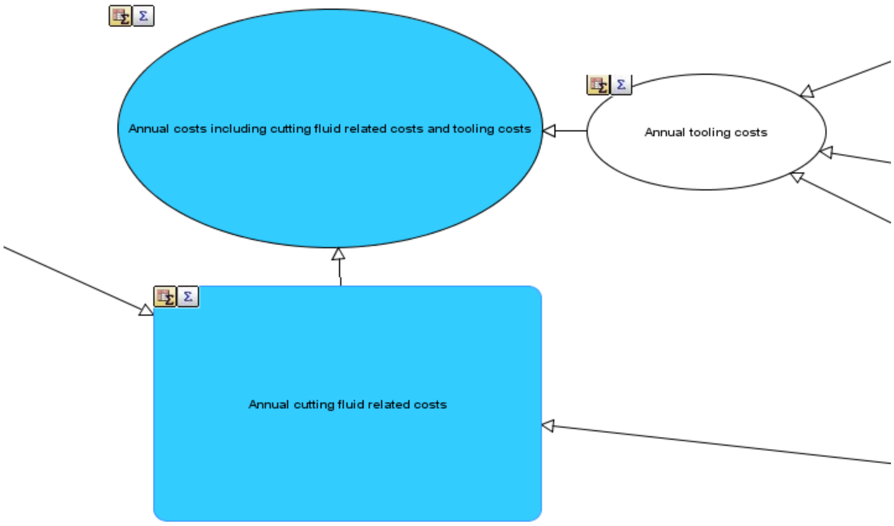


Figure 6-7 - Additional annual costs node added to BN

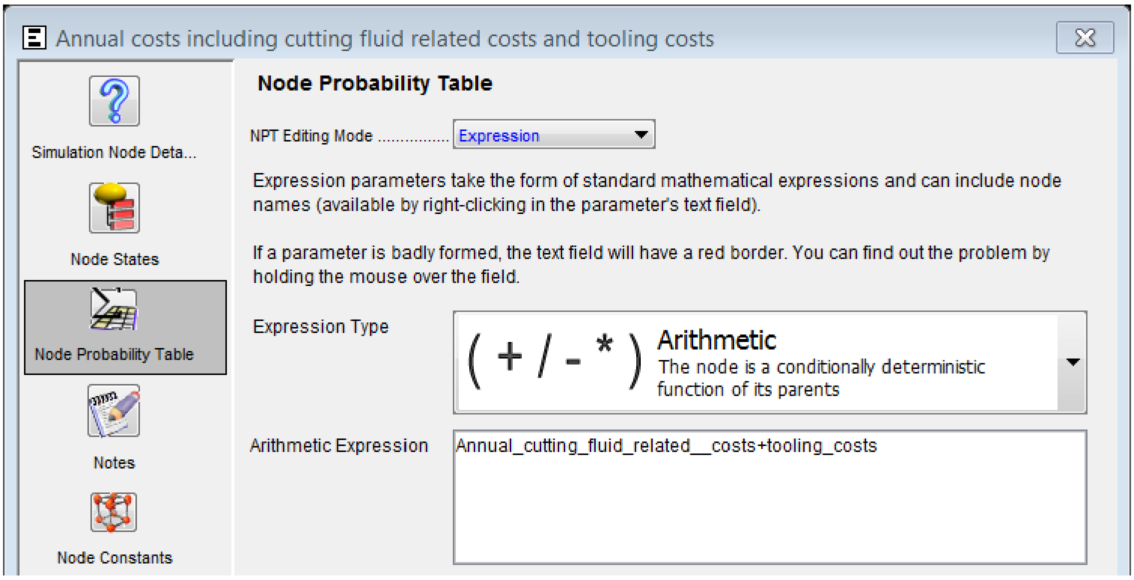


Figure.6-8 - Node probability table for additional annual costs node

Next a scenario node is added to the model which represents the three scenarios, current (No IFDR), IFDR (IFDR) and the increased tool life scenario (Tool) (see Figure 6-9).

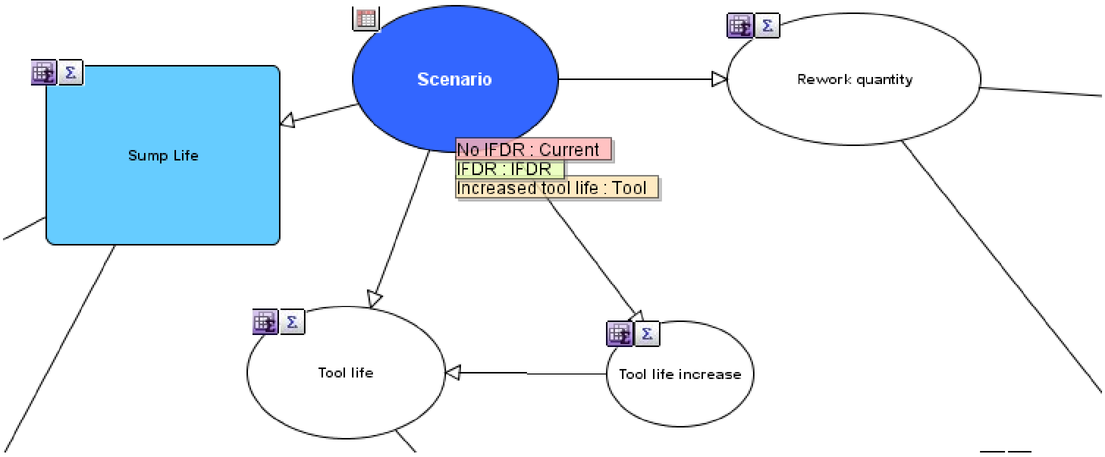


Figure 6-9 - Three scenarios- Current filtration system, with Integrated Fluid Delivery and Recycling system and increased tool life by 20%.

As tool life is now added to the model the Italian evidence is again consulted (see Table 5.24). The Italian companies reported an increase in tool life as a result of installing the IFDR. Whilst this information does not give values, knowledge gained from the previous work in Chapter 5 and Chapter 6 is used to estimate uncertainty around this evidence. A noticeable tool life increase would be between 10-20% and the maximum value stated was 50%. A Beta distribution is used to represent this data and using expert elicitation techniques the estimates for tool life increase with an IFDR are assumed to be 5th percentile 10%, 50th percentile 20% and 95th percentile 50%. Again using the SHELF software provides the parameters of a Beta distribution as $a = 6.25$ and $b = 24$, giving $Beta\ (6.25, 24)$ as the distribution represented for the tool life increase NPT for the IFDR scenario in the model (see Figure 6-10).

Parameters which differ for each scenario are populated in the model using partitioned expressions in the node probability tables of sump life, tool life increase, tool life and rework quantity (see Figure 6-10, Figure 6-11, Figure 6-12 and Figure 6-13).

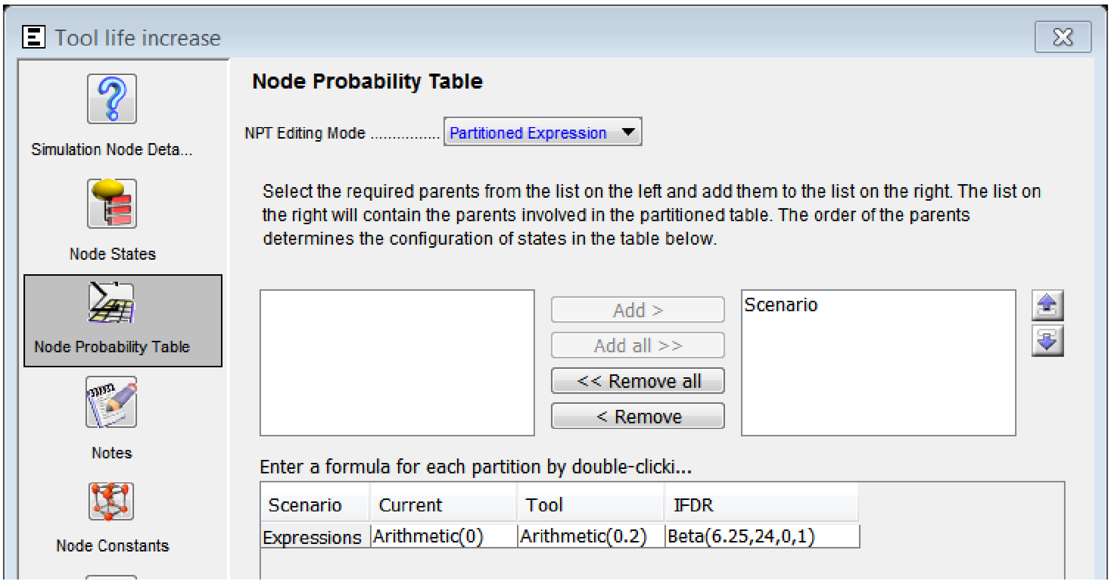


Figure 6-10 - NPT for tool life increase with partitioned expression for three scenarios

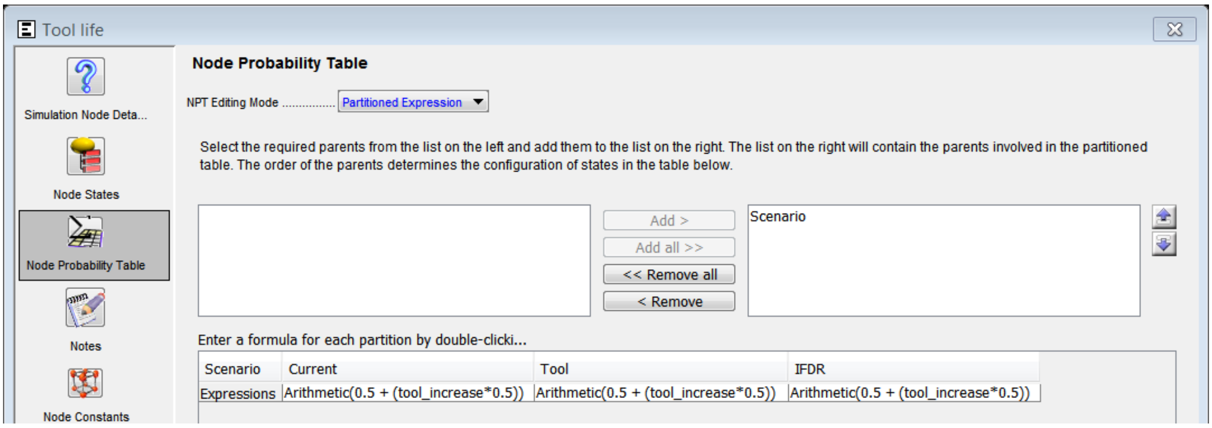


Figure 6-11 – NPT for tool life with partitioned expression for three scenarios

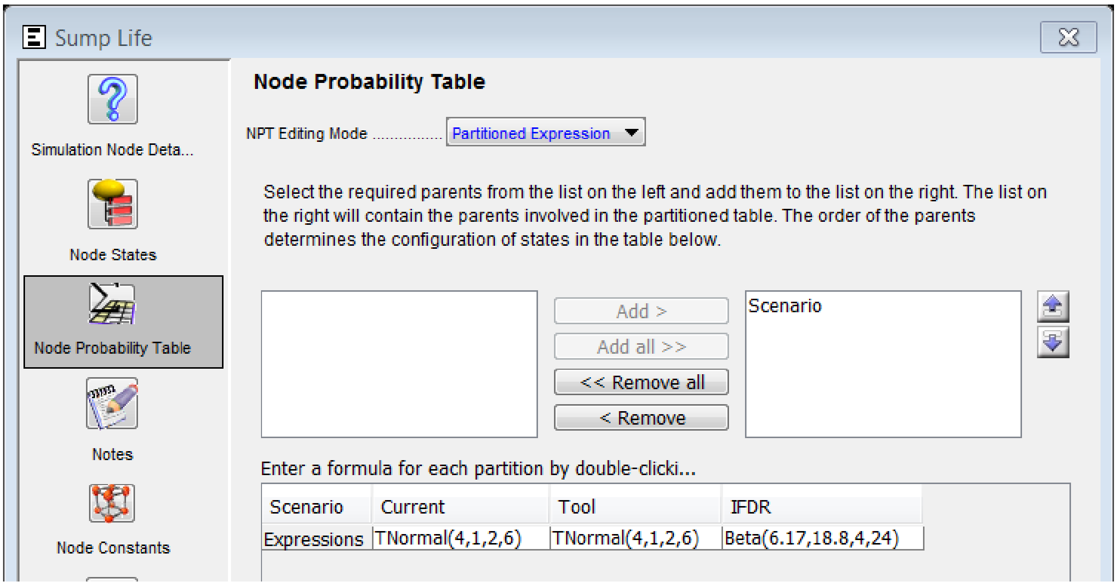


Figure 6-12 – NPT for sump life with partitioned expression for three scenarios

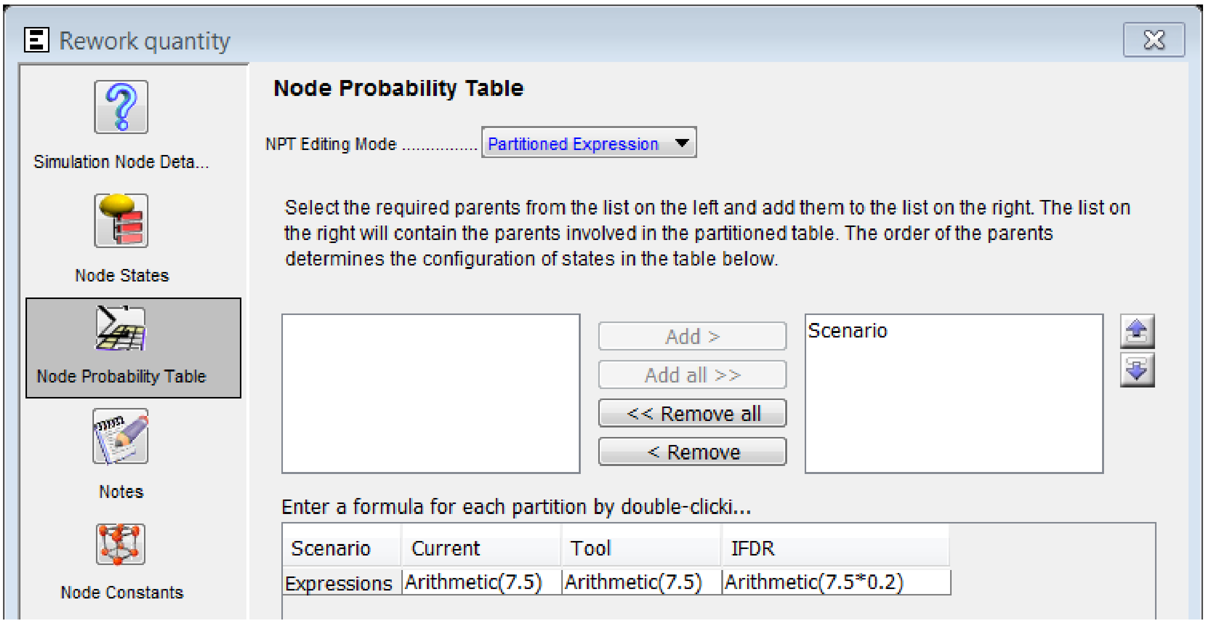


Figure 6-13 – NPT for rework quantity with partitioned expression for three scenarios

6.6.1.3 **Output**

The three scenarios, IFDR, Current (No IFDR) and increased tool life were run through the network and two sets of results were produced. The first is the annual fluid waste (see Figure 6-14).

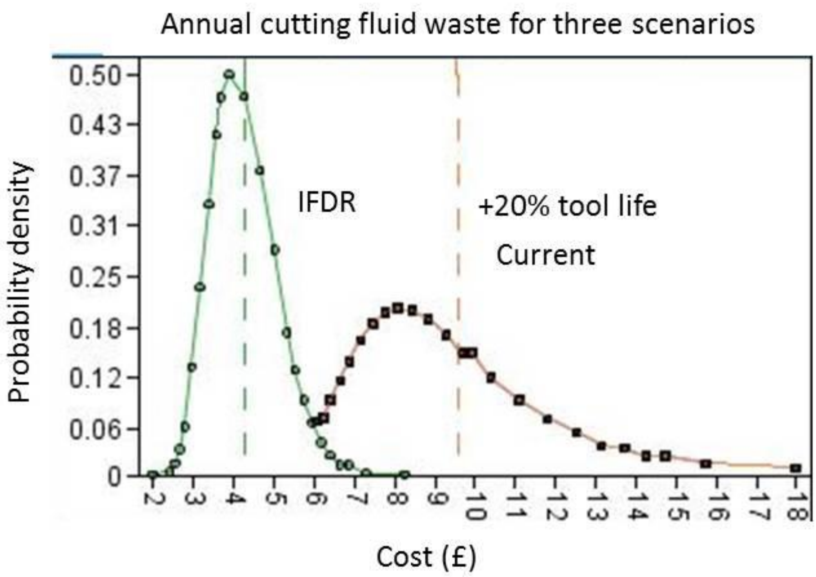


Figure 6-14 - Annual cutting fluid use results from three scenarios

Figure 6.14 shows that the use of an IFDR reduces waste fluid by 65% with the tighter distribution demonstrating improved confidence in the results. The use of media free filtration also reduces the disposal of hazardous waste attached to paper media; however neither assumptions nor data concerning these consumables were available at the time of building the model and so were not included. This and the opportunities identified in Section 6.25 offer significant opportunities to meet the 25% waste reduction target. Data and metrics strategies, as well as target setting and control of cutting fluid management including opportunities of technologies have been identified. These opportunities were identified in industry and should be built into R&D activities. Sufficient gaps in conventional cutting fluid knowledge were identified. Development of cutting fluid condition monitoring and filtration technologies should be the focus. Using the output / feedback section of the framework to ensure that all parameters related to a novel technology that are identified as inputs earlier on will provide a better value proposition.

The second set of results is for the total annual cost of fluid use, including tooling costs and fluid related costs (see Figure 6-15).

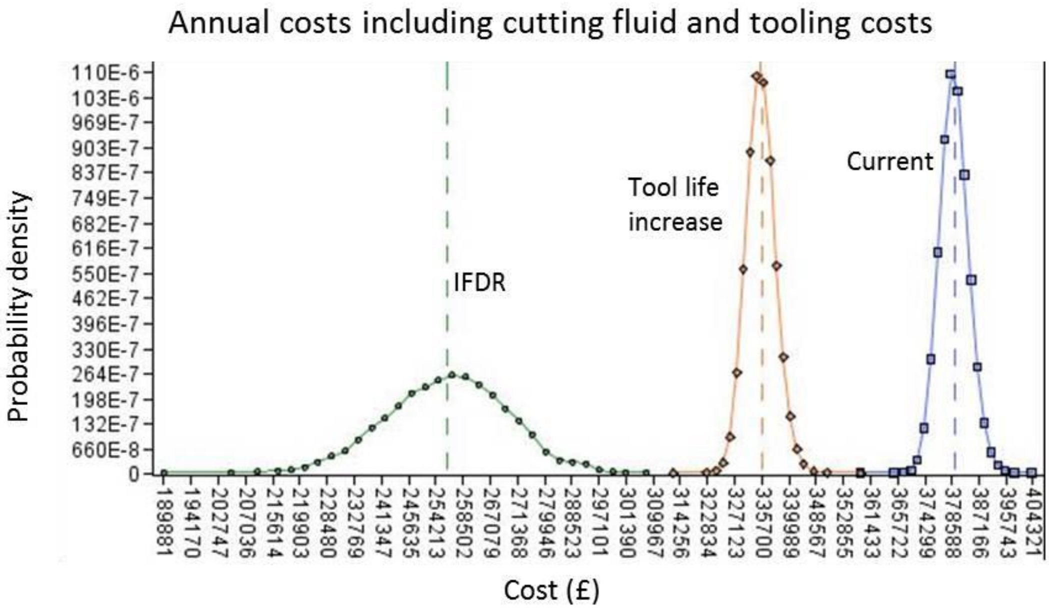


Figure 6-15 – Model 1 results of total annual coolant related costs with three scenarios

The summary statistics for total annual coolant related costs for the three scenarios are shown in Figure 6-16. These are used to determine and compare the potential cost savings between the scenarios. Although the IFDR scenario results in lower cost estimates, the confidence is spread due to the uncertainty around the tool life estimates. Further evidence gathering here would tighten the spread of data; however it was not possible to collect further details from the Italian companies at this stage.

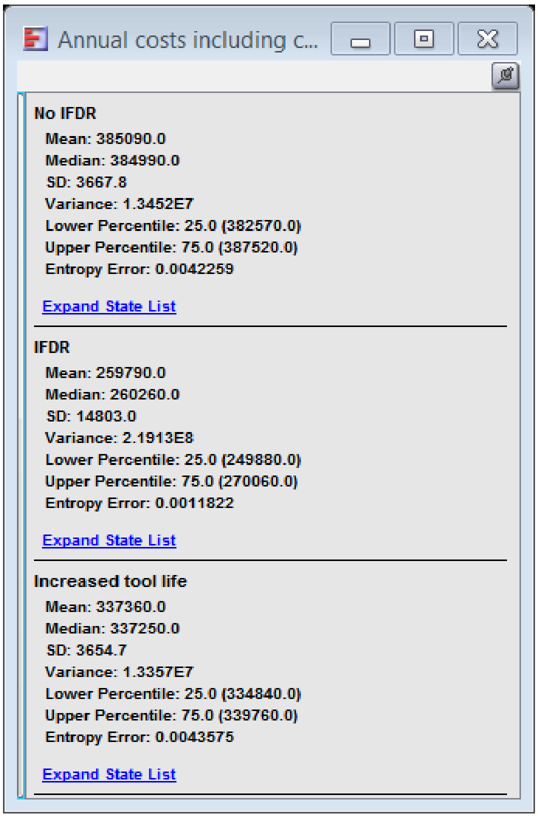


Figure 6-16 – Model 1 total annual cost summary statistics for the three scenarios

Values are extracted from Figure 6-16 for each scenario into Table 6-6 Table 6-6 which demonstrates the potential mean, best case and worst case cost savings when comparing the scenarios over the current system and also the difference in cost reduction between adding an IFDR and increasing tool life by 20%. In this table C_m C_u and C_l represent the mean, upper percentile and lower percentile cost respectively for the current (No IFDR) system. $IFDR_m$, $IFDR_u$ and $IFDR_l$ represent the mean upper and lower percentile costs for the scenario with an IFDR, and similarly $Tool_m$, $Tool_u$ and $Tool_l$ represent the mean upper and lower percentile costs of the scenario with 20% tool life increase.

Scenario	**Current (No IFDR)**	**IFDR**	**Cost savings**
Mean (=C_m - $IFDR_m$)	£385090	£259790	£125300
Best case (= C_u - $IFDR_l$)	£387520	£249880	£137640
Worst case (= C_l - $IFDR_u$)	£382570	£270060	£112510

Scenario	Current (No IFDR)	Increased tool life	Cost savings
Mean (=C_m – $Tool_m$)	£385090	£337360	£47730
Best case (=C_u-$Tool_l$)	£387520	£334840	£52680
Worst case (= C_l - $Tool_u$)	£382570	£339670	£42900
Scenario	**Increased tool life**	**IFDR**	**Difference in Cost savings**
Mean (=$Tool_m$ – $IFDR_m$)	£337360	£259790	£77570
Best case (= $Tool_u$-$IFDR_l$)	£339670	£249880	£89790
Worst case (= $Tool_l$-$IFDR_u$)	£334840	£270060	£64780

Table 6-6 – Cost saving comparisons between scenarios

The results indicate that investing in an IFDR provides around £77000 more cost savings annually than the direct impact of increasing tool life by 20%.

6.6.2 Model 2 - Coolant validation vs IFDR replacement

Consideration should also be made to the costs not yet accounted for regarding the three scenarios. A further model is developed to reflect a situation where both the validation is required for the new coolant and also the costs to replace an existing filtration system with an IFDR. Input variable estimates were elicited from a senior technology partnership manager and a machining platform technology lead at Rolls-Royce via email communication.

6.6.2.1 Inputs

Development costs for the new cutting fluid approvals process was ~ £150k plus the cost of stage 3 trials ~£30k. This cost is the development cost for all new coolant approvals across the company so will not be included in this model but should be appreciated.

The validation costs for new coolant would include filling a machine and performing a trial on a test piece which would then require a CME5043 assessment to ensure there are no issues in the sub-surface layer. The cost to the business for this would be 3 days @ £120 per hour for the trial (£2880) plus a test piece (normally free issue if a suitable part is around) then CME5043 which would be around £2k. At worst there would be the requirement to use a part for this work which could then be between £20k and

£150k – however this is deemed very unlikely so will not be included in the model. This validation would need to be repeated for the different material groups (Nickel, Titanium and Steel). This model represents a 'typical' machine tool over the space of one year where the same material is machined and therefore one validation programme is required.

Once the IFDR is in place there is no validation needed as the machining processes and procedures are not affected.

Installation and operator training costs are included in the purchase price of the IFDR and in the case of the machine in Chapter 5 there was no existing filtration system however the cost of removing the existing system and any electronic, physical changes to equipment need to be accounted for in other cases so will be included in this model, they are ~ £2k.

The 20% tool life gains would not necessarily be realised on existing machining practices and depends on part classification which in effect is a variable across the company (and the industry) however in this case the 20% tool life increase will be included for demonstration purposes.

6.6.2.2 **Process**

Nodes are added to the model to represent Coolant validation costs, depreciated costs of an IFDR (10 year depreciation) and existing filtration removal costs (see Figure 6-17). The NPT for each of these include partitioned expressions for the three scenarios (see Figure 6-18, Figure 6-19 and Figure 6-21).

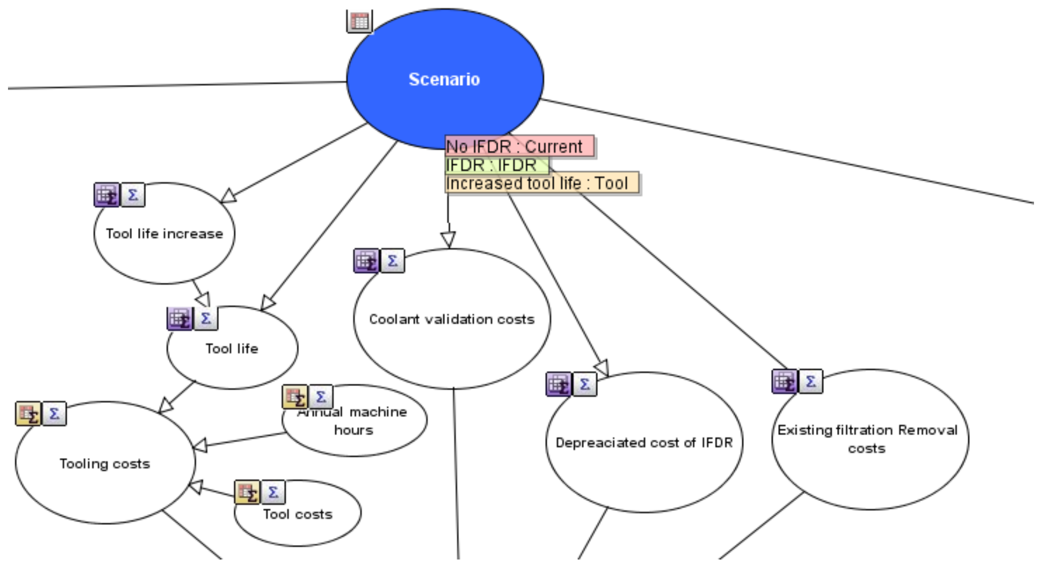


Figure 6-17 -Three scenarios, No IFDR, IFDR and increased tool life for model 2

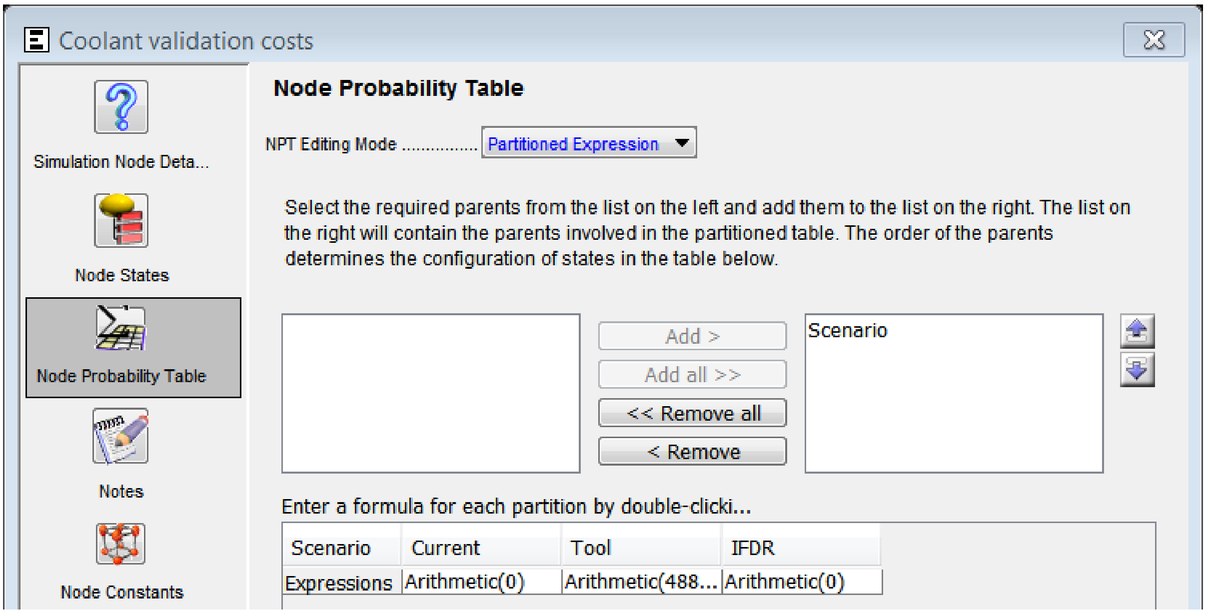


Figure 6-18 - NPT for coolant validation costs with partitioned expression for three scenarios

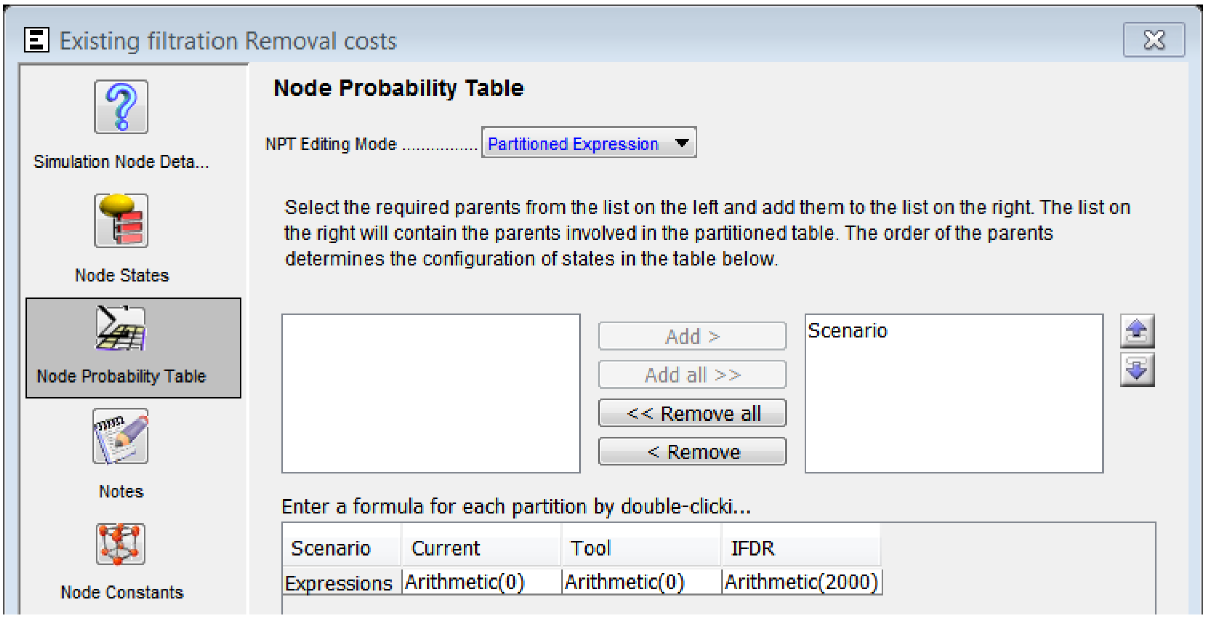


Figure 6-19 - NPT for existing filtration removal costs with partitioned expression for three scenarios

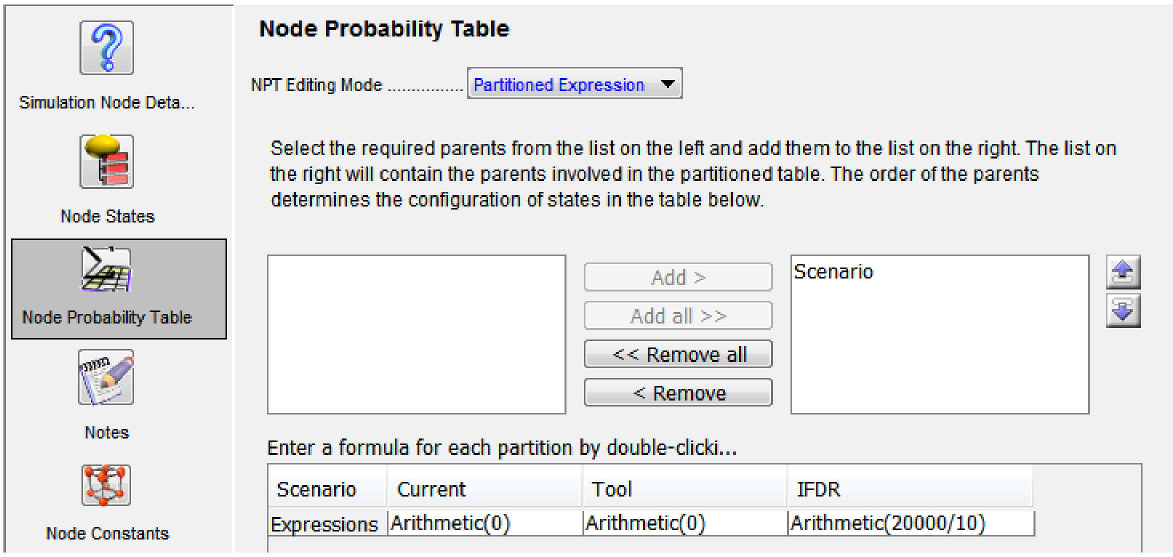


Figure 6-20 - NPT for depreciated IFDR cost with partitioned expression for three scenarios

6.6.2.3 **Output**

The outputs of the model are shown in Figure 6-21.

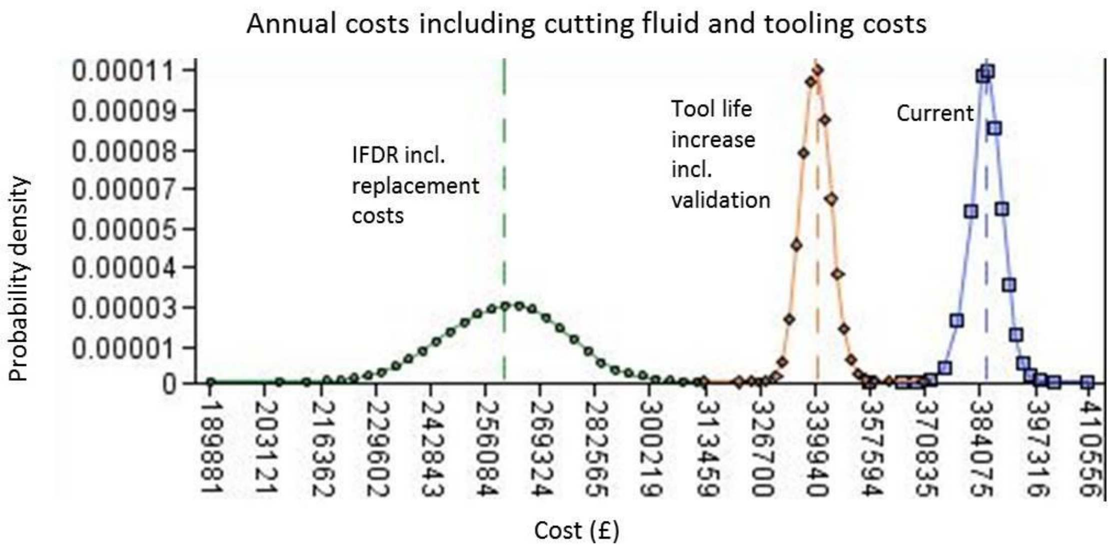


Figure 6-21 - Model 2 results of total annual coolant related costs with three scenarios

The summary statistics for this model are provided in Figure 6-22.

No IFDR
Mean: 384890.0
Median: 385010.0
SD: 4126.1
Variance: 1.7024E7
Lower Percentile: 25.0 (382320.0)
Upper Percentile: 75.0 (387600.0)
Entropy Error: 0.0078993

Expand State List

IFDR
Mean: 263780.0
Median: 264200.0
SD: 15083.0
Variance: 2.2749E8
Lower Percentile: 25.0 (253640.0)
Upper Percentile: 75.0 (274240.0)
Entropy Error: 0.0011806

Expand State List

Increased tool life
Mean: 342250.0
Median: 342140.0
SD: 3809.6
Variance: 1.4513E7
Lower Percentile: 25.0 (339650.0)
Upper Percentile: 75.0 (344730.0)
Entropy Error: 0.0043406

Expand State List

Figure 6-22 - Model 2 total annual cost summary statistics for the three scenarios

The differences in costs compared to table 6.6 are again greater when installing the IFDR compared to the increased tool life scenario with this extra information (see Table 6.7). Although the differences in cost are not significant in this example it is important to consider all available cost data when making an informed decision.

Scenario	Model 1	Model 2
Mean $IFDR_m$	£259790	£263780
Mean T_m	£337360	£342250
Difference	£77570	£78470

Table 6-7 – Difference in mean values of total costs between model 1 and model 2

6.7 Reflection on the framework, methods and tools

The framework ensures that parameters identified in industry are included in AMRC research and development decisions; these parameters would not have previously been accounted for.

The historical process did not differentiate between fluids and show the full value proposition. The new procedure improves on this process by providing a multi stage/ multi system approach which differentiates between cutting fluids and also against different machining parameters. Using the framework would ensure that existing knowledge and experience in industry is incorporated in the development phases, and communicates the results of alternative scenarios along with a level of confidence which is more useful for decision making.

The enhanced knowledge and experience from industry are used to determine opportunities and risk factors that may indirectly or directly influence the test parameters. Ensuring that lessons learned are built into AMRC projects will ensure that these issues are not missed in future. The misunderstanding of competing and affecting variables not previously encountered was demonstrated in this Case Study.

According to cutting fluid suppliers, cutting fluid should last two years in a sump with proper management (captured directly from two cutting fluid supplier technical sales managers). The best case of sump life in RR at present is set to the interval between scheduled preventative maintenance on some machines, circa 9 months. The sump is changed as standard and disposed of regardless of condition. Directing research into cost effective technologies which provide monitoring control and filtration could meet targets for waste reduction and productivity enhancements over and above that of developing new cutting fluid formulations (see Section 6.3.1). As described earlier, the ambition of the 20% tool life increase may not be achieved.

The framework can be used to ensure that all aspects of production which the new technology can affect are identified up front; this means that the financial investment in technology development is directed to those parameters that have the most significant effect on productivity. The cost of research and development is high and often unpredictable. With better understanding of the effect that novel technologies have on a process upstream then the risk of further testing in more expensive phases of development is mitigated.

The recommendations from this study are that the fundamental procedures and responsibilities for coolant changes and testing procedures are standardised so that coolant condition is accurately monitored and waste targets are met. The next stage is to assess the best in class technology to ensure, where necessary, enhancements to filtration and fluid condition capabilities are adopted. Rolls-Royce should provide minimum specifications for machine tools suppliers to provide solutions which include the most effective machining, conveyor, chiller, filtration and monitoring systems. This change offers significant potential for the reduction in coolant and water use, energy, waste, non-conformance rates, health and safety issues, treatment interventions, and the use of environmentally inefficient fluid treatment plants as well as waste disposal costs.

When new formulations are developed in future, these can then be assessed for increased machining performance as well as predicted sump life, bacterial stability and response to a range of contaminants.

The Bayesian model is relatively simple to create and adapt to a range of novel technologies. As demonstrated in Section 6.3.1, the addition of nodes into the network enables a range of variables to be included as they are captured in road mapping and project gate reviews described in Chapter 4. These models can be used earlier in the development phases but must be maintained to ensure that data is updated when new evidence appears. Expert elicitation is required, and a level of understanding of probability distributions is needed to convert this evidence to a format that can be used in the BN.

6.8 Summary

The context for this chapter has been the AMRC involvement in development and testing of novel fluid formulations. The researcher was present throughout the two years of coolant approvals system development, capturing the process, complications, and lessons learned and identifying opportunities for improvement using the framework, experience gained in Case Study 1 and the mini-project described in Section 6.2.5.

The framework was used to identify where industrial knowledge can affect the objectives of technology development and selection further down the MCRL phases. Investment in technologies which enable automated machine monitoring and filtration would have a greater impact on the company waste targets, health and safety and productivity of existing procedures. A coolant approvals process is needed as new formulations are designed to provide new parts with improved cutting tool performance and to meet health and safety regulations. However both case studies have described how unknown process variables that are affected by coolant parameters such as cleanliness can produce such variability that in reality this 20% tool life benefit may not be fully realised. The R&D investment is better spent on developing technologies which can control and stabilise the effects of process variability and those that also provide benefits in other significant ways such as reducing hazardous waste, process interventions and non-conformance. As shown earlier and in Case Study 1 the introduction of a system like the IFDR can control process variables, creating a stable predictable system. With such controlled systems it would be easier to understand better how to align the potential benefits of new coolant technologies to changes that are not only required by industry but ones which can be implemented and therefore realised in existing production environments.

The framework ensures a greater understanding of the value proposition of novel technologies, and this is true for any technology decision making process.

The results of both case studies have produced a model which links the production needs to the technology drivers.

The results of case study 1, in identifying the application of improved filtration technology to maintain coolant condition directly influenced and ultimately helped resolve the mitigating factors of inconsistent test results seen in case study 2. This will have the following two consequences; first a recognition that new research into coolant filtration and life testing technology is essential in continuing to leverage improved coolant technology and achieving maximum benefit in the application of coolant technology in the future (hence directing future industrial investment) and second that in adopting this filtration / contamination control in the research environment an improved test regime which can more effectively distinguish performance based improvement in machining productivity can be achieved. Significant further investment into this area is now being made at the AMRC and is attracting considerable industrial interest.

7 Discussions and conclusions

7.1 Introduction

This final chapter presents the main findings of the research, limitations, recommendations for advanced manufacturing environments, and reflections on future research challenges and opportunities.

This doctoral research offers a solution to the introduction of novel manufacturing technologies into industry by developing a framework that enables decision makers to more confidently select and mature the most cost-effective solutions during the phases of industrial research and development in the context of advanced manufacturing research.

The industrial aim of this research programme was to provide AMRC with: "A framework to improve value-related decision making when selecting novel manufacturing technologies."

This aim prompted the following questions:

(RQ1) "What is the link between value-related knowledge management and improved technology decision making in environments with significant uncertainty?"

(RQ2) "What mechanism will improve value-related knowledge management to support novel technology selection across MRCL?"

The framework provides a constant definition of value and decision making through the process of fundamental research, applied research and production application of new manufacturing technology.

7.2 Discussion of Research Methodology

As described in Chapter 3, the complex nature of the research situation created the need to carefully consider the most appropriate research methodology.

A pragmatic approach with a mixed method research design was chosen as the most suitable for providing a useful solution to a socio-technical problem. This choice enabled methods from both qualitative and quantitative fields to be drawn from in order to provide a practical solution to the research questions with enough flexibility to respond to the dynamic nature of technology development.

A combination of active and passive research methods were used in this study, adapting to meet the requirements of industry and applied research. Qualitative methods such as semi-structured interviews, questionnaires and focus groups were used to elicit information from a range of stakeholders, while quantitative methods were used to analyse and communicate the data. This novel mixed methods approach extends existing methods within qualitative and quantitative research to offer a more effective methodology for researchers who are working within this context. This approach enabled the researcher to develop and test the framework throughout the case studies and manage the disruptive effects of moving timescales, staff changes, research developments and changes to stakeholder requirements, which are inevitable factors in these environments.

The cyclic nature in which the framework developed worked in conjunction with the mixed methodology. Incremental improvements to the framework were developed when opportunities arose to engage with further stakeholders as the case study projects progressed (see Figure 7-1).

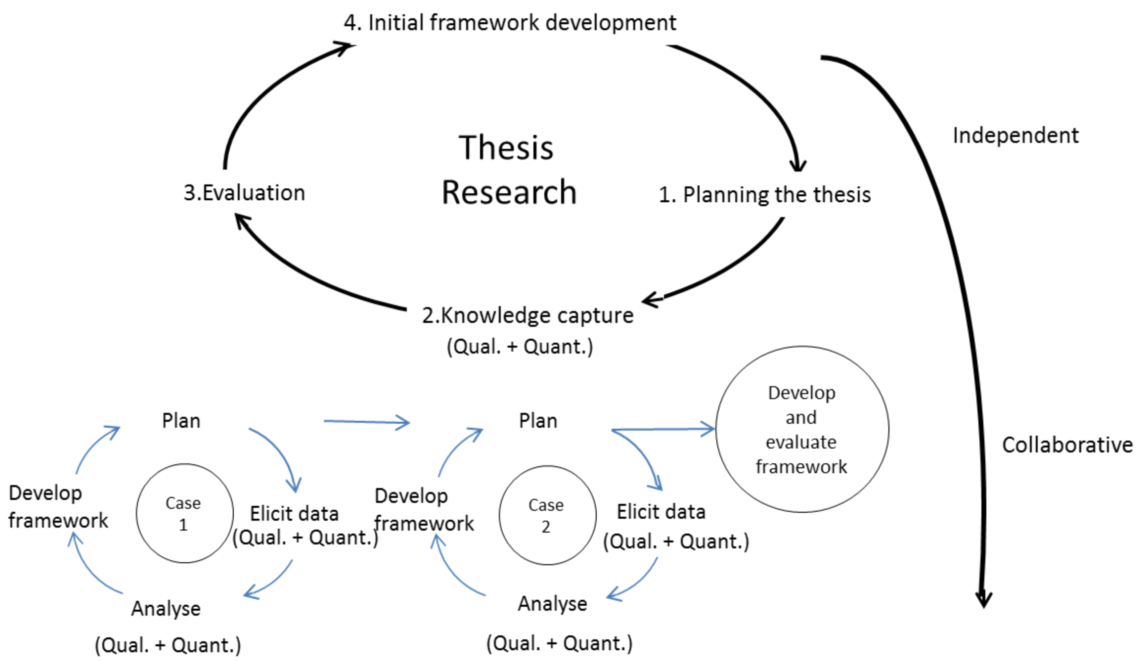


Figure 7-1 – Thesis research design

7.3 Discussion of research findings

This research includes two case studies: one within the applied manufacturing research and development context and one in the application of technologies within the aerospace sector. The results provide a framework to support cost-effective decision making across the development process, while ensuring that knowledge, issues and opportunities are regularly fed back and forth across decision phases.

The results can be extended to similar models across the AxRC network [185] where a similar culture, knowledge management and decision making exist across a series of technology development gateways.

Further generalisability is possible across systems of technology/product/process development with a number of stakeholder requirements and where uncertainty in knowledge resides. The framework would be better suited to an institutional culture that promotes/embraces information sharing. The automotive sector has contrasting cultures. Whilst in Western-based carmakers, low levels of information sharing between suppliers is common due to the competitive culture of multiple supply chains – and, as such, the framework would be difficult to apply – in Japan the Toyota model encourages more sharing of knowledge and so the framework can be used [186], [187].

Concurrent engineering, value driven design and supply chain management practices across a number of industries such as aerospace, automotive and pharmaceuticals employ knowledge management practices which could exploit the framework described [188], [189] . While the boundaries in the context of this research are the interfaces between academia, applied research and industry, the framework is also relevant across the boundaries of suppliers, competitors and customers and the relevance of passing knowledge for innovation and ensuring the most cost effective decisions are relevant to a range of stakeholders is essential [190], [191].

Industries grounded in science – for example chemical, metallurgical, electrical and food industries – adopt a wider share of university cooperation than customer/competitor/supplier cooperation as do innovative industries producing novel products [192]. These industries can use the framework to exploit academic innovations into products which meet the needs of their customers.

Finally there are a range of public research institutes across the world who adopt a similar model to the AxRCs, working on a range of funding models which include public funding, membership models and industrial collaboration, bridging the gap between academic discoveries and industry. These include the German Fraunhofer- Gesellschft (FhG), the United States National Institute of Standards and Technology (NIST), the Japanese National Institute of Advanced Industrial Science and Technology (AIST), the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO), and the Taiwanese Industrial Technology Research Institute (ITRI) [193]. Each of these institutions could adopt a framework similar to that developed in the thesis for use in their decision making across technology development phases [194].

7.4 Main Contribution to Knowledge

The framework draws on and extends existing research in the appreciation and challenges of introducing considerations of *cost* into early phases of technology development. Specifically, the framework: (i) synthesises the areas of knowledge and uncertainty management within the context of applied manufacturing R&D; (ii) introduces decision making processes through the early phases of technology development; and (iii) develops and tests the application of Bayes networks for decision making in applied manufacturing R&D.

Chapter 2 highlighted that cost estimation research is often based on static models with little mechanism for updating in a dynamic environment, although several authors have addressed the need for improved cost data in early stage design and ways to capture uncertain values [7], [30], [195], [196]. The novel framework offers an extension to this field of knowledge, providing a mechanism for evidence and uncertainty propagation with feedback loops throughout the MCRL phases of technology development. The cost engineering research community has highlighted the need for integrated ways of identifying, quantifying and managing uncertainties in cost as well as the need for ways to combine aleatory and epistemic uncertainties [3]. This research has provided a solution to both of these requirements, combining expert elicitation techniques and a modelling methodology capable of propagating a range of uncertainties in knowledge.

A novel use of expert elicitation methods has been demonstrated, drawing on the ability to capture expert judgements as well as hard data, enabling the synthesis of experiential and empirical research in a manufacturing environment. Novel applications of Bayesian elicitation methods and tools to elicit expert judgements have been demonstrated (see Chapters 4, 5 and 6). This research complements existing elicitation methods [95], [173], [197], [198] and combined with Bayesian Network modelling, extend their use by providing a novel means of capturing and managing the uncertain and dynamic environment of manufacturing research therefore providing a solution to the issues raised by the cost research community.

The novel technologies used to develop and test the framework are in the area of cutting fluid technology. The review of literature in Chapter 3 found that several authors have attempted to model costs associated with the use of cutting fluids. However even the most comprehensive model by Hubbard et al. [146] fails to capture the impact of cutting fluids on machining parameters in enough detail to determine a number of coolant parameters that have been shown to significantly affect the production environment (e.g. fluid stability, sump life, contamination and control) while managing their uncertainties. The opportunities for novel cutting fluid formulations and management technologies may not, as a result, have been fully exploited. The framework and methodology in this research extends current models by providing a way to capture these elements and demonstrate that cutting fluid is an enabling technology and should be the specific focus for improved control and further fundamental research (See Chapters 3 and 6). This example demonstrates how the current cost estimation techniques can be enhanced to provide further opportunities that have not been exploited in one particular environment but that these enhancements can be related to a number of other technologies.

The requirement for improved feedback and sharing of knowledge between and across the MCRL phases has been discussed throughout this research and supports the views of existing research in this area (as discussed in Chapter 2). The framework ensures that cost and value are captured during project gate reviews, lessons learned are captured and new evidence is propagated to decision metrics. The framework will help ensure that manufacturing research organisations are progressing elements of technology which provide the greatest value to industry and are consistently identifying knowledge gaps. The example of cutting fluids in Chapter 5 shows how a previously disregarded technology can have a major impact across the technology development stages and so if the framework is effectively implemented then the cost related impact of less appreciated technologies can be identified earlier in the process.

The ability of the framework to communicate multiple outputs across a range of technology options and stakeholder drivers has been demonstrated. These findings contribute to the field of decision making within applied manufacturing research settings. In contrast to decision making methods which point the decision maker to an ideal or optimum solution [82], the resultant modelling method compares and conveys the impact of multiple scenarios. Including the uncertainty in outputs extends the value of traditional cost estimation methods and provides additional value to the decision maker. A feedback mechanism which passes technology value information between industries, applied manufacturing research and fundamental academic research has been demonstrated (see Chapters 5 and 6). The research builds on and compliments current cost estimation techniques by offering a novel mechanism of updating the model by propagating new evidence. This ensures that the dynamic environment of technology development is emulated and that industry data and value requirements are aligned to research and development activities within applied manufacturing research. As the application of the framework in cutting fluid shows, if the overarching company driver of waste is used to bring together stakeholders across an organization together then the common requirements provide a more compelling business case for improvements.

7.5 Fulfilment of Research Aim and Objectives

The research aim was to develop a framework to improve value-related decision making when selecting novel manufacturing technologies. This aim has been met.

Chapter 4 describes the framework in detail, including methods to elicit and analyse the required information. Further, the framework has been tested in the case studies in Chapters 5, in an industrial context, and in Chapter 6, within the applied manufacturing research context. A summary of how the research has fulfilled the main research objectives is provided in Table 1.

Objective	Thesis deliverable
Study existing decision making processes in novel technology development to identify gaps in cost related knowledge	This was carried out in Chapters 1 and 2. Section 1.2 describes the current context in detail and highlights the complexities and requirements for improved decision making throughout the MCRL phases of technology development. Chapter 2 critically evaluates current state of the art in cost modelling and determines where existing studies offer the potential for a novel solution to the challenges described at the AMRC.
Capture the requirements for cost modelling	Chapter 2 investigates existing research into cost modelling methods and identifies where and how these methods can be used to provide a solution to the research problem.
Identify and elicit the extant quantitative and qualitative knowledge, and interrelationships	Chapter 4 identifies the knowledge requirements for the study and describes methods to effectively elicit this knowledge. The development of the framework in this chapter explains how the interrelationships of knowledge can

	be captured through cost modeling and Bayesian network techniques.
Identify the most suitable methods for handling uncertainty, changing information, and to support value-related decision making	Chapter 2 discusses methods to manage the uncertainty in knowledge and demonstrates how Bayesian Networks can provide the most effective solution for this. Chapter 5 describes how Bayesian network modeling can improve on existing cost modeling methods in order to manage the more complex aspects of uncertainty management and the dynamic environment.
Develop and validate the framework, using multiple case studies across the technology development phases	Chapters 5 and 6 use two case studies to develop and validate the framework across the interfaces between both the academic research environment and applied research as well as between applied research and the industrial environment.

Table 7-1 Thesis objectives and deliverables

The research questions developed from the aim and objectives of the research have been answered as follows:

7.5.1 RQ1

(RQ1) "What is the link between value-related knowledge management and improved technology decision making in environments with significant uncertainty?"

The research shows that when industry drivers are aligned with knowledge and decision making in advanced research, this alignment directs research towards areas which are likely to have the most significant impact for industrial processes (e.g.

machining). The parameters of the technology which affect the ability to realize potential gains are identified and become the focus. The framework encourages the involvement of a wider stakeholder group, which helps ensure that parameters which are less understood, or unknown are identified sooner. The framework therefore acts as an enabler for identifying and subsequently introducing the most cost-effective technologies at an earlier stage in technology development, and therefore at a lower cost/risk to industry.

7.5.2 **RQ2**

(RQ2) "What mechanism will improve value-related knowledge management to support novel technology selection across MRCL?"

The framework proposed in Chapter 4, implemented with the Bayesian Network model demonstrated in Chapters 5 and 6, offers a solution to this question. The expert elicitation techniques described in Chapters 4, 5 and 6 offers a comprehensive means for capturing the uncertainties present in development of novel technologies. Ensuring that the framework is embedded into existing road mapping sessions and gate reviews will help ensure that multiple opportunities are provided for feedback loops by a range of stakeholders. New evidence can be propagated in the model to ensure the results are a reflection of current knowledge.

7.6 Research Limitations

Although the research has provided a framework with meets the aim and objectives of this research, there are a number of limitations.

The case studies available to the researcher during the time of research were both related to cutting fluid technologies. These case studies were chosen by the industrial sponsor, and reflect the usage of cutting fluids on the vast majority of machining processes across numerous industries. Although the similarity of the case studies was useful in terms of consistency, a wider range of technologies would have been beneficial in exploring the wider validity of the framework.

A key objective of the research was to identify a way to display cost/impact across multiple stakeholders. In this context, the actual software tool used is not critical but the tool must be able to demonstrate a range of outputs that are relevant to multiple stakeholders. Again further tools and their capability could have been tested.

Successful deployment of this framework requires it to be embedded into existing processes but a means of centrally storing knowledge needs to be in place before the benefits of the framework can be fully exploited.

For useful decision making, uncertainties must be resolved to some extent by seeking out embedded knowledge. This process of knowledge capture requires resources. However, time costs, availability of resources and the rapidity of decision making in industrial time frames can create challenges. Inclusion of value of information concepts could be useful in this regard [199].

The framework relies on experience, knowledge and understanding of a range of stakeholders. Only under the scrutiny of detailed research programmes, such as the present study, do some parameters become apparent. For example, there was no prior insight into the contamination issues that affected Chapter 6; even the most experienced coolant suppliers did not highlight this potential issue. This may be due to the fact that fundamental research into fluid formulations are often not tested on representative machine tools so variables in the production environment that can affect the deployment of a novel technology may not be understood.

This research explored the use of the framework in advanced manufacturing technologies in highly regulated aerospace environments. The methods and tools are arguably transferrable to a range of different environments; however it important to acknowledge that such transfer has not yet been demonstrated.

7.7 Conclusions

This research has provided a better understanding of the transition of knowledge across different contexts, i.e. fundamental research applied research and industrial application. The research provided an appreciation of evolving knowledge and evidence and how that can be captured and managed effectively within a dynamic system. The research also demonstrates how uncertainty can be appreciated in terms of relationships between uncertain variables and the way in which uncertainty affects outcomes which in turn affect multiple stakeholders' requirements.

This research was framed around the aims and objectives of a real industrial research problem. Successful achievement of the objectives has delivered a new framework to improve value-related decision making when selecting novel manufacturing technologies.

The research consulted literature and used contextual exploratory work to formulate a robust problem definition and to identify the key issues facing knowledge management in uncertain and dynamic environments (Chapters 2 and 3). A conceptual model was produced and developed into a comprehensive framework through novel use of existing methods (Chapter 4). The framework was shaped and tested using two case studies from across technology development process and a new modelling methodology has been created to deal with some of the more complex quantitative/qualitative data issues using Bayesian Networks (Chapters 5 and 6).

The resulting Bayesian Network model is simple to use, and is suitable for use by industrial research centres as well as industry. Where, for example, research engineers in an applied research centre are demonstrating the value of a novel technology to a range of industrial users then the network model is a powerful visual tool for communicating information. The model is useful for stages of baseline data collection, relationship mapping, and validation. The capture of knowledge as mathematical relationships in the model enables users to access the assumptions and variables easily and to make changes where appropriate.

When a business case is to be prepared for the introduction of a novel technology, adoption of this framework *within* the current procedures has the potential to widen the value proposition and so improve the decision making process. Cross departmental justifications could provide support to individual business cases as well as sharing knowledge and support for improvements across a major OEM and its supply chain. This cross departmental justification has been demonstrated in the mini-project (Chapter 6), the results of which are a set of recommendations which are being used across Rolls-Royce in its waste management programme.

The key findings of the research are captured in the five main elements of the framework (see Figure 7-2) and will be addressed in turn.

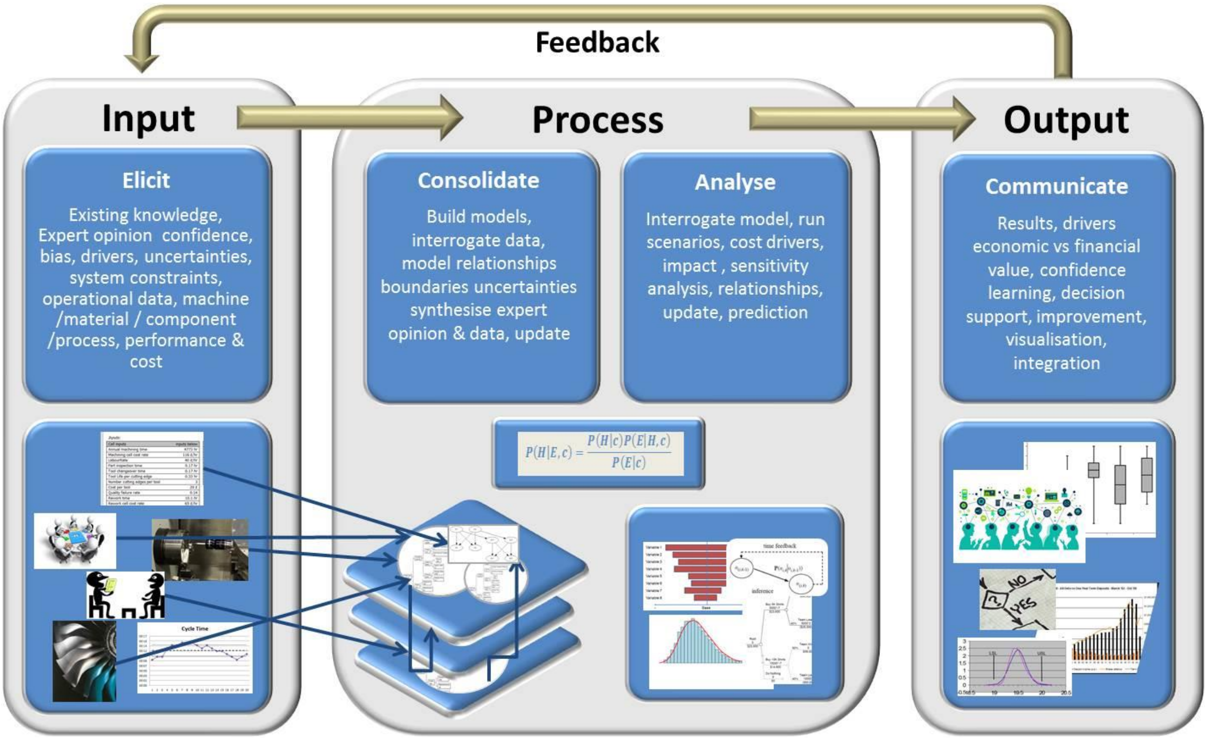


Figure 7-2 - Value focussed framework for use in applied manufacturing research

7.7.1 Elicit

Appropriate elicitation techniques were surveyed and an example given of eliciting both hard evidence and a prior judgement as a probability distribution that can be used in the Bayesian model which can update as new evidence arrives (see Chapter 4).

- Ensure that cost related drivers and input parameters are identified as early as possible in road mapping sessions and at the scoping phase of all projects.
- Capture both hard and soft evidence including uncertainties using expert elicitation where necessary.

7.7.2 Consolidate

The causal relationships between variables can be mapped. The capability of the Bayesian network model to combine and propagate different types of data has been demonstrated.

- Map all cost and value related parameters, uncertainties and their interrelationships, using existing cost models as a basis where available.
- Ensure that continuous nodes represent the data appropriately, identifying parameters using Maximum likelihood where necessary.

7.7.3 **Analyse**

Sensitivity analysis can be performed on any target node against a number of sensitivity nodes for each scenario in the modelling methodology as demonstrated in Chapters 5 and 6.

- Identify sensitivities to cost of parameters using the built in sensitivity analysis and scenario capability.

7.7.4 **Communicate**

A combination of possibilistic (i.e. scenario-led) probabilistic (i.e. density function) approaches has been used to represent uncertainties, with appropriate choice of summary statistics for communication to stakeholders.

- Results must be communicated as multi-objective outputs required by a range of stakeholders. This will ensure that the value proposition is communicated widely and provides an opportunity to validate the model as it is being built.

7.7.5 **Feedback**

The model is capable of updating the level of confidence in decision metrics as new evidence appears using propagation.

- Ensure that when new evidence emerges during road mapping sessions or at gate reviews that this in incorporated into the knowledge base and added to any relevant models. This will ensure that throughout the research project the most up to date information is available for decision making.

7.7.6 Implementation requirements

For this framework to be implemented into the advanced manufacturing research environment the following recommendations would need to be followed:

1. Provide a central knowledge repository;
2. Embed the framework into gate reviews and road mapping sessions;
3. Establish ownership of the framework so that updating can occur;
4. Train project representatives in the use of Bayesian Network software.

7.8 Future research

An appreciation of the future direction of industry is needed to understand how this research can be applicable in the long term. The move towards 'Factory 2050' provides both challenges and opportunities to the research in terms of data security and artificial intelligence advances [13]. The framework would be enhanced with the input from more automated 'real time' data capture as the information could be kept updated as further evidence is available and this could be automated. However when considering multi-agent and potentially robot assisted manufacture, the capture of subjective knowledge could be affected. One of the essential aspects of this research is to ensure that all stakeholders are consulted during the transition across technology development to ensure that their drivers and requirements are included in decision making. This becomes problematic when the data moves towards entirely quantitative data. Identification of subjective data from experts will become more important as this transition happens.

The research has also highlighted the need for more fundamental cutting fluid use research, specifically in the areas of contamination, tool life, waste and control. There are wide reaching opportunities in terms of improved tool life, substantially extended sump lives and re-use of fluid. Novel filtration technologies could ultimately provide an opportunity for the redesign of fluid formulations to significantly remove biocides, remove consumables and extend sump life to many years which could have a major impact on sustainable outcomes. As climate change is influencing the agenda more emphasis will be put on elements of manufacturing that can improve the sustainability of processes and reduce hazardous waste and energy consumption.

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Appendix A: Ethics approval

The University Of Sheffield.

Downloaded: 16/10/2018
Approved: 24/02/2016

Claire Jeavons
Registration number: 130121143
Automatic Control and Systems Engineering
Programme: Engineering Doctorate in Machining Science

Dear Claire

PROJECT TITLE: Advanced Cost Engineering for High Value Manufacturing
APPLICATION: Reference Number 005969

On behalf of the University ethics reviewers who reviewed your project, I am pleased to inform you that on 24/02/2016 the above-named project was **approved** on ethics grounds, on the basis that you will adhere to the following documentation that you submitted for ethics review:

- University research ethics application form 005969 (dated 16/10/2015).

If during the course of the project you need to deviate significantly from the above-approved documentation please inform me since written approval will be required.

Yours sincerely

Matthew Ham
Ethics Administrator
Automatic Control and Systems Engineering

Appendix B: SHELF Code

SHELF is used to fit parameters to distribution which have been elicited from experts. To use the software the program R must be installed and the following code can be used to find the distribution needed to represent the elicited data:

```
library(SHELF)
```

A judgement could be made that the number of non-conforming parts per 100

$$\phi_{0.5} = 15 \,, \phi_{0.05} = 3 \,, \phi_{0.95} = 30$$

The values for non-conforming parts and respective probabilities are inserted in the software as follows:

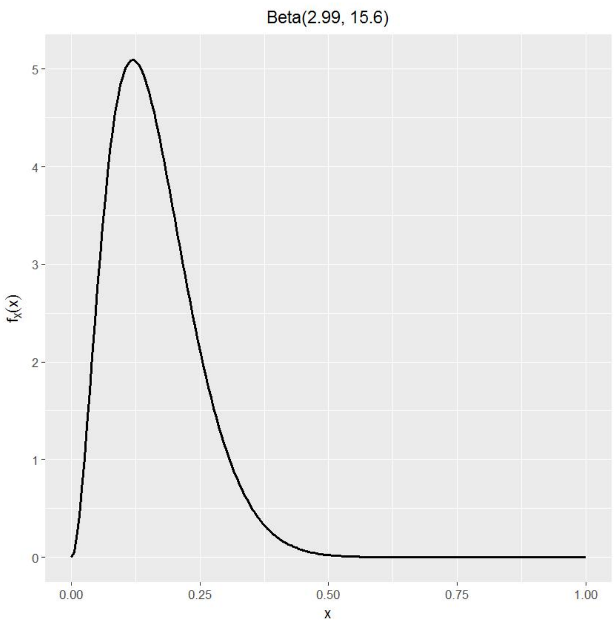
```
v <- c(3, 15, 30)/100
p <- c(0.05, 0.5, 0.95)
myfit <- fitdist(vals = v, probs = p, lower = 0, upper = 1)
myfit$Beta
```

Which returns the alpha and beta parameters as

```
2.99 15.6
```

This can then be plotted

```
plotfit(myfit1, d = "beta")
```



Appendix C: Requirements capture sheet for coolant management

Requirements capture for coolant filtration and management

This sheet aims to capture information on current machining performance against coolant management (including filtration, condition monitoring and tramp oil removal) systems in order to identify which areas could benefit from a more detailed investigation/trial into improved solutions.

Stakeholder information	**Details**
Name	
Job title	
Function	

Process information	**Details**
Manufacturing process (Mill, Drill, Turn, Grind)	
Machine make / model - number of machines	
Modifications to existing machine tools from original spec (incl. photos where applicable)	
Application (part description being produced)	
Material	
Material removal rates	
Utilisation of machines	
Quantity of material processed on site (parts per, year plus the mass of the condition of supply part)	

Existing process data	**Descriptio n**	**Cost related data**	**Uncertainty capture**
Cutting fluid			
Concentration			
Sump size			
Coolant flow rate and pressure			
Coolant delivery mechanism			
Nozzle type /issues			
Pressure relief valve issues			

Sump life			
Top - up dosage and routine			
Existing filtration system			
Filter media consumables			
Filtration system maintenance/management requirements			
Existing chiller system			
Chiller system maintenance/management requirements			
Tramp oil removal system			
Tramp oil maintenance/management requirements			
Existing water treatment requirement (demin or mains water?)			
Dosage volume/requirement for machine lubrication oils			
Fluid inspection routine			
Coolant farm/site delivery system			
Coolant delivery system maintenance requirements			

Interest in filtration	**Description**
Lessons learned	
Current issues	

Business drivers of interest	**Description**	**Driver/target**
Fluid waste / environmental		
Consumables		
Productivity		
Non-conformance issues		
Alternative technologies		
Maintenance		
Health & Safety		

Process metrics of interest	**Description**	**Driver/target**
Non-conformance		
Sump life		

Maintenance		
Concentration		
Coolant use		
Coolant cleanliness - particle content		
Coolant cleanliness - tramp oil		
Top up		
Coolant exhaust fluid wastage		
Bacteria		
Health and safety		
Water treatment		
Coolant chemistry stability		
Control of waste stream		
Swarf recovery and recycling		

lessons learned	**Description**	**Details**
Previous results from onsite testing		
Decisions/changes made as a result of previous experience		

Future activity requirements (detailed business case and trial)	**Description**	**Target metrics**
Business case metrics		
Business impact - test metrics		
Aims and deliverables required for the project		
Time /milestone constraints		
RR acquisition constraints		
Would you prefer an onsite test? One at the AMRC?		
Testing of alternative systems, off-line/online		
Integrating new and existing technologies		
Suitability for a trial		
Opportunity for trial		
Availability of data		
Data security issues		

Other comments/observations	

Appendix D: Literature review articles

Microsoft Excel - Literature review

	B	C	D	E	F	J	K	L
1	Section	Journal/Conference/Book	Year	Title	Authors	Data Mangement	Uncertainty/ Variation	Decision Support
2	Process/Product Development	Journal of Operations Management	2007	Process Cost Modelling: Strategic Engineering & Economic Evaluation of Materials Technologies	Field F, Kirchain R, Roth R			Defend technology decisions, support design choices for cost effectivemness, affect the approach to material and process innovation
3	Design/R&D environment		2004	Inter-firm cost management in high-tech product development projects in the plastics industry	Barbosa C, Afonso P			
4	Design/R&D environment	International Journal of Production Economics	2003	Activity-based cost manegement for design & development stage	Ben-Arieh D, Qian Li			Identification of R&D cost drivers
5	Process/Product Development	Mangement Accounting Research	2001	Product diversity and costing system design choice: field study evidence	Abernethy M A, Lillis Anne M, Brownell P, Carter P	Collection sources, interview, obsertvations and documentation		
6	Process/Product Development	International Journal of Production Economics	2009	Target costing operationalisation dusring product development: Model & application	Filomena T P, Neto FJK, Duffey MR	Decomposition of costs, parts, features and common elements		Cost control
7	Design/R&D environment	Journal of Engineering Design	2002	Cost modelling for aircraft design	Scanlan J, Hill T, Marsh R	Specific data Structure, set of databases see fig	Uncertainty factor is built in to model and this evolves while data emerges, product definition increases	Optimisation through choices
8	Design/R&D environment	CIRP Annals - Manufacturing Techology	2014	Part cost estimation at early design phase	Molcho G, Cristal A, Shpitalni M	database of material cost, material volumetric mass density, speed per machine type and manpower tarif.		cost assesment at design and manufacturing stages
9	Design/R&D environment	United States Airforce	2002	Military Jet engine acquisition - Technology basics and cost-estimating teqhniques	Younossi O, Arena MV	Break down data into parameters, performance and physical, production and development costs	technical risk and design maturity parameters	Development cost vs performance gains
10	Cost estimating Techniques	Mangement Accounting Research	2007	A survey of factors influencing the choice of product costing systems in UK organisations	Al-Omiri M, Drury C	Need high quality databases to store level of data required		
11	Cost estimating Techniques	International Journal of Production Research	1998	Product life cycle cost analysis:state of the art review	Asiedu Y, Gu P		Uncertainty and dependancies should be added but it may not be worth the effort	Aids decisions on design implications to cost
12	Cost estimating Techniques	Readings in program control	1995	Cost estimating methods for advanced space systems	Cyr K	Use lots of data sources. Define variable interactions, weight, cost, quantity, and culture (cost vs weight curve indices to show imopact of diffeent hardware)	Learning curves are used	estimating cost of new space programs
13	Process/Product Development	International Journal of Production Economics	2005	Estimating the cost of a new technology intensive automotive product: A case study approach	Roy R, Colmer S, Griggs T	Separating new and existing technologies is preferred	Confidence Intervals	Decision support for selecting new technology in concept stage
14	Cost estimating Techniques	Acta Astranautica	2014	What is wrong with space stystem cost models? A survey and assesment of cost estimating approaches	Kellar S, Collopy P, Componation P	The need for high quality data capture and it to be updated so there is no lag between information gathering and information use.	Cost growth must be managed	Estimation of space program costs
15	Cost estimating Techniques	Journal of Manufacturing Science and Engineering	2006	Product Cost Estimation: Technique Classification and Methodology Review	Niazi A, Dai J S		Fuzzy Logic and expert systems	Decision support for methodology selection
16	Decision Support	Decision Support Systems	2002	Past, present and future of decision suppport technology	Shim JP, Warkentin M	Data Warehousing to store data from many sources. Data mining to find patterns within the data	Identification of tools to support incomplete and uncertain data	Using web-based tools to interact with ERP systems for decision support

	M	N	O	P	Q
1	Cost method	Cost definition	Cost scope	Points of interest	My opinion
2	Product cost models & process cost models	product & process & development cost	product & process & development cost	technology option competitiveness is a function of the context of its application. Cost development carefully to offset new technologies. Include cost as vital performance metric throughout product development.	Cost management as an effective communication tool, rarely stated as an output, to integrate cost with decisions across the company. Educate engineers in the meaning and importance of cost. To create process, operation, and financil models to support this.
3		Material, Design & Production cost	material suppliers & R&D and Production	Cost management should be extended to suppliers to so cost reductions can occur in the concept and development stage. Value chain analysis to identoify cost driver activities.	Like the idea of relating cost management to suppliers and material developers in cost manegemnt of new technologies
4	Activity Based Costing	Design and development cost	R&D	Now life-span of product reducing, R&D activities becoming prominent part of cost	It is important to add R&D activities as well as part production activities. An extension of ABC
5	Activity Based Costing	Product cost	Product cost	Product diversity, cost structure and AMT influence the design characteristics of costing sytstems	This paper goes some way in expalining that understanding the influence oof operatinmg factors such as product diversity need to be fully understood before adopting sophisticated costing systems.
6	Target Costing	Target price-profit		Selection of appropriate method to break down cost based on innovation/novelty of product	I agree with idea that to manage cost we need to break them down into smnaller manageme ble sizes.
7	Life Cycle Costing	Life cycle and manufacturing cost	Life cycle	Models of possibility in the design space	Like the idea of uncertainty evolving this is very importatnt and rarely included. High degreee of uncertainty at conceptual stage, less so later on
8	Activity Based Costing	product cost	Design phase and manufacturin g	Small database to remove issues of data acquisition. Have two separate models CFD (designers) and CFM (manufacturing)	literature review about lack of data sources and complex to create cost systems. Create more simplistic design to capture less specific data. Not sure about validation though. Surely this will take time and the inout fromn compaby seems high. should'nt databases interact?
9	see table. Parametric	dvelopment cost	development program	offers insight into egffect of new product vs deriviative product cost. Supplier technology capture to determine cost impact	Ensure cost estimators are working closely with manufacturing suppliers to capture changes in technology practices which may influence cost. Useful for cost estimating, influence design decisions down the supply chain which could influence cost.
10	Activity Based Costing	Product cost			Seem although to talk about sophistication of "costing stystems" and influences which support adoption of these systems, however seems to omnlyu be discussing ABC and no deatil on costing methods and systems. Would be better to widen research to all systems? More influences?
11	Life Cycle Costing	Product lifecycle		Accuracy is inversly proportional to the time between cost estimate & event. End of life decisions tend to affect procesude decisions not design decisions	Good point that cost competition has spurred development of 'design for' methodologies which tend to influence cost but the evaluation criteria is not cost. Most data and methods are stated to be focused on a particular life cycle stage, this is seen as a flaw, I agree to some extent but in some cases that is necessary, maybe a linkage is the important aspect.
12	Parametric	programme cost	space programme costs	using lots of data sources increases degrees of freedom, deeper insight to nature of re;lationships, spanning time with data can enable future predictions to be more accurate, and economies of scale.	Very specific to sapce systems
13	A mixture of case based, parametric and ABC and expert judgement	Product & new technology cost	Product	Reauirement of two m,odels Current technology model and New technology model. Identify cost drivers from these sections of data manipulation. Add new technology ncost to product cost.	I like the idea of breaking down the product into new and existing technology then using appropriate cost methods from each set of data. Theere does seem to e further work to be domne to create a fully validated and automated system.
14	Cost control as opposed to Cost estimation, cost growth renders parametric tools useless	program cost		Complexity in space programs grow during the life cycle therefore rendering cost estimates inaccurate	The changes through out a costing ptrogram are relevant to aerospace programs as well, manageing the changes which happen during the project or development of a technology need to be captured and the risk needs to be mangemeg up front and included in the estimate.
15	See table	Product	mainly process, production	Separates methods into Quantitive and Qualitative	Significant and in depth review and explination of methods for product cost estimation used in industry, very useful
16				To expand the DSS to all stakeholders to develop best practice. To turn qualitative insights and uncertain & incomplete data into useful knowledge	I agree that it is necessary to use as many perspectives on decision problems as is available and use this approach to formulate a solution and devbelop tools which provide a syetem which compliments this approach.

Sheet1 (3) | **Sheet1** | Sheet1 (2) | Sheet2 | Sheet3

Microsoft Excel - Literature review

	B	C	D	E	F	J	K	L	M	N	O	P	Q
1	Section	Journal/Conference/Book	Year	Title	Authors	Data Mangement	Uncertainty/ Variation	Decision Support	Cost method	Cost definition	Cost scope	Points of interest	My opinion
16	Decision Support	Decision Support Systems	2002	Past, present and future of decision suppport technology	Shim JP, Warkentin M	Data Warehousing to store data from many sources. Data mining to find patterns within the data	Identification of tools to support incomplete and uncertain data	Using web-based tools to interact with ERP systems for decision support				To expand the DSS to all stakeholders to develop best practice. To turn qualitative insights and uncertain & incomplete data into useful knowledge	I agree that it is necessary to use as many perspectives on decision problems as is available and use this approach to formulate a solution and devbelop tools which provide a syetem which compliments this approach.
17	Process/Product Development	Internation Journal of Production Economics	2007	Product development process with focus on value engineering and target costing: A case study in an automotive company	Ibusuki U, Kaminski P C			Comparing the cost estimate to the target in order to focus improvements to developme nt.	Integrate VE with target costing			Reverse engineering to break down activities linked to cost	Integration of VE and Target costing makes sense. VE identifies areas where cost reduction is possible and Target costing is the strategic cost goal to ensure a profit. These techniques together would control costs during the development stages.
18	Uncertainty	Engineering costs and production economics	1988	Beyond Parametics: The role of subjectivity in cost models	Beltramo M N	use empirical and general data	Weight scaling factors, learning curves, labour hour and material cost features			Product, production cost		Create base model before you estimate any future methods, or systems. Get that base data right.	I agree with the point that you have to design your estimate on the data availability rather than the other way round.
19	Uncertainty	Procedia CIRP	2010	Cost estimation method for variation mangement	Mirdamadi S, Etienne A, Hassan A	CAPP	Probability of occurance, variation monitoring		Quality driven ABC	Life cycle cost, material cost, remanufacturing cost, inspection cost, recycling cost	Manufacturing cost	Cost related to activity drivers not just acvtoivity cost. Probability of qwuality failure includes rangwe of costs	I like the idea of looking at the cost of activity cost drivers but it doesnt demonstrate what the drivers are
20	Decision Support	Internation Journal of Production Economics	1997	A knowledge-based decision support system for cost estimation and procing decisions in versatile manufacturing companies	Kingsman B G, Antonio A	3 databases, historical cost data(estimated&actual) financial planning & prodn oplanning. Applied rules	Judgement of experts for confidence in estimation	pricing and enquiries	ABC, based on production time	production costs	production	Costing should be the same activity as pricing and not just be the allocation of known data but also include expert judgement	This is a good judgement of errors and comples issues which appear in estimates and collection of heuristic rules applied by experts. The system developed was able to capture this knowledge and prepare a knowledge decision system built around these rules.
21	Process/Product Development	Procedia Engineering	2014	Estimating the cost of the new product in development process	Chwastyk P, Kolosowski M	Design feature, technological feature and direct/indirect cost feature databases. Cluster analysis at the planning stage.	Analogical regression		Feature based costing at design stage, parametric modelling	Cost of a future product	planning development and operational activities in NPD	Uses analogical regression of historical data as based on incremental product changes, however this is complicated and requires expert judgement.	Very good feedback loop which is often overlooked. Improving and checking accuracy as the data increases.
22	Uncertainty	International Journal of Advanced Manufacturing Technology	2011	Understanding service uncertainties in industrial product-service system cost estimation	Erkoyuncu J A, Roy R, Shehab E, Cheruvu K		NN, Fuzzy logic, CBR, Genetic algorithms. Identify uncertainties and reduce impact on cost and decisions		CBR		Bid to dosposal	Service uncertainty is driven by the quality of the information flow and knowledge across a given service network, however it commonly suffers from unavailability of useful data to assist cost prediction.	Good literature review. Uncertaintly in data has major impact on cost modelli ng and ways in which to manege this are critical.
23	Knowledge capture and knowledge engineering	ISPE International conference on concurrent engineering	2001	Capturing Quantitive & Qualitastive Knowledge for Cost modelling within a CE environment	Rush C, Roy R	Manual Excel, PRICE model		Capture cost modelling knowledge within CE environment for re-use by novices	PRICE parametric	Cost of new system		.Knowledge = Expert - Novice Catogarisation of assumptions as well as knowledge and checking these are still valid are built into the system which is often not included	Knowledgre management is impoirtant particularly in industries where the product estimation is done years before proiduction starts. The calibration of the model when data & assumption change.
24	Knowledge capture and knowledge engineering	Internation Journal of Production Economics	2010	A dynamic process-based cost modelling approach to understand learning effects in manufacturing	Nadeau M-C, Kar A, Roth R, Kirchain R	Break into sub-models, process model, operations model and financial model	learning effect, cost evolution		PBCM to identify cost impacts	Cost of production		Cost evolution of new technologies depends on material learning vs labour learning	I am interested is the use of Learning theory to see the impact of learning and use this to influence future decisions. However where is the uncertainty in the model? Montecarlo could be used here.
25	Knowledge capture and knowledge engineering	Expert systems with applications	2010	A multidisciplinary implementation methodology for knowledge based engineering:KNOMAD	Curran R, Verhagen W J C, Tooren M J L, Laan T H	Explicit and Implicit knowledge capture is necessary		Expert systems, KBE systems for design first time right	Choose the most appropriate method based on the best use of data available	cost of production elements	part production costs	Include capturing trade-off decisions and ensure the capture of truly quality information.	Good systematic methodology for knowledge capture see fig.
26	Knowledge capture and knowledge engineering	Expert systems with applications	2009	Architecture of a knowledge based engineering system for weight and cost estimation for na composite airplane structures	Choi J W	Gather process and geometric data linked to optimised structure data.	fuzzy based theory	To automate the design process to determine weight and cost implications of design decisions	text expressions used for cost estimation	process manufactyuring cost	process costs	The KBES system benefit is to perform experts estimation at trhe conceptual design stage, along with automation of CAD andf FEA optimisation to rwduce time efforts.	This is a very complex system which would require a lot of planning and implementation but the model of heierrarchy depicts the knowledge structure and the data requirements v well.
27	Knowledge capture and knowledge engineering	Mangement Accounting Research	2006	Inter-organisational cost management: Towards an evolutionary prespective	Coad A F, Cullen J	limit inter organisational differences in cost manegement		Value chain analysis and cost estimation	Activity Based Costing	Value chain		Heuristics and cost evolution is important for cost manegemtn	
28	Knowledge capture and knowledge engineering	Advanced Engineering Informatics	2012	A critical review of knowledge-based engineering: An identification of research challenges	Verhagen W, Bermell-Garcia P, Dijk R, Curran R	Data mastering		Un derstanding of cost commitment at preliminary design stage	Life Cycle Costing		LCC	If thwe design time is reduced with KE then this gives more scope for creativity during this stage.	Interssting to hear how KE has not been developed intensively. Collecting the knowledge and how this is done is not explained in detail but the issues surrounding the lack of methodology is well sytated.
29	Design/R&D environment	CIRP IPS2 Conference	2009	An aerospace component cost modelling study for value driven design	Cheung J, Scanlan J, Wisseal S	cost model database & simulation model	Monte carlo	Value information on the design choices	Value driven design, activity based, parametric and discreete event	manufacturing costs	production	Integration of static cost modelling and discrete event modelling for factory process estimation. In novel cost modelling the little data available has to be used to a greater extend. The system is robust to incorporate new data as it becomes availabel.	dynamic model supports the static model when manufacturing costrs are being estimated, providing more credible data. Vanguard studio is a good communication tool enabling visual representation of costing assumptions and formulae, ensuring buy in from industry and easietr validartion. The model is able to incorporate changes to data as the program progresses.
30	Tools	Expert systems with applications	2010	COMEX: A cost management expert sytstem	Grahovac D, Devedzic V			Billing support	Activity Based Costing				very specific to software architecture

Sheet1 (3) | Sheet1 | Sheet1 (2) | Sheet2 | Sheet3

Microsoft Excel - Literature review

	B	C	D	E	F	J	K	L	M	N	O	P	Q
1	Section	Journal/Conference/Book	Year	Title	Authors	Data Mangement	Uncertainty/ Variation	Decision Support	Cost method	Cost definition	Cost scope	Points of interest	My opinion
30	Tools	Expert systems with applications	2010	COMEX: A cost management expert sytstem	Grahovac D, Devedzic V			Billing support	Activity Based Costing				very specific to software architecture
31	Tools	Internation Journal of Advanced Manufacturing Technology	2013	An innovative cost modelling system to support lean product and process development	Wasim A, Shehab E, Abdalla H,	Knowledge Management database, features, machine, material. Historical costs and poke yoke rules		Selects value targets to help decision on which is the best apoproach at conceptual design stage, at detailed design stage determines the cost estimate for the product.	Set based concurrent engineering(narrowing down alternatives)	cost of alternative materials, and manufacturing processes	product cost	Look at the two design stages separately to assist in decisions at key points.	I like the incorporation of cost of mistakes, this is rearely adressed. Also takes into account customer needs changing not just data changes. No use of methods to adress uncertainty.
32	Techology selection	Proceedings of PICMET '13	2013	Managing technology selection and development decisions in new product development process	Sanayei A, Monplaisir L F		Exponential random varia bles used to depict uncertainty in development time and therefore resource usage	Does the use of more resource outweigh competitive advbantage, benefits analysis	developpment cost and number of resource hours needed for achievbemnent	development cost	development activities	Development choice impacts with reference to externalforvces, ie competition	useful in terms of adressing decisions between technology options based on maturity and competition
33	Techology selection	International Journal of Information Technology & Decision Making	2011	An integrated interpretive structural modelling-fuzzy analytical network process-benefits, opportunities, costs and risks model for selecting technologies	Lee A H I, Kang H, Chang C	Interpretuive structural modelling,fuzzy analyticasl network process	Fuzzy weightings	Benefits, Opportunity, Costs and (Risks (BOCR) of technology alternatives		production cost, inventory cost, ROI	production	Cost is linked to strategy. Need to have a systematic method to capture costs, uncertainties and expert knowledge for decision making	Extensive literature review into previous work in this area. Covers lots of interrellationships
34	Techology selection	IEEE	2012	Intelligent Experience based Support tools for Aerospace Manufacturing Technology Selection	Evans L, Lohse N, Summers M	Split data into knowledge types, collect data as it occurs naturaly thoughout TRL 6, create lessons learned database		Use lessons learned log as cased based decision system for selecting technologies at TRL 9	Cased Based Reasoning		TRL to 9	Using knowledge mangement for informing at gate stages. Scope at TRL up to 9, link production info to TRL 6	Good survey but the acgtual data is not discussed in detail which would be more helpful. This idea could be apoplied to a cost system
35	Techology selection	International Journal of Production Economics	2011	A marginal analysis guided technology evaluation and selection	Tan K H, Noble J, Sato Y, Tse Y K	Multi-criterea data needed. Security, quality, risk, novelty, deployment etc		Criteria priority ranking to select alternative scenarios.	Marginal analysis guided approach	cost of technology		Clarity of decision making. Mathematical anaysis are unusable in industry as they are too complex. Combination of quantitative and qiualitative data capture over extended time before a decision is made needs clarity of dexcisions	I like the clarity of decisions and the reasons they are made, trade off information. This method helps to capture knowledge too.
36	Techology selection	International Journal of Advanced Manufacturing Technology	2012	Technology selection in the presence of fuzzy data and dual role fators	Sadeghi A A H, Ahmady N, Ahmady E	dual role factor Data Envelopment Analysis model to select technology	Fuzzy set theory	Weighted decision of technology(robot) selection based on, cost, vendor reputation, load capacity, velocity		cost of robot	capital cost	Fuzzy data and dual role date are often present in technology selection but rarely adressed togther	When decision systems are created they seem to be very specific to the application, ie vendor repuitation, however this could be applied to adress boudaries in other decision systems. This mathematical anaysis is very complex and would not be usefuul for non experts
37	Uncertainty	Research showcase at CMU	2011	Quantifying Uncertainty in Early Lifecycle cost estimation (QUELCE)	Ferguson R W, Goldenson D, McCurley J M	Decision structure matrix technique and Bayesian belief network	Dependancy matrix, cause and effect (uncertainty and change) Calibration training for experts, cost estimation anchors	Use gate stages to assess potentail changes to drivers and calculate the probability of that change which affects the niominal state of the driver occuring and the impact on cost	Life Cycle Costing	cost of developing new systems - pre-system acquisition	life cycle	Important change drivers and their interdependancies among them that may not otherwise be coinsidered are made explicit to improve realism and likely accuracy of estimates. Intuitive visual representation of data to explicitely model influential data relationships. Assumptions and contraints underlying the estimate are well documented. Contributing to better manegemnt of cost, schedule, adjustments to prgram scope as more is learned and conditions change.	Interelationships of data. Developing flexible systems to provisde more accurate and credible estimates is key. Also the basis of the estimate is documented explicitely which is rare, estimation is renowned for having a black box image within the decision systems. The cost anchor and calibration techniqure is similar to the LEAN notion of standardisation.
38	Cost estimating Techniques	The Routledge companion to Cost manegement - Book	2013	Mangement accounting techniques for inter-organisational control	Mitchell F, Norreklit H, Jakobsen M		Develop power and/or trust within the relationship and this will reduce uncertainties. Mangement strategies perform well here.	Target costing triangles tpo highlight functionality and allowablke costs through value analysis, qauntifying the value of each component and the function of the product.	Target Costing			Cost of outsourcing a product including cost of product and all other costs needs to be manegmed. Clarity of cost drivers across organisational boundaries need to be collaoratively adressed. Evaluation of open book discussions can be done by using knowledge from previous in house methods or other inter operational realtionships.	In an R&D environment there are interations between suppliers and partners and strategic cost decisions need to be made. The open book system to manege cost strategy is useful
39	Design/R&D environment	Cost & Effect	1997	Strategic Activity-based management:supplier relationships and product development	Kaplan R, Cooper R			provide designers wiyth excellent predictive cost information to inform design choices using a disciplined target costing system. Identify cost savings that can be shared across supplier and customer. Understand the cost of design and development to manage these costs.	Activity Based Costing and target costing			Traditional cost methods provided designers with distorted info. Cost data which ignores use of common vs unique parts and vendors, simple vs complex production systems. Choose activity cost drivers for product design while understanding accuracy vs influencing behaviour. Integration of ABC and TC can aid design decision support	Using ABC information across entire value chain product design, develpopment, purchasing, manufacturing, logistics and distribution. I found the section on integration of ABC with TC interesting, in design stage the book staes that designers can make trade-offs between direct and indirect costs. Target costing reduces direct unit-level costs ABC manages indirect and support costs. Supplier customer cost analysis is interesting.
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Sheet1 (3) Sheet1 Sheet1 (2) Sheet2 Sheet3