A Cost Estimate Maturity Benchmark Method to Support Early Concept Design Decision-Making

A Case Study Application to the Small Modular Nuclear Reactor

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Wolfson School of Mechanical, Electrical and Manufacturing Engineering

Author’s Declaration

This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in acknowledgements or in footnotes, and that neither the thesis nor the original work therein has been submitted to this or any other institution for a degree. Neither the submission nor the original work contained herein has been submitted for an award of this or any other degree awarding body, except in accordance with an agreement between universities.

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Date:

Acknowledgements

Completing this doctorate has been the most challenging and the most rewarding part of my working life so far. But it was not a task that I could complete by myself. The support group around me pushed me through to the end. I have so much gratitude to these individuals who showed me the value of the work I have done even when I forgot.

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Abstract

Constructing large Nuclear Power Plants (NPPs) is synonymous with significant cost and schedule uncertainty. Innovative Small Modular Reactors (SMRs) have been identified as a way of increasing certainty of delivery, whilst also maintaining a competitive Life Cycle Cost (LCC). Previous research into the cost of SMRs has focused on the economics of a design from the perspective of an owner or investor. There is a significant gap in the literature associated with cost estimating SMRs at the early concept development stage from the perspective of a reactor developer.

Early design stage cost estimates are inherently uncertain. Design teams, therefore, need to make decisions that will achieve a cost competitive product by considering uncertainty. Existing cost uncertainty analysis methods lack standardisation in their application, often relying on the subjective assessment of experts. The central argument presented in this research is that the SMR vendor can make more effective decisions related to achieving cost certainty by understanding the drivers of knowledge uncertainty associated with early design stage cost estimates.

This thesis describes research spanning the concept design phase of the UK SMR development programme. The research investigation is divided into two distinct phases. The first phase identifies the requirements for cost information from the perspective of the SMR vendor through interviews, a participatory case study investigation and surveys. Limited access to cost information means that early design cost assessment is highly subjective. Cost uncertainty analysis should provide decision makers with an understanding of the level of confidence associated with the estimate. A survey investigating how cost information is interpreted revealed that providing more granular detail about cost uncertainty would support the design team with additional rationale for selecting a design option. The main requirement identified from phase 1 of the research is the need for a standardised method to identify how sources of cost uncertainty influence the maturity of the estimate at each stage of the design development process. The second phase of the research involved a participatory research approach where the Acceptable Cost Uncertainty Benchmark Assessment (ACUBA) method was developed and then implemented retrospectively on the case study cost data. The ACUBA method uses a qualitative measure to assess the quality and impact of engineering definition, manufacturing process knowledge and supply chain knowledge on the cost estimate confidence. The maturity rating is then assessed against a benchmark to determine the acceptability of the estimate uncertainty range. Focus groups were carried out in the vendor organisation to investigate whether the design team could clarify their reasoning for decisions related to reducing cost uncertainty when given insight into the sources of cost uncertainty. The rationale for a decision is found to be clearer using the ACUBA method compared with existing cost uncertainty analysis methods used by the case study organisation.

This research has led to the development of a novel method which standardises and improves the communication of cost information across different functions within a design team. By establishing a benchmark acceptable level of cost maturity for a decision, the cost maturity metric can be employed to measure the performance of the SMR development programme towards achieving product cost maturity. In addition, the ACUBA method supports the more effective allocation of limited resources available at the early design stage, by identifying design activities which could lead to an acceptable cost maturity.

Abbreviations

ACUBA – Acceptable Cost Uncertainty Benchmark Analysis

AGR – Advanced Gas-cooled Reactor

ANN – Artificial Neural Network

BoM – Bill of Materials

CER – Cost Estimation Relationships

DSM – Dependency Structure Matrix

EML – Estimate Maturity Level

FEED – Front End Engineering Design

FOAK – First of A Kind

LCC – Life Cycle Cost

LCOE – Levelised Cost of Electricity

LWR – Light Water Reactor

MRA – Multi Regression Analysis

NPP – Nuclear Power Plant

OCC – Overnight Cost of Construction

O&M – Operations and Maintenance

PBS – Product Breakdown Structure

PWR – Pressurized Water Reactor

QFD – Quality Function Deployment

NPP – Nuclear Power Plant

SMRs – Small Modular Reactors

TCIC – Total Cost of Installed Capital

WBS – Work Breakdown Structure

List of Publications and Reports

Agar, AS; Goodfellow, MJ; Goh, YM; Newnes, LB (Drafted). “A Method for Supporting Early Design Decision Rationale Using a Product Cost Estimate Maturity Metric: An Application to the Small Modular Nuclear Reactor Development Programme”. Research in Engineering Design

Agar, AS; Locatelli, G (Accepted for publication 2019). “Chapter 4: Economics of Nuclear Power. Advances in Nuclear Reactor Technology Development and Utilization.” Elsevier, Oxfordshire, England

Agar, AS (2019). “Cost Uncertainty and Design Decision Making at the Early Development Stage,” Working Paper for the Technical Meeting on Cost Estimating, International Atomic Energy Agency, Vienna, Austria

Agar, AS; Goodfellow, MJ; Goh, YM; Newnes, LB (2019). “Stakeholder Perspectives on the Cost of Small Modular Reactors,” Progress in Nuclear Energy. 112. Pg. 52-62 doi.org/10.1016/j.pnucene.2018.12.006 (Appendix A)

Agar, AS; Goodfellow, MJ; Goh, YM; Newnes, LB (2018). “Expected Accuracy of Cost Estimates for Small Modular Reactors at the Early Concept Design Stage,” Proceedings of the International Conference on Nuclear Engineering, *ICONE26*, July 22nd – 26th 2018. London, England (Appendix B)

Agar, AS (2018). “Cost Estimate Management Plan for the Rolls-Royce SMR Development Programme,” Internal Rolls-Royce Plc document

Agar, AS; Fry, AJ; Goodfellow, MJ; Goh, YM; Newnes, LB (2017) “Quantifying Cost Uncertainty to Support Early Concept Design-decision Making for a Nuclear Power Plant,” Wolfson School Student Research Conference, 6th-7th June 2017, Loughborough, England

Agar, AS; Goodfellow, MJ; Goh, YM; Newnes, LB (2015). “Fission Possible: UK Nuclear New Build,” International Conference on Manufacturing Research, 8th – 10th September 2015, Bath, England

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1 Introduction

For the UK to meet future electricity demand and to transition to a low carbon energy economy the installation of new power generation technology will be required. Nuclear power is a low carbon, highly reliable and energy dense source of electricity. In the UK 14 of the 15 operational reactors are likely to be shut down towards the end of the 2020s (National Grid, 2018). The Energy Technologies Institute (ETI) estimate that around 40GW of new Nuclear Power Plant (NPP) capacity will be required by 2050 for the UK to traverse to a green economy in the fastest, least cost and most feasible way (ETI, 2016).

Since the Department for Business, Enterprise and Regulatory Reform (Berr, 2008) announced that NPPs are to be part of the future energy mix the “nuclear renaissance” has struggled to gain momentum in the UK. The global economic crash in 2008 and the partial meltdown of the Fukushima Daiichi nuclear reactor in Japan in 2011 have contributed to the perception of risk associated with large NPPs. However, in Western Europe and the United States the risk of investing in large NPPs has focused predominantly on the financial burden of the capital-intensive construction phase associated with new builds. Figure 1 illustrates how every new large NPP build program in the West has experienced severe construction overruns, with two out of the four US reactors having been cancelled. Significant construction delays and cost overruns even with the most recent Generation III+ large reactors contribute to the huge uncertainty in the cost of a NPP. In liberalised markets, such as the UK, Investment in large NPPs are potentially restricted to the biggest utility companies who can debt finance the project by leveraging against their asset portfolio (Gross, Blyth, & Heptonstall, 2010).

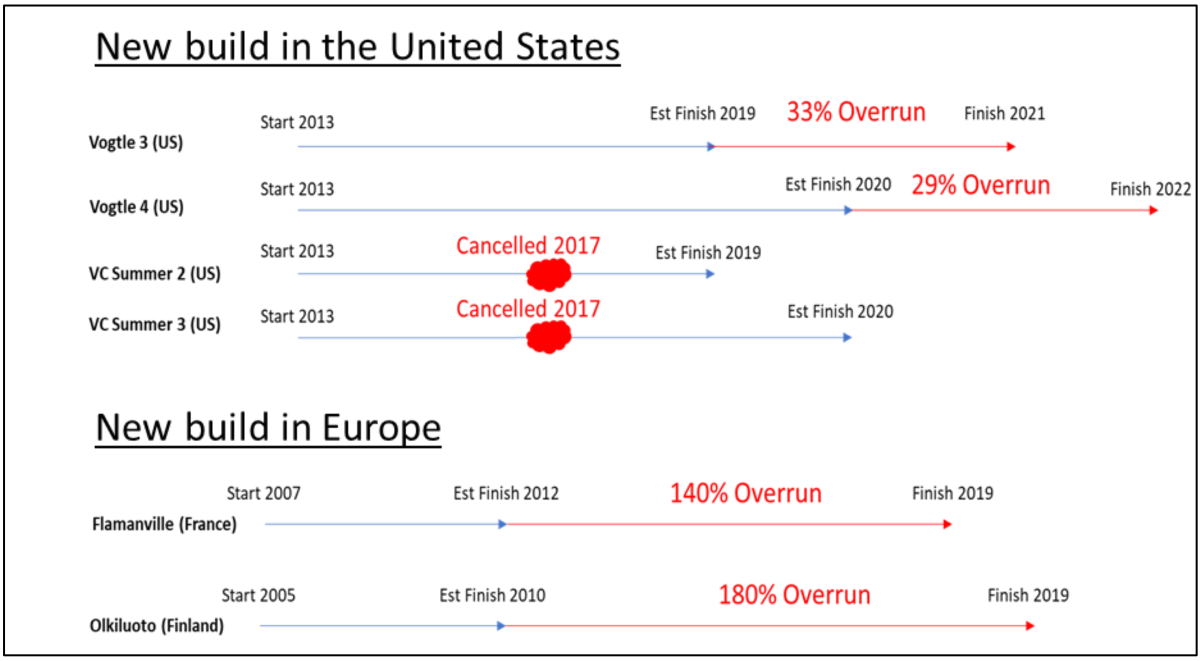


Figure 1: Schedule overruns and project cancellations in recent nuclear new build

The need to provide construction cost and schedule certainty and to lower the upfront cost of nuclear power has led to the consideration of Small Modular Reactors (SMRs) as part of the future energy mix (Sovacool & Ramana, 2015). Small reactors are NPPs which have an electrical output of less than 300MW(e), while SMR stretches the definition to include modular reactors with a capacity of up to 600MW(e). Traditionally the SMR has also referred to Small and Medium Reactors which have an electrical output of up to 700MW(e) (IAEA, 2001). The National Grid (2018) estimate that the installed capacity of new SMRs in the UK will be around 17GW by 2050, while the ETI estimate that as much as 7GW will be needed by 2035 (ETI, 2016). Recommendation reports such as those published by Policy Exchange (2018) propose that near-term deployable SMRs (using conventional Light Water Reactor technology should be supported by the UK Government. By providing funding at the Front-end Engineering Design (FEED) stage to reduce the development risk burden on the vendor organisation (Rooney, 2017).

There are currently more than 50 SMR designs at various stages of development around the world with many potential applications. Different designs have different characteristics, related to technology, physical size, electrical output and operating parameters. No single SMR concept resolves all the problems identified with large NPPs (Ramana & Mian, 2014). Designing the right SMR for the right market is an important consideration for the vendor committing to a lengthy and financially significant development programme. To develop a new product an organisation needs to design for customer requirements considering the entire product lifecycle (Hansen & Andreasen, 2004). SMR vendors need to provide confidence to investors that they will deliver to cost and schedule certainty, as well as developing a product that will be cost competitive with other power generation technologies throughout their operational life.

1.1 Background to the research problem

The research problem focuses on early design stage cost estimating for the SMR. In this section the reasons for considering SMRs as a solution to the risks perceived with investing in large NPPs is outlined.

1.1.1 Small, modular and less risky?

SMRs have been identified as a potential solution to the problems associated with investing in large NPPs (Boarin et al, 2012). The economic advantages of SMRs have been described in several studies which also present high-level cost estimates (Carelli et al, 2010; Shropshire, 2011). SMRs are likely to have a reduced upfront total investment commitment (Carelli et al., 2007). Providing a more manageable cash flow introduces flexibility to the investment strategy, allowing series construction of multiple small units (Ingersoll, 2009). In markets where the cost of large NPPs is a barrier to investment SMRs are an opportunity to provide a means of incrementally investing in capacity addition to the grid. The financing of an SMR then becomes easier and potentially less risky, resulting in a lower cost of capital (Ramana & Mian, 2014).

By standardising the design, and through constructing a greater quantity of SMRs sequentially, there is a greater opportunity to learn from experience (Neij, 2008). Greater emphasis on factory production and the design of smaller, standardised components, introduces greater certainty of reducing construction cost by taking advantage of the controlled manufacturing environment and by minimising site work (M. Cooper, 2014).

The Energy Innovation Reform Project (EIRP) state that “for advanced reactors, certainty about total plant cost, even if some low-cost components have low certainty” is a key requirement of advanced reactor concepts (EIRP, 2017). The challenge for a reactor vendor is to prove to the market, to investors, and to the public that the SMR can achieve cost competitiveness with other technologies and provide more certainty of delivery to time and budget.

1.1.2 Developing the SMR to Cost

In this thesis, the SMR is considered as an engineered product that is developed using a systematic New Product Development (NPD) approach known as the Stage-Gate process (Cooper, 2008). The NPD shown in Figure 2 involves managing uncertainty and risk to create a design which meets customer requirements. The feasibility of the design is continually assessed throughout the development stage. “Conceptual estimates are crucial to pioneering plants for which the company has no previous experience and few or no similar plants exist” (Tsagkari et al, 2016). This research focuses on the needs for cost information at the concept definition stage.

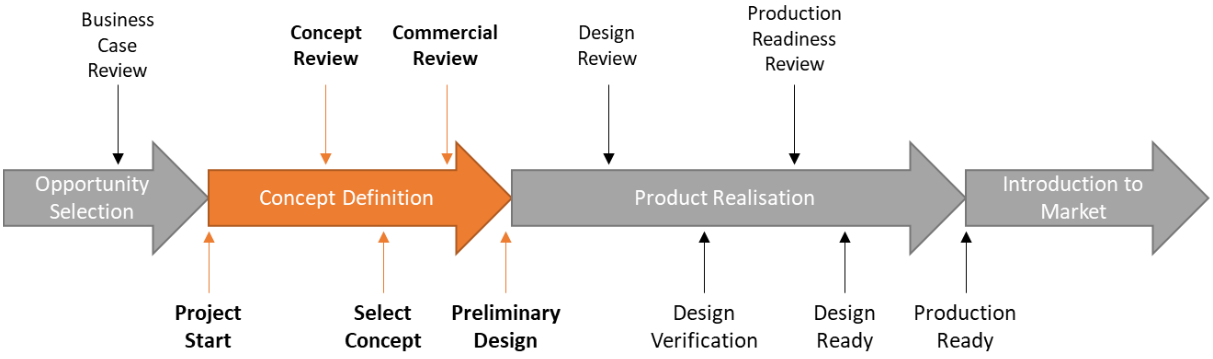


Figure 2: Phases of the Stage-Gate© process

Cost Estimates are used to test the commercial feasibility case and to support the rationale for design decisions (Figure 3). In the literature, 80% of total product cost is committed at the early stage of the design lifecycle (Rapp, 2000). As well as influencing product cost, design changes later in the product development lifecycle can result in increases from 3 to 1000 times the original development cost (Kennedy et al, 2014). Concept design decisions, therefore, have a major effect on the total product cost (Cai & Tyagi, 2014; Stewart, 1991).

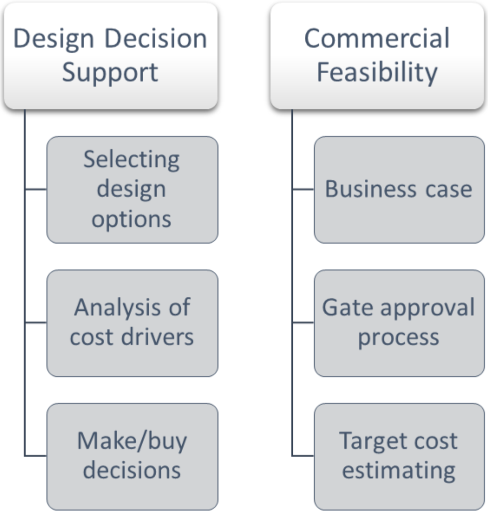


Figure 3: Use of cost estimating at the early concept design phase

The decisions made by the design team are influenced by different types of cost (Figure 4). Development cost and time to market considerations are key to the commercial viability of the SMR; too late and other competing technologies may become market leaders. Too early, and the lack of a mature design may cause change-induced delays reducing investor confidence and public acceptance of the technology.

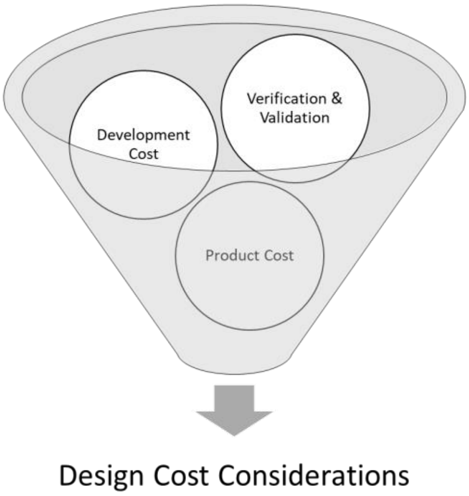


Figure 4: Optimising for cost at the design stage

One of the key requirements to support decision making at the early concept development phase is the ability to evaluate performance given different scenarios (El Amine et al, 2017). For the design team, there is a need to understand how early development stage decisions affect the product cost and, in parallel, the commercial viability of the project. At the end of concept development a high degree of concept maturity is required to reduce the risk of programme cost and schedule overruns (Katz et al, 2015). The design team have limited time and resources to select the “best concept” that will meet customer requirements. The level of certainty needed to identify the best option is balanced against the need to innovate and produce novel concepts in the face of external competition.

There is a duality in early design stage cost estimating. On the one hand the designers are keen to understand the impact of their decisions on the product cost requirements. At the same time, the cost estimator requires (at least some) information about the physical form of the design to present an estimate which the designer can use to make a rational decision. At the early development stage for innovative products there is a limited amount of information available to the design team upon which to base a decision. An organisation with no previous experience in designing a NPP will produce cost estimates that are inherently uncertain, because of a lack of access to proprietary reference historical cost data (EIRP, 2017).

There is a limit to the availability and accuracy of cost information that can be presented at the early design stage upon which to base a decision. There is a tendency for experts to focus more on the confidence of the estimate when asked to determine an accuracy and confidence level (Serpell, 2004). This was particularly the case when estimates did not have a historical set of information supporting the assessment. The successful identification of relevant cost drivers and critical factors for the economic success of a design are influenced by the accuracy and confidence in a cost estimate (Cai & Tyagi, 2014). In this thesis, cost uncertainty refers the confidence in the estimate from the perspective of the estimator.

1.2 Research Problem and Knowledge Gap

The main gap identified in the literature is a convergence of three research areas (Figure 5). Specifically, the research presented in this thesis centres on the need to establish the adequacy of the cost information used by the design team to make a design decision at the early concept development stage. By standardising the approach to assigning cost uncertainty ratings to the estimate generated, the design team can better understand the impact of carrying out design activities to improve the confidence in the estimate.

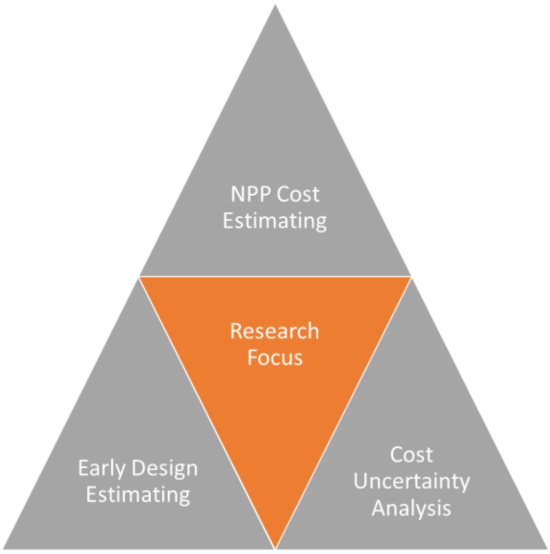


Figure 5: Research context

1.2.1 Contribution to knowledge

The main contribution of this thesis is the Acceptable Cost Uncertainty Benchmark Analysis (ACUBA) method. The method utilises a more in-depth analysis of the components of knowledge-based cost uncertainty to support the design decision-making rationale for the SMR. Using the ACUBA method the design team are provided with a rating for the sources of cost estimate uncertainty associated with the engineering definition, manufacturing process and supply chain knowledge information.

The identification of a sufficiently mature product cost estimate is a key requirement to satisfy the sign off point and to progress to the next phase in a standard Stage Gate approach (Cooper, 2008). The ACUBA method can support the development team in planning when decisions need to be made, and to determine what information is required, thus optimising the limited resources available at the early concept design phase. When presented with a cost estimate, an associated maturity rating, and the drivers of uncertainty for the estimate, the designers are provided with more information as a rationale for the design decision. By setting targets of acceptable product cost uncertainty level for each major decision point the development team can determine a range of approaches to designing the product.

Following an extensive literature review and to the best knowledge of the author no research to date has presented a method for managing the design decision making process at the early concept design phase for SMRs through the application of a knowledge-based, qualitative cost uncertainty metric.

1.2.2 Implementation into industrial practice

Research is often criticised for its inapplicability to practical situations, and the difficulty of implementation to the real-world (Blessing et al, 2009). One of the main requirements for the ACUBA method is its usability in an industrial setting. The research described in this thesis has been carried out during the early development stages of the UK SMR, spanning the early stages of the concept development process. The requirements for cost information in early design decisions in the case study organisation were key criterion providing the basis of requirements for the development of the ACUBA method.

1.3 Research Aim and Objectives

In this section the research aim, objectives and main research activities are presented. To successfully meet the aim and objectives several research activities are carried out. These are described alongside the research objectives.

1.3.1 Research aim

The aim of this research is: *to develop a method which uses cost uncertainty information to support decision making at the early development stage for the UK SMR*.

1.3.2 Research objectives

Table 1 presents the objectives and their related research activities. The deliverables from carrying out the research activities are also listed.

Table 1: Research objectives and related activities

Research Objective	Research Activity	Research Deliverables
RO.1: To identify how cost estimating is applied in the context of nuclear power plants and where the knowledge gaps and limitations are.	Review of literature in nuclear power plant cost estimating, early design stage cost estimating, and cost uncertainty analysis.	A list of key gaps in the literature identified. Defining the problem which the research will attempt to solve.
RO.2: To define the design for cost decision making process at the early design stage for the SMR.	Semi-structured interviews; Case study analysis of industrial process.	Case-specific model to interpret the use of cost information at the early concept design phase to support decision-making for the SMR.
RO.3: To identify how cost uncertainty information is used in the case study organisation to support design decision-making	Case study analysis. Structured questionnaires.	A set of requirements for a method to support the case study organisation to make decisions using cost estimate uncertainty information.
RO.4: Develop a method to determine the acceptable uncertainty range for the defined stage of the design process.	Design development research practice	A method which can be applied as a support to early design decisions in the case organisation.
RO.5: Validate the developed method.	Case study analysis; Focus group.	Evaluation of the method showing its feasibility, usability and applicability in the industrial setting.

1.4 Thesis Structure

The thesis is structured into four main sections representing different stages of the research (Figure 6). The preliminary section provides an underpinning for the research and sets out the research methods adopted. Part I focuses on identifying the requirements of a support method from the perspective of the case study organisation. Part II then describes the developed method to support early design decision making using cost uncertainty information. The concluding section incorporates a discussion on the merits and limitations of the research approach, concluding remarks on the overall thesis and further work.

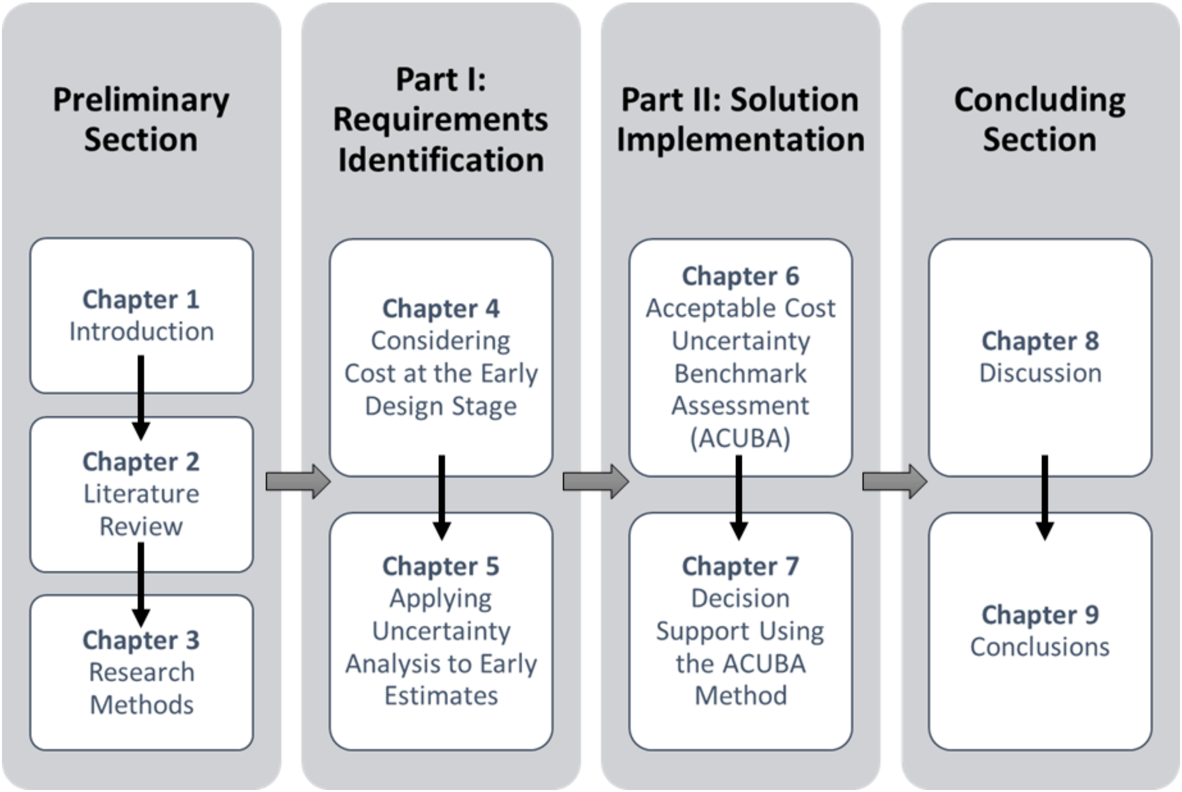


Figure 6: Structure of the thesis

1.4.1 Preliminary Section

Chapter 2 presents a critical evaluation of the existing literature within three specific research domains. The previous research investigating the cost of NPPs are combined with a review of SMR cost literature to identify the key challenges in cost estimating and limitations to cost estimating techniques applied to SMRs. A wider view of cost estimating techniques and a review of approaches to cost estimate uncertainty analysis at the early concept design phase are used to provide further context to the challenges for SMR cost estimating. The literature review thus provides a foundation for the remainder of the thesis by identifying the research gap.

Chapter 3 details the research methods applied to meet the objectives identified in Section 1.3.2. The methodological approach is presented, based on the identified challenges and knowledge gap presented in Chapter 2 and the industrial context of the research. The research methods applied to achieve each of the objectives are then detailed along with a justification for their selection and the possible limitations of the research approach.

1.4.2 Part I: Requirements Identification

The chapters in Part I describe the research undertaken within the case study organisation to understand the current use of cost estimating and the requirements of a new method to use cost to support design decisions. A detailed analysis of the NPD process applied by the case study programme is presented in Chapter 4. An investigation is carried out into the use of cost information to support design decisions and the key cost requirements driving the product design. The design decision-making process is modelled and the interaction of cost in the development process are used to develop an understanding of the cost information requirements at the early concept design phase.

One of the key challenges associated with early cost estimates is the implementation, interpretation, and use of uncertainty information in early design decision making. Chapter 5 presents a survey carried out in the case study organisation where the use of cost uncertainty information and the shortcomings with how the information is understood are investigated. The conclusions of Chapter 4 and Chapter 5 lead to the identification of a set of requirements for a method to support design decisions that is developed in Part II of the thesis.

1.4.3 Part II: Solution Development

The contribution of this research is a method for using cost uncertainty information to inform decision-making. In Chapter 6 the method is broken down into several steps, where a description of the steps is supplemented with the justification for the approach.

A discussion on the benefits and limitations of each step are then discussed, supported by a comparison with the requirements identified in Part I.

Chapter 7 provides the proof of concept and validation of the method by implementing the developed method using a practical case study example. The method is employed on existing cost data generated by the case study organisation up to the current stage of product development. The efficacy of the ACUBA method compared with conventional cost uncertainty analysis techniques is investigated through controlled focus groups with the case study design team.

1.4.4 Concluding Section

This research is carried out to provide a solution to an identified industrial need as well as providing a contribution to knowledge. The developed method is applied to the case study organisation. Chapter 8 discusses the ACUBA method and how it might be generalised to apply more widely. Further, the chapter identifies the gaps in the ACUBA method and how it might be integrated into the NPD process. Finally, the limitations of the methods applied in the research are discussed. Further work and Conclusions are presented in Chapter 9 providing a summary of findings and next steps for the research. The contribution to knowledge is stated along with implications for the research field investigated. Future areas of research which are informed by the findings in Chapter 7 and 8 are then listed.

2 Literature Review

2.1 Outline

In this chapter the existing literature on cost estimating for NPPs and SMRs is critically reviewed. The challenges in SMR cost estimating are described, providing a basis for the research aim and objectives outlined in Section 1.3 and the research methods presented in Chapter 3 (Figure 7). The gaps and challenges identified in this chapter also provide the evidence base to verify the unique contribution of this thesis to knowledge.

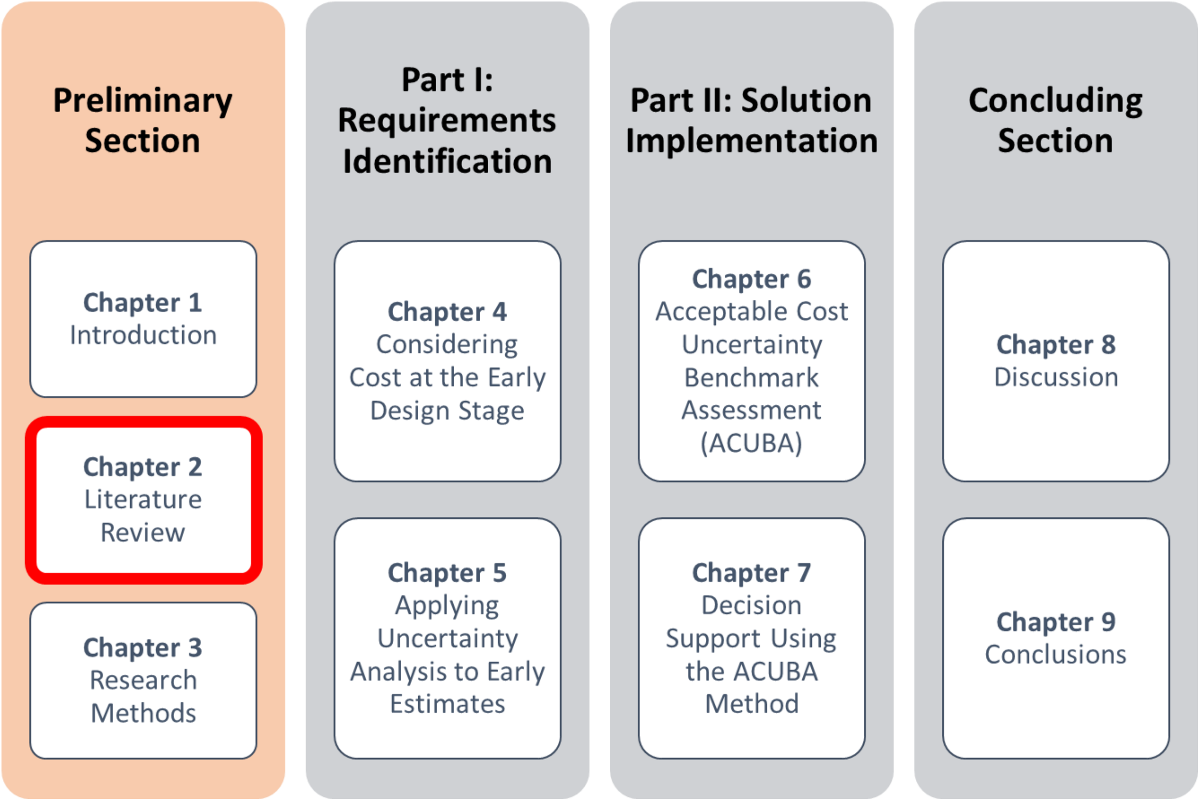


Figure 7: Literature review in the context of the thesis

This chapter aligns with research objective 1:

To identify the knowledge gaps and limitations associated with early cost estimates for SMRs.

Figure 8 presents the structure of the literature review. A brief summary of nuclear within the context of future power generation is presented in Section 2.2. A detailed review of the cost estimating literature associated with NPPs in Section 2.3 provides the context for the research. Beginning with the identification of key metrics used to understand the lifecycle cost the cost drivers for large NPPs are then presented and compared with the expected drivers for SMRs.

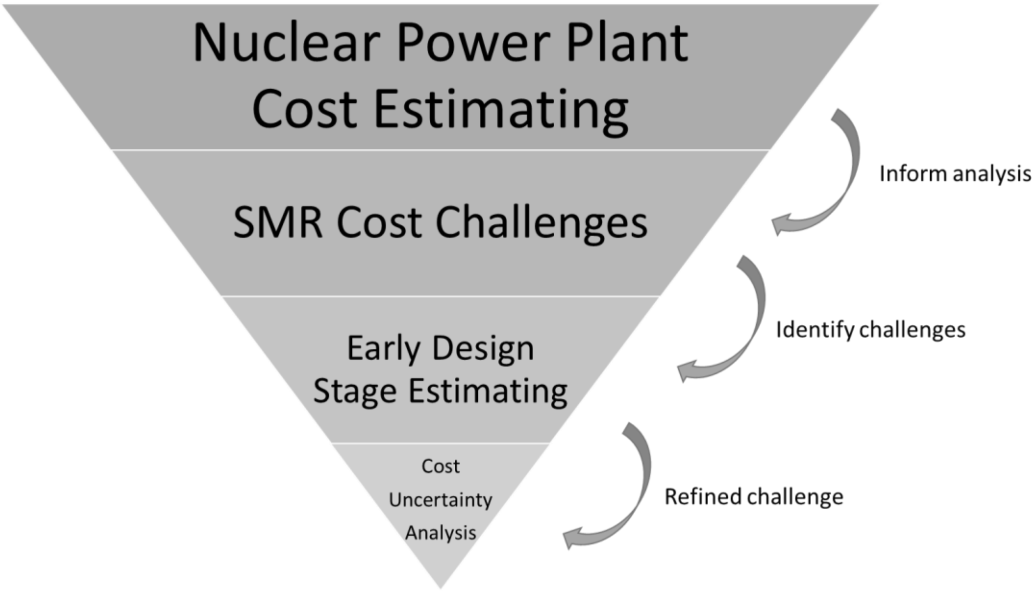


Figure 8: Literature review structure to identify the research problem

Section 2.4 narrows the scope of the literature review with an in depth assessment of the cost challenges associated with SMRs. The key challenges identified are then used to frame the research problem of cost estimating at the early design stage which are detailed in Section 2.5. The research problem is then further refined in Section 2.6 to focus on approaches to cost uncertainty analysis at the early design stage. A summary of the gaps in knowledge identified in the body of literature is presented in Section 2.6 along with the research problem which forms the basis of the research methodology presented in Chapter 3.

2.2 Nuclear Power in the Global Context

There is an active global movement towards decarbonising electricity generation. Traditional coal (which accounts for around 50% of greenhouse gas emissions from power generation) and petroleum based technology are being replaced with nuclear, renewables and carbon-capture and storage (CCS). Globally, power generation is a significant contributor to greenhouse gas emissions (Wendling, 2019). Nuclear power (which provides around 50% of CO2-free power generation in Europe) has been identified as an important technology to support the transition to a low carbon source of electricity generation in conjunction rather than competition with other low carbon technologies (WNN, 2019).

The context of the viability of nuclear power generation often includes the competing tensions of the energy security, low greenhouse gas emission and energy dense value that nuclear brings against the high capital cost and radioactive waste dilemma (Bandoc et al, 2018). Since the year 2000, more than 101 nuclear reactors construction projects with a capacity of more than 300MWe have been started (Figure 9). Of these, 59 are in operation, while 42 are under construction. In the West (i.e. Europe, North America and South America) there have been 9 reactor construction projects started since 2000, while 92 construction projects have started in Asia (including the Middle East and Russia). The average reactor construction time in the West is 10 years, compared with 6 years in Asia.

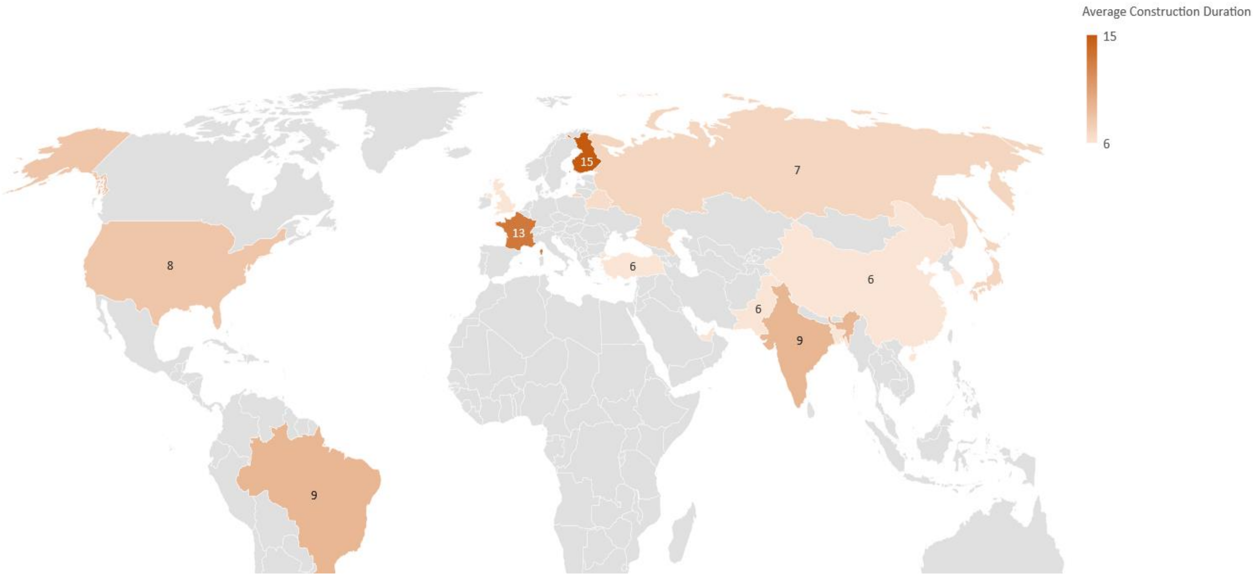


Figure 9: Average years of construction duration for new build projects commencing construction after the year 2000 (Data sourced from PRIS, 2019)

Wendling (2019) states that the selection of an optimal energy strategy depends on “the ultimate costs of each technology as well as the social costs from greenhouse gas emissions.” Increased variable renewables, stable, baseload electricity. Low carbon, secure supply of electricity. Traditional, large nuclear power is capital intensive, with payback achieved through economies of scale, with large amounts of electricity produced over the operating life of the plant. Significant construction durations and uncertainty associated with delivery time associated with the most recent Generation III and Generation III+ large reactors have contributed to great uncertainty in the delivery time and cost of an NPP (Locatelli 2018). The cost, size, flexibility and modularity of SMRs offer an emissions reduction solution not only for electricity generation but also in other sectors, like district heating and for water desalination (Figure 10). The Energy Technologies Institute (ETI, 2016) forecast that around 21GW of SMR technology would be required by 2050 in the UK alone.

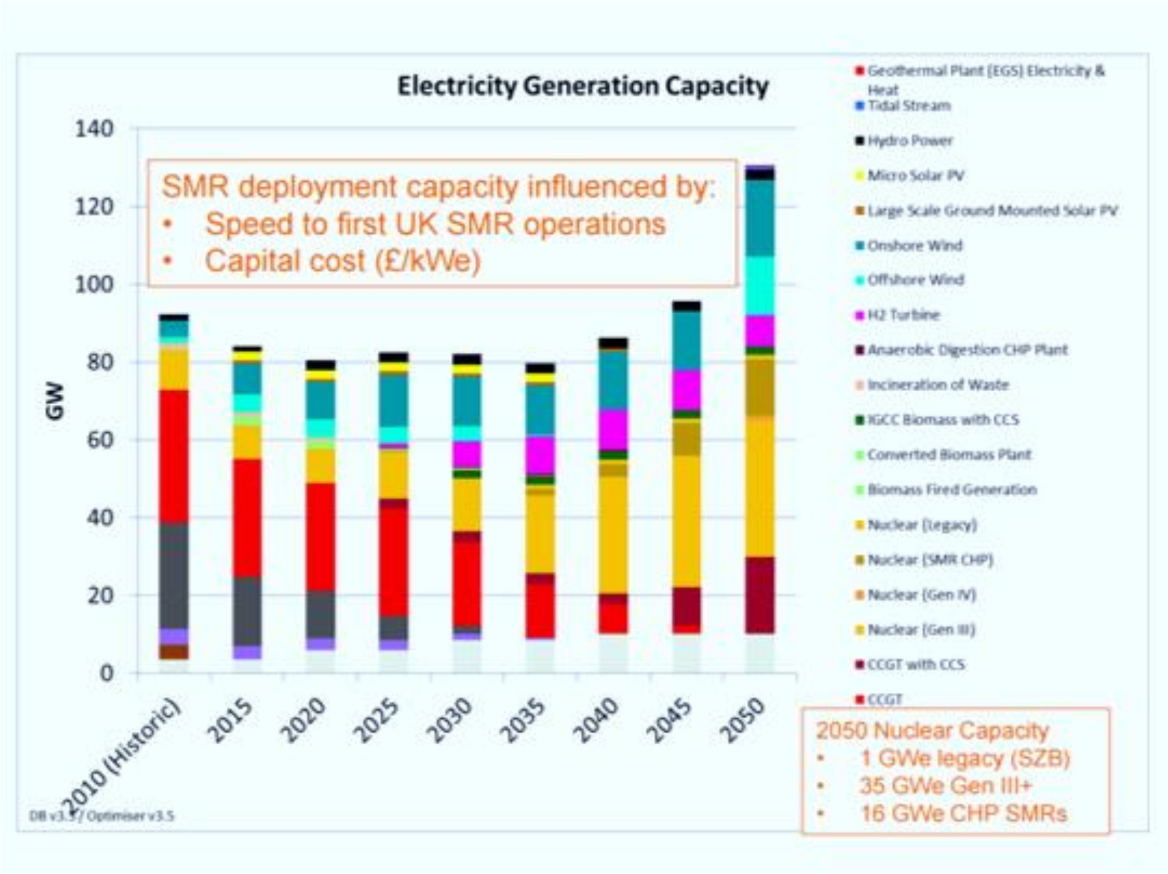


Figure 10: Forecasted UK Energy Supply Mix over time (ETI, 2016)

2.3 Cost Estimating Nuclear Power Plants

In this section the review of literature attempts to answer two questions. Firstly, how NPPs are estimated and the key metrics used to assess their cost. Secondly, the identification of NPP cost drivers. Although the focus of this research is on cost estimating as applied to SMRs, there is significant research applied to understanding the cost of large NPPs, which is reviewed to provide context for SMRs.

2.3.1 Literature Review Strategy

A literature search of peer reviewed journal articles was carried out using the primary search term “nuclear cost estimate” (Figure 11). The search conducted in Compendex, Scopus, and Web of Science databases identified 221 journal articles and conference papers.

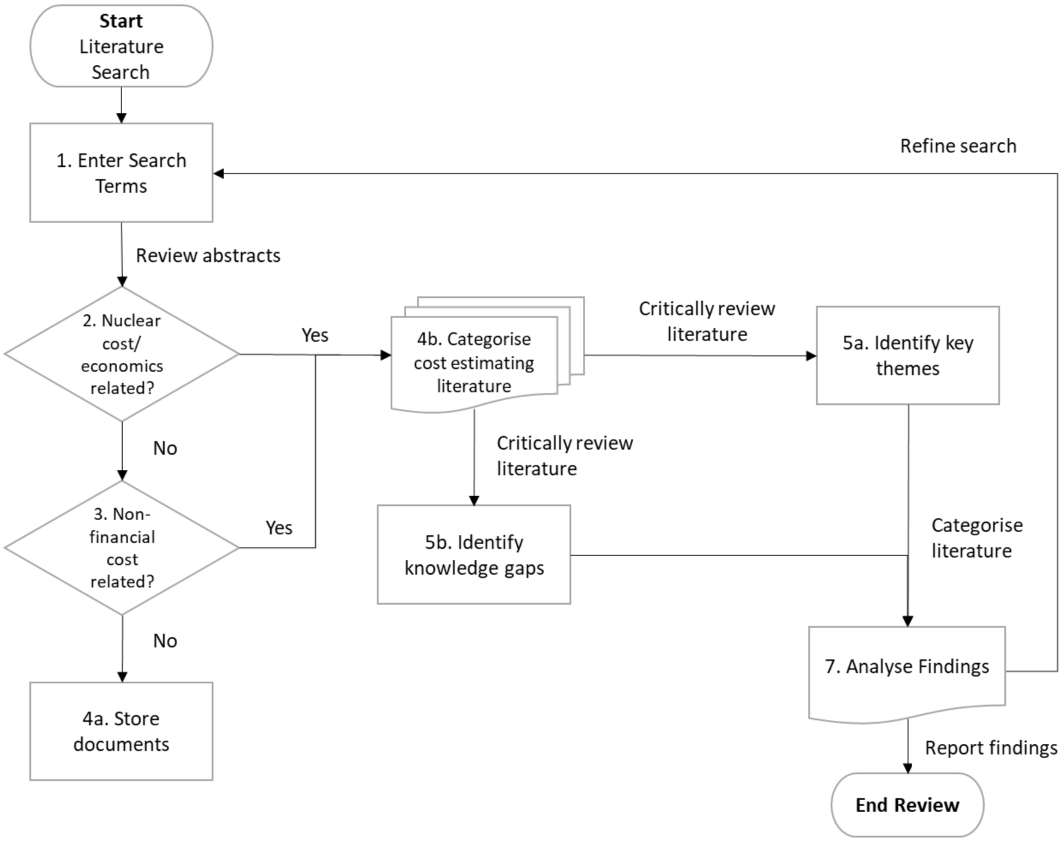


Figure 11: Literature review process

The search returned articles encompassing energy, government policy, engineering, manufacturing, science and a variety of social sciences incorporating the human, economic and environmental cost of nuclear to power generation and defence applications. In Mignacca & Locatelli's systematic review (2020), a total of 233 documents related to the key search term "SMR economics and financing" were identified, and 46 were reviewed in detail. This compares favourably with the breadth of literature reviewed in this chapter.

The focus of this research is cost estimating related to nuclear power generation. To narrow the review to the most relevant articles the abstracts of articles associated with financial or economic considerations of NPPs were selected for further analysis. Environmental and human costs were also considered where the paper identified these costs in relation to financial or economic considerations.

2.3.2 The Levelised Cost of Electricity (LCOE)

The Levelised Cost of Electricity (LCOE) is the most widely used metric for Life Cycle Cost (LCC) analysis of NPPs. Alternative methods for estimating the cost of NPPs have been proposed in literature ((Linares & Conchado, 2013; Roques et al, 2006)). However, these alternative methods are not widely implemented in industry. Mignacca & Locatelli (2020) confirm that the LCOE is the most common metric used to estimate the comparative cost of SMRs with other forms of power generation. This section focuses on the LCOE metric to understand the cost of NPPs.

The scope of the NPP lifecycle used in the LCOE analysis begins at the start of the construction period and finishes at the end of the useful life of the NPP (De Roo & Parsons, 2011). The LCOE represents the LCC of the plant per unit of electricity produced discounted to the base year of construction ((Kula, 2015); (Kreith, 2014). The LCOE, therefore, defines the “break even” cost for a power generation project at a specified rate of return, such that the lowest value of LCOE is identified as the most beneficial option as a comparative assessment tool for different power generation technologies (Palacios et al., 2004).

2.3.3 Purpose of LCOE Analysis

LCC calculating methods and assumptions vary depending on the intent of the study and therefore any such calculation requires a viewpoint (Settanni et al, 2014). The scope of an LCOE estimate can vary significantly depending on the purpose of the study (Table 2).

Table 2: Purpose of estimates and conclusions from various studies

Author (year)	**Purpose of estimate**	**Conclusions due to Estimate**
(NEA, 2015)	Policy Decision Support	Market structure, policy environment, resource availability drives the LCOE
(Deutch et al, 2009)	Policy Decision Support	Nuclear power can reduce risk-premium through proven performance. Carbon tax positively impacts on nuclear competitiveness
(University of Chicago, 2004)	Policy Decision Support	Nuclear power cost driven by financing options due to high capital cost contribution to LCOE. Availability of more detailed overnight construction cost information may impact future investment in new nuclear plants.
(NREL, 2010)	Utility Investors	Small improvements to technology or manufacturing processes can lead to significant cost savings. Cost is site-specific. LCOE impacted by variation in required rate of return, O&M costs, and debt-financing structure
(Macdonald & House, 2010)	Policy Decision Support	Less mature technologies have a more extensive first of a kind premium. Cost uncertainty associated with fuel and carbon prices.

(Lazard, 2014)	Policy Decision Support	Cost drivers for capital intensive technologies are engineering, procurement and construction cost, build time, and the annual capacity factor
(DECC, 2013)	Policy Decision Support	Capital costs the biggest driver of nuclear LCOE
(Allan et al, 2011)	Policy Decision Support	Cost reduction for newer technology achievable with technology-differentiated financial support
(Harris et al, 2013)	Policy Design. Decision Support	Policy makers need to maintain awareness of revenue risk as well as initial capital (cost) risk. Government support to fixed price for electricity where technology uncertainties are greater is right
(Kennedy, 2007)	Policy Decision Support	Lower LCOE can be achieved when investing in multiple units rather than one off. Coupled with carbon tax nuclear would be competitive in the UK context
(Carelli, et al., 2010)	Utility investors	Carbon tax improves investment attractiveness of a small NPP.
(Locatelli & Mancini, 2012)	Utility Investors	Large reactors meet traditional metrics of IRR and LCOE better than SMRs. Other metrics associated with design robustness and spinning reserves better achieved by SMRs.

The LCOE is used as a comparative benchmark between different power generation technology options (Locatelli & Mancini, 2012) to support the rationale for energy policy and for investment decisions made by utilities (Gross et al., 2010; Kessides, 2010; Kula, 2015). The LCOE can be used to identify the required level of financial support to encourage investment in a technology which might not be selected if left to the market (Gross et al., 2010) For example, the US Energy Policy Act of 2005 introduced loan guarantees, production tax credits and guarantees against construction delays for the first 6GWe of new nuclear power plants (Deutch et al., 2009).

External costs are considered in a number of LCOE studies, and are considered within scenario analysis particularly where comparative impact of different technology options on the environment are considered. Although there is no standard mandating their inclusion. The LCOE is an effective tool for Government to identify both the societal impact of power generation technology (e.g. carbon emissions and waste), and the sensitivity to market influences such as the risk factor associated with investment in a liberalised or regulated environment (Mari, 2014). Roth & Ambs (2004) produced a comparison of LCOE figures for different electricity generating technologies by incorporating externalities such as air quality and energy security.

2.3.4 LCOE Cost Categories Defined

The review of literature has identified that there is no single method or standardised process for applying the LCOE analysis across different power generation technologies. For the purposes of conducting a standard analysis of NPP cost the general categories associated with the LCOE have been defined here using the most common components of a LCOE calculation. Generally, the LCOE can be broken down into Total Cost of Installed Capital (TCIC), Operations and Maintenance (O&M) and fuel costs (Figure 12). Additional categories which may or may not be included within the LCOE calculation are identified in the box on the right-hand side of the diagram with the number in parenthesis identifying where in the main cost elements (middle boxes) these costs are likely to be included. Each of the main cost elements are now described in turn.

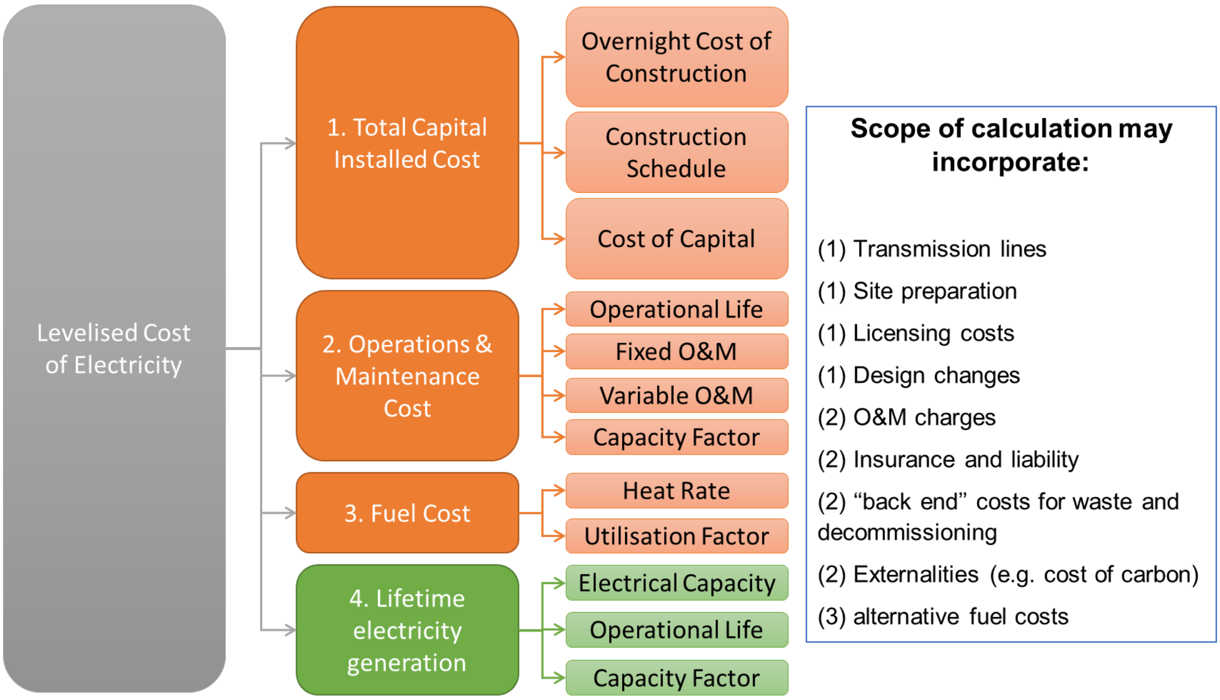


Figure 12: Cost elements included within the LCOE analysis

2.3.4.1 Total Cost of Installed Capital (TCIC)

The main inputs to the TCIC consist of the Overnight Cost of Construction (OCC), the Construction Schedule and the Cost of Capital. An additional category, known as the Pre-construction cost is defined separately. Pre-construction costs are associated with the acquisition and preparation of a site, the effort required to obtain an operating license, to conduct and accept the technical reactor design, to carry out public enquiries, and to have appropriate financing in place (Harris et al., 2013). The inclusion of pre-construction costs in the scope of the LCOE is dependent on the project scope, organisation structure and the purpose of the estimate.

The OCC is used as an indicator of the cost of the technology itself, removing costs attributed to the financial structure of specific projects (Berthélemy & Escobar Rangel, 2015). It is, therefore, an important metric to understand the direct cost of the NPP design. The OCC incorporates the infrastructure development, commissioning activities, the first loading of fuel and connection to the electricity grid.

The construction schedule can be defined as the time taken from the point where design approval is obtained to build a reactor to the point where a reactor is able to send electricity to the grid (Schulz, 2006). Construction schedule has been identified in literature as having a major influence on the cost of capital (Lévêque, 2013).

One of the major influences on the construction cost is the cost of capital. The cost of capital is the financing cost to construct the NPP (Gross et al., 2010). The cost of capital is usually presented in the LCOE as a discount rate, although some studies such as the Future of Nuclear Power Study by MIT (2009) detail the gearing (ratio of debt to equity) associated with the cost of capital. The level of gearing can influence the risk associated with an investment, such that investments requiring greater debt financing incur a larger cost of capital, and therefore require a higher rate of return (and associated discount rate). The cost of capital is dependent on a number of extrinsic variables related to the risk associated with investing in a NPP construction project (Lévêque, 2013). According to Thomas (2005) the cost of capital is dependent on the competitiveness of the electricity market, the utility, the country risk and the credit rating of the company. Kessides (2010) identified that, even when nuclear technology is said to be mature, and has equivalent costs to other power generation technologies, the perceived riskiness of the project can significantly drive the cost.

2.3.4.2 Operations and Maintenance

Operations and Maintenance (O&M) costs are incurred after the construction phase is completed and can be defined as those costs related “to the management and upkeep of a power station during its lifetime” (DTI, 2007). The University of Chicago study into the economics of nuclear power refers to 5 distinct cost components associated with the operations phase, namely the annuitized capital cost, insurance, fixed O&M, variable O&M, and fuel costs (University of Chicago, 2004). Externalities such as the cost of carbon, environmental impact of waste products, and ongoing research and development activities could also be included (Sovacool, 2010).

O&M costs can also be separated into those which are fixed, i.e. costs incurred even when the reactor is not online, and variable, i.e. costs incurred depending on the electrical output of the plant. Fixed O&M costs include staffing, spares, labour, regulatory fees, maintenance, decommissioning contribution and taxes. More detailed analysis may include regulatory fees, offsite technical staff, pensions and benefits, and corporate overhead costs (ORNL, 2003). Regulatory or tax costs can be considered as variable costs if these are linked to the output of the plant (Vegel & Quinn, 2017).

The capacity factor is the measure of the output of the plant, given as a ratio of the net electricity generated by the plant over a period to the energy that could have been generated at continuous full power operation during the same period. The capacity factor and operating life of the NPP have a direct influence over the generating revenue potential of the NPP.

The back-end phase for an NPP involves the dismantling and decommissioning of the plant at the end of its operating life, together with its long-term management and the disposal of conventional and radioactive waste. The cost of decommissioning can be spread across the operating life of an NPP, and many LCOE calculations have costed for decommissioning as a fixed annual fee in the O&M cost (Locatelli & Mancini, 2010). As a result, decommissioning becomes a very small percentage of the LCOE.

2.3.4.3 Fuel Costs

Fuel cost is usually treated as a commodity which remains fixed throughout the operating life of the plant. For the analysis of conventional large NPPs fuel costs are considered as a fixed cost and are determined by extrapolating historical fuel cost data. However, fuel cost can be used as a figure of merit for comparing different types of NPP design, such as fast breeder reactors comparison with Pressurised Water Reactors (PWRs) (Shropshire, 2011).

2.3.5 Critique of the LCOE

The LCOE has been described as inadequate in its inability to provide an all-encompassing and directly comparable assessment of different energy generation technologies (Khatib, 2016). Linares & Conchado (2013) argue that the importance of construction durations, competitive gas prices, the potential cost of carbon and the risk premium associated with nuclear power means that the LCOE figure is not a good indicator of the best investment strategy in a liberalised market. The LCOE effectively penalises technologies requiring a larger upfront investment. Instead the LCOE should be presented with a specific environmental context such as the expected market structure, expected electricity demand growth, and the societal or environmental impact (using a carbon tax factor, for example).

Several inconsistencies in the LCOE estimating approach have been identified in the literature where different assumptions are used to estimate the LCOE by different studies, while findings are directly compared. The result obtained depends on the individual treatment of data and the allocation of the data in each input (NEA, 2015). Attempts have been made towards standardising the set of assumptions and to provide guidelines towards a standard application although this uniform set of assumptions is not being utilised in the wider literature for current generation reactor technology (EWMG, 2007).

The LCOE does not appear to incorporate risks and opportunities effectively. The uncertainty associated with the LCOE estimate, i.e. its sensitivity to different inputs to the calculation undermines its usefulness in applications such as to support policy decisions. In the LCOE analysis, however, other cost factors which may not have a representative importance based on cost driver analysis could be just as important to the commercial success of a future design. For example, fuel costs account for only 5% to 15% of the LCOE but could be an important decision driver in the future energy mix, particularly in a scenario where uranium prices increase, and alternative fuel types are considered (Baschwitz et al, 2017).

Environmental and social aspects have also been incorporated into the LCOE estimate (de Jong, Kiperstok, & Torres, 2015; Kiriyama & Suzuki, 2004). One of the drivers of the nuclear renaissance has been the positive influence of nuclear as a low carbon form of baseload energy. For example Kiriyama & Suzuki (2004) have attempted to incorporate the cost of carbon as a possible driver during the operational phase of the NPP. Gross et al (2010) also identify the need to quantify the impact of non-cost associated risks which are not identified within the LCOE analysis. For example, when considering whether to invest in a new NPP, the net positive benefit to the environment should be included. Thus, the LCOE analysis needs to be complemented with methodologies that account more completely for the risks in future costs and revenues.

All projects, from conception to end of life are subject to influences outside of the direct control of management. The influence of tax rates, regulatory upgrades due to new safety concerns, and lower gas prices all have an effect on the viability of operating a NPP, and all increase uncertainty and risk in operating over 40 years (ORNL, 2003).

In liberalised markets where low gas prices have reduced the competitiveness of NPPs, forcing the closure of reactors in the United States, whilst taxes and required upgrades have resulted in utilities operating reactors and selling electricity at a loss (King & Yang, 1981).

An important critique that is not identified in literature is the definition of LCC of a NPP taken in most studies. Agar et al (2019) identified that decision makers at different lifecycle stages of a NPP are influenced by different aspects of cost. Given that the LCOE is usually taken from the perspective of an investor or policy decision maker, the approach is to understand the economic competitiveness of the project compared with other options. In the analysis of plant competitiveness, there is no inclusion of the design and development cost of the reactor technology itself. In Figure 13 the conventional LCC definition is illustrated with the development cost. The combination of the two can be defined as the total product cost (Curran, Raghunathan, & Price, 2004). There is a significant gap where the design and development activities which could impact on all elements of the LCOE are not considered by the metric.

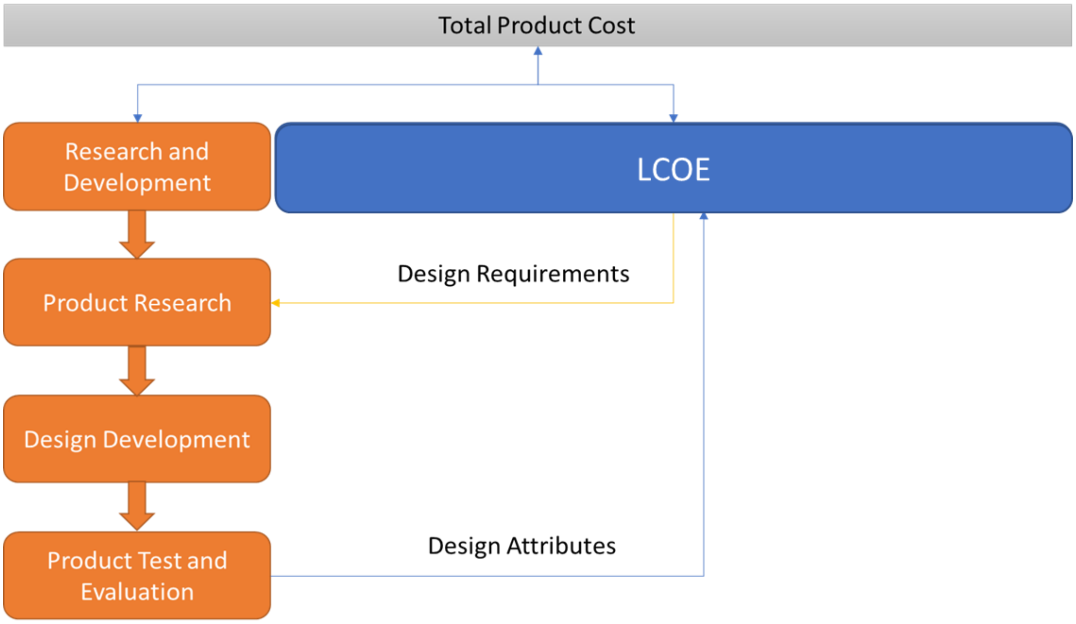


Figure 13: Total product cost with LCOE and design development cost modified

2.3.6 Cost Drivers for Large Nuclear Power Plants

A cost driver can be described as any factor that has an influencing effect on the total product cost including both financial or related non-financial causes (Rush & Roy, 2001). To provide a basis for understanding the cost drivers for SMRs this section begins with a reflective comparison of the expected cost of NPPs. The actual cost drivers as a result of experience in constructing and operating NPPs are presented.

2.3.6.1 Expected Cost Drivers

The UK constructed and operated one of the first civil NPP programmes in the world. To meet the expected increase in future energy demand, the first generation of NPPs were constructed to “enable electricity authorities and private industry to obtain as quickly as possible the practical experience in designing and building nuclear power stations necessary for a big expansion” (COI, 1962). The Government set a target of ordering 1 new Magnox station per year. Such a targeted and clear order book could have led to the assumption that saving through learning could be achieved by from lessons on the First of A Kind (FOAK) plant. NPPs were expected to eventually generate 70% of the UK’s electricity mix by the late 1970s, requiring the construction of around 40 of the second-generation Advanced Gas-cooled Reactors (Bainbridge & Farmer, 1971). Together with economies of scale, a more secure and lower cost fuel supply would make these next generation plants more economical.

Estimates of future cost savings based on the evidence of a learning curve during the build of coal-fired power plants after the second world war meant that cost of fuel was the perceived cost driver when compared to other types of power generation (Cowan, 1990; del Pozo, 1971; El-Fouly, 1970; George, 1960). Similar conclusions were drawn for the early French nuclear construction programme, where it was estimated that nuclear costs would be competitive when compared with the lifetime cost of coal and oil power generation (de Carmoy, 1979).

2.3.6.2 Actual Cost Drivers

Having gaining experience of the first generation of nuclear build in the UK, the most significant cost driver was identified as the TCIC (Sweet, 1990). Experience from constructing the earlier Magnox stations showed that two-thirds of the cost of the NPP related to the initial capital charges (Sandford, 1965).

Early drivers in the US civil nuclear construction program were due to labour cost increases and simultaneously lower productivity, stricter quality requirements and an increase in licensing costs (King & Yang, 1981). Higher O&M costs as a result of counterproductive regulation, ongoing capital expenditure, larger cost of staffing, and lower than expected capacity factors also influenced the higher than expected LCC of large PWRs throughout the 1980s (Simnad, 1989).

The most significant cost driver for an NPP is the construction cost (Maronati, Petrovic, Van Wyk, Kelley, & White, 2018). Although literature identifies consensus on construction being the driver of NPP costs, the underlying causes are disputed. The construction cost drivers experienced in the UK were influenced by design issues resulting in late changes, and consequently cost and schedule overruns (H. J. Rush, MacKerron, & Surrey, 1977). During the 1970s there were many regulatory induced changes issues with quality control during construction, increasingly complex reactor designs, and greater financial constraints on the utility in the US resulting in longer construction durations (Komanoff, 1981). Koomey & Hultman (2007) showed the cost escalation experienced during the 1980s was at a much greater rate than experienced in the 1970s. The TCIC increased due to changes in the regulatory requirements after the Three Mile Island accident in 1979, lower than expected electricity demand growth, greater reactor size and complexity, and quality control issues during construction.

The experience of the French nuclear program contrasts with that of the US and UK. The construction of a standardised design with cost estimates developed being based on the build experience of the US. Cost projections for the first reactors built in the 1970s and early 1980s were based on actual experience and appeared to be reasonably accurate (Grubler, 2010). The French program was able to keep construction costs in line with estimates due to the size of the order program, achieving economies of production, and serial standardisation of reactors sharing learning and expertise during construction. Due to the upscaling of the new, French reactor designed N4 (1300MWe), there was a loss of standardisation, a lack of learning curve, and an inability to maintain the knowledge and skill of the workforce after 1981, when nuclear construction activity in France decreased significantly (Grubler, 2010). Construction cost projections no longer reflected historical experience.

Construction time is a key cost driver. Figure 14 presents the distribution of global PWR construction time for 268 reactors in operation in 2010. Considering global experience there is a skewed distribution showing the most common average construction time interval between 6 and 7 years. Moreira et al (2013) considered several factors which influence construction schedule for PWRs. They identified that serial construction of standardised plants lead to the average construction time dropping to 4 years. Harris et al (2013) identified the uncertainties associated with the duration of pre-construction and construction phases having a significant impact on the upfront capital cost, causing the LCOE estimate for a NPP to have a wide range. Construction delays impact directly on the TCIC as a result of a lack of standardisation (Berthélemy & Escobar Rangel, 2015). Due to lengthy leads times, some major components such as the reactor vessel and steam generators are ordered at the pre-construction stage, to mitigate for potential delays further on in the construction stage (IAEA, 1985). The time associated with pre-construction and construction activities are dependent on the technology, construction experience and site-specific costs (DECC, 2013).

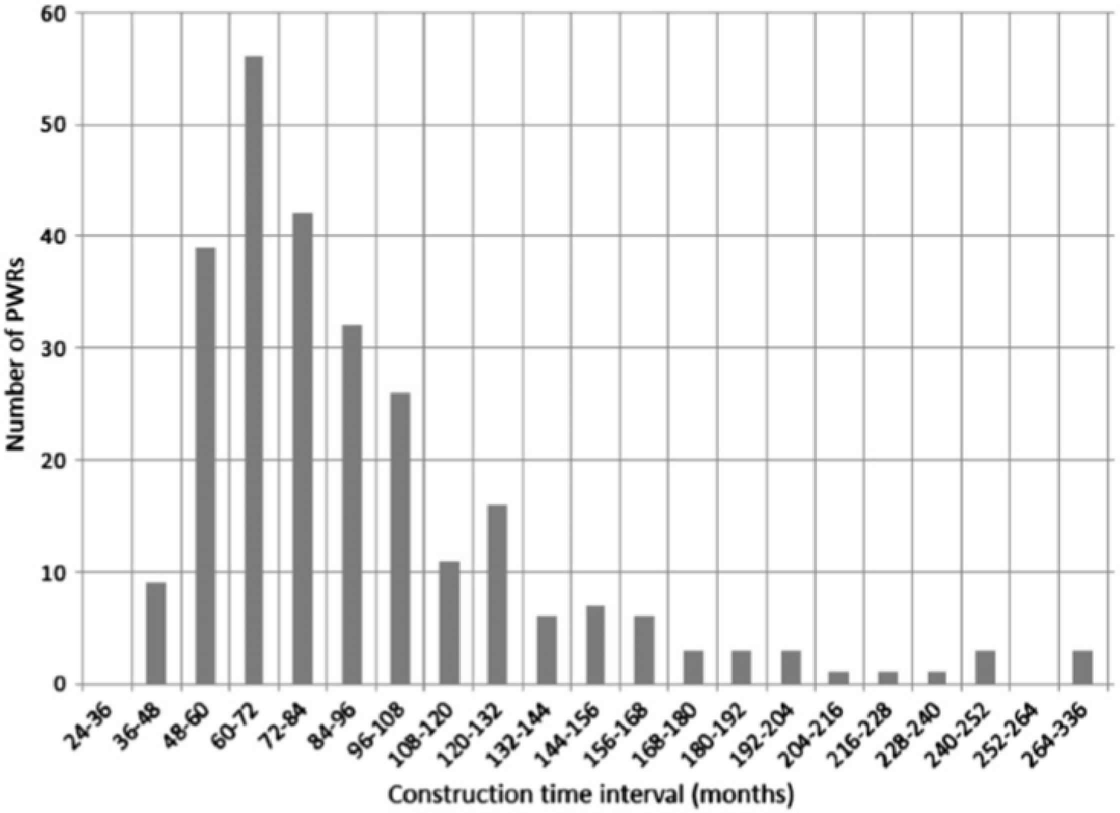


Figure 14: Number of PWRs in operation in 2010 distributed by construction time interval (IAEA, 2012)

NPPs are generally considered to have low, fixed operational costs compared with other baseload power generation technologies. Operational costs for NPPs are driven by fixed costs, rather than the fuel cost which has remained quite low relative to other types of power generation (Gross et al., 2010).

One of the primary differences between the US and French nuclear programs has been the operational performance. Boccard (2014) found that operational costs for the French reactor fleet was greater than originally estimated. The annual operations cost estimated by Grubler (2010) is 4 times less than that calculated by Boccard. This was primarily due to increased operational cost through a greater insurance premium and annual decommissioning provision. The expected lower cost of operating NPPs, compared with the actual experience was a major factor in the decision to close several US NPPs during the 1980s (Stucker, 1984).

O&M costs for NPPs are predominantly fixed, driven by onsite staffing and offsite technical support costs (Kessides, 2010). With high utilization and the large scale of the NPP, the fixed operating costs can be spread over the total lifetime electrical output (Thomas, 2005). Large NPPs must operate at as close to their stated electrical output capacity as possible in order to payback on the upfront cost of construction (Lévêque, 2013).

2.3.6.3 LCOE Sensitivities

LCOE estimates are most sensitive to the capital cost (Maronati et al., 2018). Construction cost escalation has been a significant issue in each generation of NPP build. Up-front investment costs are often the determinant of the chosen reactor design (Berthélemy & Escobar Rangel, 2015). In a liberalised market, the investment in nuclear power comprises of business risks (Kessides, 2010). which are influenced by:

- the demand for electricity and impact the supply of capital and labour;
- regulatory controls
- policy decisions that affect revenues, costs, and financing conditions;
- price and volume risks in the electricity market.

There is little consensus in literature as to whether economies of scale have been achieved in the nuclear industry to date, where construction projects are widely reported to be subject to severe delays and cost escalation. The experience of the nuclear industry has been to design and build ever larger capacity reactor units to achieve economies of scale. Increasing the size of NPPs has led to more complex build programmes. The limited experience in cost curves in NPPs show that cost for new builds is likely to increase in the future, i.e. they will suffer from negative learning (Neij, 2008). Contrastingly, having a large and systematic nuclear build programme has been shown to lower capital costs in France and South Korea (Lovering, Yip, & Nordhaus, 2016; MacKerron, 1992; Moreira et al., 2013). The findings of these studies suggest that countries with a more centralised regulatory, construction and operation environments were able to build PWRs more quickly.

2.3.7 Cost Drivers for SMRs

Placed within the expected and actual cost driver context for large NPPs described in Section 2.2.6, a review of the expected cost drivers for SMRs is presented in this section.

2.3.7.1 Construction Cost

SMRs may take advantage of the experience curve through construction experience at a far greater rate than larger, non-modular units as there are more opportunities for learning (Neij, 2008). The LCOE for an SMR, however, is generally considered to be higher primarily because of the smaller capacity of the reactor (Carelli et al., 2010).

The advantages of SMRs versus large NPPs are summarised here:

- **Modularisation**: allowing power plant systems to be fully factory-manufactured, assembled, and commissioned prior to being sent to site. “Modularity” can be defined as either a complete steam supply system module already loaded with fuel, a plant whose large components or modules are standard, and factory manufactured or an overall plant design comprising multiple small reactor units on a single site, deployed sequentially (Söderholm et al 2014). The reactor design is simplified and can be divided into different modules minimising site work to just assembly and testing.
- **Co-siting Economies**: several units can be built on the same site, sharing some fixed costs, enabling flexibility to meet demand requirements in the area and reducing costs through shared learning.

- **Learning factor**: Learning factors are obtainable through controlled factory processes and through the same construction team assembling the various units at the same site. Multiple units being produced for a single site, as well as achieving co-siting economies, there is also the potential to achieve economies of production.
- **Investment scalability**: The lower plant capacity is more readily adaptable to changing market conditions. With potentially shorter construction times, the investment timing of SMRs can be more flexible, with incremental capacity decisions reducing the risk of nuclear investment.
- **Lower cost of capital:** The reduced risk for investors in SMRs which may be more capable to match the new market conditions. There is also more potential for a utility to be able to self-finance the SMR construction project, and so have access to cheaper financing.

Shaw (1979) identified that the nuclear programme in the UK was a series of one-offs, prototype power plant builds. The construction of large reactors in a liberalized market is difficult to finance. Constructing a series of standardised large reactors requires even greater financing, potentially more than any utility is willing or able to produce. SMRs may provide a viable means of achieving mass standardisation.

Using the Gen IV code of accounts, a cost breakdown structure was used to determine the “target cost” estimates for the reactor capital, operations, and fuel cycle costs of an SMR (Shropshire, 2011), with values populated from previous SMR studies. SMR capital costs were shown to be lower when compared with LRs due to the simplified design, integrated power system, economies of production, reduced construction time, and easier method of financing. Fuel costs were identified as higher, primarily due to increased enrichment due to the extended refuelling cycles.

To evaluate the cost of an SMR scaling factors for economies of scale, learning, co-siting, financial and modularity & design factors were used to compare a construction cost of a large reactor with a SMR (Sultan & Kattab, 1995). Jain et al (2014) studied the sequential and concurrent investment strategy into SMRs identifying the flexibility in investment strategy with SMRs enable due to smaller size and potentially quicker build. A study was conducted to review the investment strategy in SMR units, sequentially or concurrently using a real option decision analysis method (Jain et al., 2014). This allowed a view of how an investing utility could strategically purchase modules or delay the purchase of modules due to considerations such as electricity price fluctuations, construction duration, and comparison with investment into large reactors.

When comparing the cost of a large nuclear reactor with an SMR it has been shown that when the cost of capital is high (and outweighs scaling advantages), a smaller reactor is cost competitive because it may be cheaper to finance a staggered series of smaller reactor units (Behrens, 1985). A “bottom-up” estimation of the construction costs for, what are described as, “deliberately small reactors” focussing on Light Water Reactor technology was conducted developing parametric relationships with equivalent larger reactors (Paparusso, 2012). This was followed up with a top-down review of costs, and a comparison made between the two methods. The influence from capital costs and financing rates are somewhat less for SMRs due to their reduced fraction of total costs.

2.3.7.2 O&M Cost

The capacity of the reactor is the main determinant of the annual revenue received for the electricity produced. During the operations phase, the plant owner will attempt to maintain a positive cash flow, to make the plant financially viable and to pay back on the initial investment as quickly as possible. Those reactors which operate less efficiently and below an expected capacity factor are open to market competition, particularly during times of cheap fossil fuel. In a climate where conventional, large capacity reactors are struggling to compete with other electricity generation technologies, the operating costs for SMRs could be a significant cost driver.

The expected O&M cost of SMRs is a higher proportion (50-60% higher for an SMR when compared with a large LWR) of the overall cost (Pannier & Skoda, 2014). The relatively high O&M costs are due to the predicted minimum staffing requirement to meet human health, safety, and security needs, but may also reflect higher fuel cycle costs (Shropshire, 2011). Carelli et al (2010) concluded that a site with four SMRs (335 MWe) would incur a greater O&M cost than a single 1340 MWe large reactor. Through the operational phase of the plant, there is an expectation that this cost will decrease due to improvements in fuel economy and through modifications to the plant. Certainly, there is evidence from the US (Koomey & Hultman, 2007) and French programme (Boccard, 2014). that operations cost have reduced as experience has increased, and efficiencies realised.

2.3.7.3 Decommissioning Cost

Xu et al (2012) describe the increasing importance of considering the end-of-life cost in estimates during the development of products. For NPPs the lengthy lifecycle makes the costs of disposal and decommissioning significantly smaller than upfront capital and operations. Locatelli & Mancini (2010) categorized the cost drivers within the decommissioning lifecycle phase of a “generic” large PWR and an equal capacity rating series of 4 International Reactor Innovative and Secure (IRIS) reactors. By building multiple units on the same site, they identified the potential cost reductions through learning and standardisation. The specific cost of decommissioning is seen to almost double when compared with the same output from a large reactor.

2.3.7.4 Summary of Expected Drivers

The findings from various SMR cost studies generally consider that SMRs will have a comparatively low absolute construction cost and that they can compete with large NPPs based on capital cost, and the reduced risk of financing the smaller construction project. The main gaps in SMR cost estimating identified in the systematic review carried out by Mignacca & Locatelli (2020) relate to the cost benefit analysis of modularising the power plant and the decommissioning phase.

In summary, the main driver of the whole-life cost of a NPP project is the construction cost. The uncertainty over this cost is influenced by a wider variety of internal and external factors, but with the development of advanced SMR technology other drivers related to operational costs could become similarly critical. Factors which are likely to drive the cost of the SMR are likely to be more influenced by the capacity factor and the costs from the fuel cycle and O&M.

2.4 SMR Cost Estimating Challenges

In this section the key challenges to cost estimating SMRs are summarised. Most SMR designs around the world are at the concept design development stage. Therefore, the perspective taken for this section on cost estimating challenges is that of the vendor developing a new SMR concept. From the review of literature several challenges have been identified relating to cost estimating and applied to SMRs, described in the following sub-sections.

To a degree each of the challenges identified are interrelated, such that the availability of data, the ability to validate estimates and the purpose of the estimate each has an influence on cost accuracy. For example, the applicability and availability of data depends upon the purpose of the estimate, which will then determine the validity of the estimate. The subsections that follow describe each of the identified challenges.

2.4.1 Challenge 1: Applicability/ Availability of Existing Data

The estimation of costs is driven by both predicted and actual experience of the performance of similar technology (Woodward, 1997). One of the main challenges associated with estimating the cost of SMRs is the application of reliable data to represent future costs. Actual SMR cost data is not available, nor are detailed cost estimates for the designs under development (Shropshire, 2011). The literature review has identified a variety of sources and methods used to estimate SMR costs ranging from large NPP data, expert elicitation, to simulation and modelling.

2.4.1.1 Existing NPP Data

The large nuclear reactor fleet in the US provide the richest data source for generation costs, with the most comprehensive analysis produced by Koomey and Hultman (2007). In their analysis, Koomey & Hultman obtained capital cost, construction duration and capacity information from the database produced by Komanoff (1981) and extrapolated to 2006 rates using operations costs, including fuel costs, together with thermal efficiencies derived from The Nuclear Energy Institute, US Energy Information Administration, and IAEA data sources. Komanoff’s database of capital cost data was based on utility records produced by the Energy Information Administration, converted to 1979 dollars.

Both the Grubler (2010) and Boccard (2014) studies relied upon data released by the French government showing actual data, via the Court of Audit. The OCC for nuclear reactors built in the UK, France and US have been analysed to try to identify the causes of cost escalation when comparing NPPs produced in the first generation (construction start 1966-67) versus later generations (construction start 1974-77) (MacKerron, 1992). Moreira et al (2013) use the construction time to represent cost escalation of PWRs built in the 30 years before 2012.

Actual data regarding construction and operational costs are difficult to obtain, and the methods used to record actuals in different countries and different times is dependent on the accounting procedure employed. The data is subject to different methods of accounting, use of financial and inflation cost indices, and other adjustments. Analysing and comparing performance using the different sources of data available will be subject to error due to the number of assumptions needed to normalise the data.

One method for estimating novel technologies is to verify the assumptions in new estimates with historical data of costs for a similar technology (Roy, 2003). Carelli (2010) estimated the LCOE for an International Atomic Energy Agency reference design SMR using an analogy type estimate from large reactor data. Using bottom-up estimation with parametric cost estimating relationships to scale down a large NPP, Paparusso (2012) showed that SMR costs are less subject to capital costs. For an SMR, the comparative parameters usually include economies of learning, co-siting, and degree of modularity of the design relative to a large reactor (Sultan & Kattab, 1995).

2.4.1.2 Simulation and Modelling

Models can be used to understand the future cost of energy generation technologies using experience curves based on historical data (Neij, 2008). Historical experience curves are reliant on a standardised product to analyse the associated cost reductions. Scenario analysis is often used to understand the comparative energy costs with varying costs of wholesale electricity or other, technology specific costs (Kennedy, 2007). For future wholesale electricity prices, the University of Chicago (2004) study considered different future electricity demand scenarios, all based on the predictions of electricity market models.

There is great uncertainty as to the level of standardisation achieved historically by the nuclear industry, with potentially only France able to claim a level of learning from doing (Boccard, 2014). Different NPPs technologies, specific site related conditions, production methods, construction companies, operating strategies, operating environment and financing all contribute to the reduction in NPP product standardisation.

2.4.1.3 Expert Elicitation

Where historical data is not considered representative of future designs, or in situations where there is a lack of available historic data, expert elicitation is identified as a reasonable method of understanding future costs (Levi & Pollitt, 2015). For example, Anadón et al (2013) used expert elicitation to obtain values for the overnight construction cost for a SMR, using this to form an input into the LCOE calculation. Database cost estimates are often supplemented with expert judgement to make the data fit the new scenario (Roy, 2003).

2.4.1.4 Problems with Data Sources

There is a lack of consistent treatment of cost data and financial reporting structure. Actual data regarding construction and operational costs are also difficult to obtain, making the consistent recording, analysing and comparing of cost performance a challenge. The variability is in part due to a lack of available data or granularity of data. It is also the result of the long timescales and lack of experience in construction of new NPPs, leading to great uncertainty in the estimates produced. Reviews of historical experience, therefore, tend to rely on non-financial data, such as construction time, to interpret the likely cost of capital. The extent to which causality can be established between construction time and construction schedule is questionable. Different studies use different values for the construction time, based on the historical trend for construction around the world, reactor vendor marketing information, or based on a range of possible scenarios. Other parameters should be considered such as the reactor type, power output, and average availability over time.

Even when the LCOE estimate is based on statistically valid historical data from a nuclear build programme, there is still a high level of uncertainty with respect to the future cost of construction, operation and decommissioning. Selecting the most relevant data for estimating the cost of SMRs is dependent on many assumptions. Determining which assumptions are representative of the SMR relies on data that may not be statistically valid and may therefore be highly uncertain. An understanding of the sources of data and assumptions used to calculate the estimate is required to assess the reliability of results. Due to the large number of direct and external influencing variables, historical experience may not be a valid benchmark to identify the future LCOE of the SMR.

2.4.2 Challenge 2: Validating Estimates

Once an estimate has been generated the reliability of that estimate needs to be understood. Gross et al (2010) identified that, for emerging technologies, policymakers have poor cost information upon which to base decisions. The cost estimates generated by the technology vendor may be perceived as being subject to optimism bias, downplaying the risks associated with new or unproven technology. The value of using the LCOE as an estimating tool and as a basis for decision making is called in to question where the data cannot be validated. With new, innovative products for which there is not data validity the cost competitiveness of SMRs is uncertain. One way of establishing the reliability of the estimate would be to validate it. The ability to validate the NPP estimate is severely hampered by the very long lifecycle phases experienced.

2.4.3 Challenge 3: Estimate Scope and Purpose

Rush & Roy (2001) defined a cost estimate as a commercial business process which provides a specified customer with a cost for a product or service. They proposed that this differed from cost engineering which is defined as the generation of cost information to support design activities. One key challenge is associated with how a design team can use the LCOE to support design decisions which are likely to influence cost. The intent of the cost estimate requires a viewpoint.

The LCOE for NPPs is often estimated in the literature from the perspective of an owner, utility operator, or policy maker. The reviewed articles refer to a range of costs from different points of view, for example from the point of view of the Government, the cost to the electricity consumer, the environment, and potential investors. From all perspectives minimising the overall LCOE appears to be the primary goal. The vendor would, therefore, also have the goal to minimise the LCOE through design of the SMR. At policy level, variables used for producing an LCOE will not be greatly influenced by the type of reactor being built (other than assumptions around the capacity of the plant).

2.4.4 Challenge 4: Estimate Uncertainty

Risk and uncertainty is identified as a significant disadvantage associated with the investment decision for NPPs when compared with other forms of power generation (Riesz et al, 2017). The lifecycle of a NPP is lengthy, and subject to a number of sources of uncertainty at each stage.

As previously stated, the OCC is the biggest driver of the LCOE. The OCC is also considered the biggest driver of cost uncertainty, and the area at most risk of cost increase, influenced by the geographic location, the reactor type being analysed, and the technological maturity of the design (Anadón et al., 2013).

2.5 Early Design Stage Cost Estimates

Considered over the entire product lifecycle, it is the design and development phase which has the greatest influence on cost (Layer et al, 2002). Figure 15 illustrates how the decisions made at the early design stage account for up to 80% of the production costs incurred later in the product lifecycle (Eversheim, Neuhausen, & Sesterhenn, 1998). In later stages of the product development process there are significant penalties (time and cost increases) which result from the need to modify the product or production processes because of changes to earlier decisions (Sheldon, 1990). The concept design stage provides the design team with the most opportunity to make decisions which will lead to the achievement of total product cost requirements (Cross, 2004). Incorporating cost as a decision tool effectively changes the philosophy behind cost estimating, becoming a requirement as part of the design process rather than the result of a design activity (Thurston & Essington, 1993).

Layer et al (2010) identified that for innovative products and technologies there is a limit to the availability, and usefulness of existing data. Approaches to early cost estimating involve either high level qualitative approaches or modelling and implementing techniques to resolve problems associated with a lack of available data. A key driver to the implementation of a method or model is time (and the limited resources available).

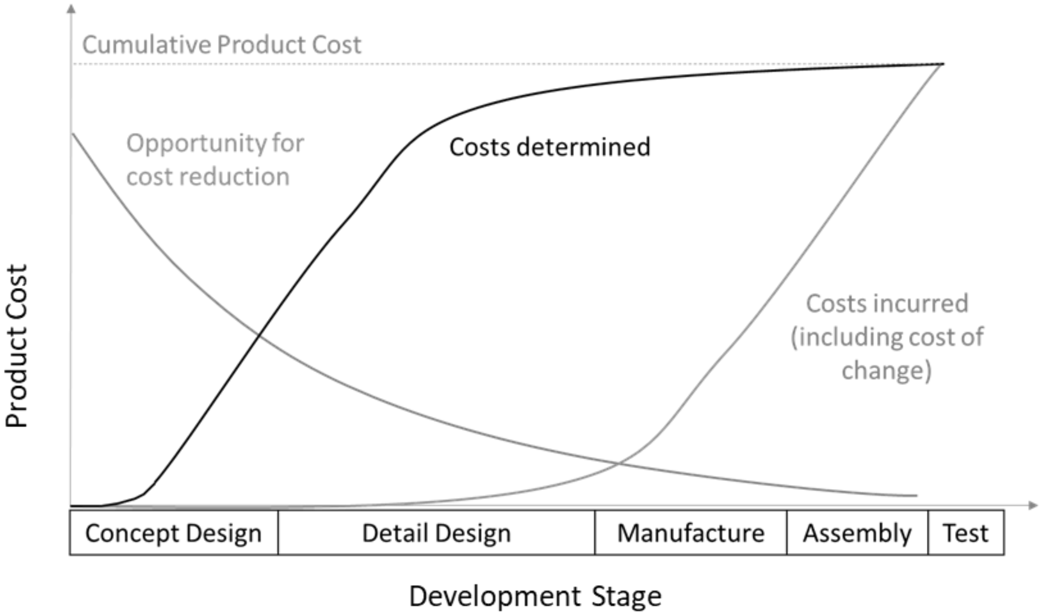


Figure 15: Early design decisions determine costs incurred later in product lifecycle adapted from Layer et al (2002)

In this section a brief overview of the structured design process is first presented. The purpose of cost estimates developed at the early design stage is then reviewed. The cost estimating techniques applied at the early design stage and the determinants of technique selection are reviewed. Finally, a critical assessment of the estimating approaches available and their limitations are discussed.

2.5.1 The Design Development Process

Figure 16 presents a standard process recognised in industry known as the Stage-Gate® system (Cooper, 2001). The process involves a series of gated stages where the gate acts as a decision point. The gate is either opened to the next stage indicating that the requirements to proceed have been sufficiently presented, the gate is temporarily closed where the design team require additional work to be carried out to sufficiently meet requirements, or the gate is closed, and the project no longer proceeds.

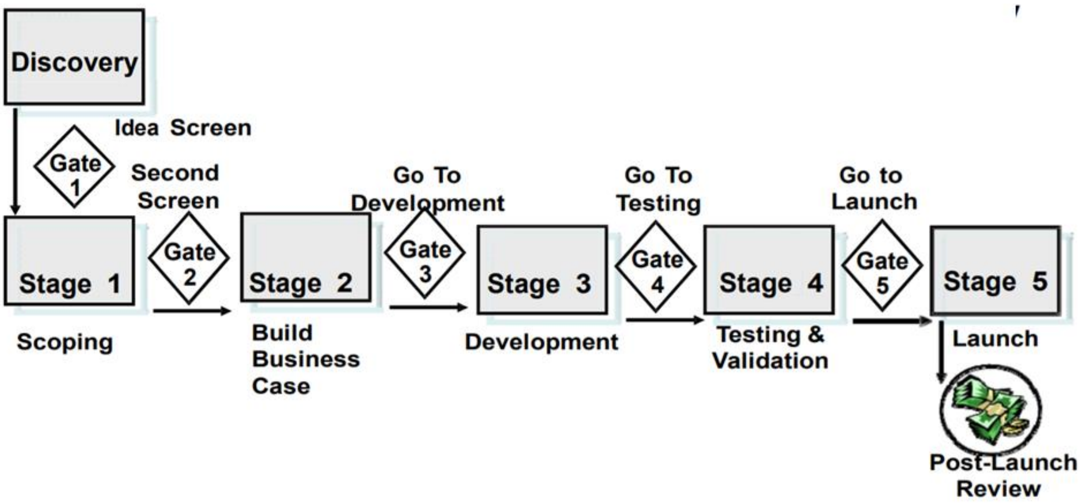


Figure 16: Stage-Gate® process for new product development (R. Cooper, 2008)

Within each stage gate the design process can be further broken down into 4 steps (Cross, 2000 pg.30):

1. Exploration – At the concept stage this is an exploration of an ill-defined problem area
2. Generation – Of possible solutions to the problems identified
3. Evaluation – Depending on the results of the evaluation, the next step may be to move to communication, or feedback the findings to further generate ideas.
4. Communication – Satisfactory solution to the initial problem area identified

In the decision-making process the selection of a particular option is carried out with as much rational as possible related to a consideration of the design attributes or objectives of the design solution. The gated process should lead to a reduction in the uncertainties as the design matures progressively through each stage (R. Cooper, 2008). As the design matures the requirements become defined more robustly, and the risks identified earlier in the development process are either retired or realised. The front end of NPD is often described as fuzzy given that there is uncertainty and rapid evolution of unstructured information used to contribute to design development and decision making (Eckert & Clarkson, 2005). The information may limit rational to intuition, past experience or an arbitrary selection process (Cross, 2004).

2.5.2 Purpose of Early Design Cost Estimating

At the early concept design stage the cost estimate is based on limited information and is generated in a relatively short amount of time (Oberlender & Trost, 2001). Gardner et al (2016) identified that the objective of early cost estimates is not necessarily to increase the accuracy of understanding the final cost of a potential product or project. There are likely to be diminishing returns related to the amount of effort and expense spent on conducting the conceptual model, and the available information to reduce uncertainty in the estimate. The purpose of a cost estimate changes from the initial scoping phase to the detailed designed phase. For the commercial viability of a product development program affordability is a key metric that should be assessed regularly throughout the development program.

2.5.3 Overview of Available Cost Estimating Techniques

Cost estimating techniques can be categorised into qualitative and quantitative methods (Niazi et al, 2006). Qualitative methods are those which utilise statistically valid or data from similar products to understand the cost of the new product. Where empirical data is not available, expert judgement is used to identify and allocate costs. Quantitative methods rely on a detailed understanding of the product design, features and the manufacturing process. Figure 17 shows the available techniques to cost estimating at different stages of product lifecycle (NASA, 2015). Initially the cost estimate generated may be based on a top-down approach incorporating parametric or analogy techniques.

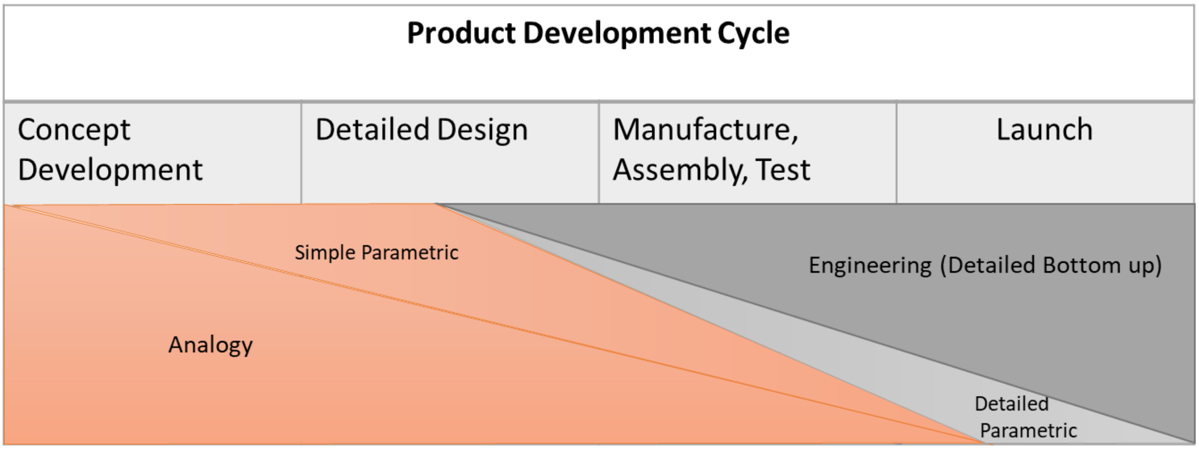


Figure 17: Cost estimating techniques at different stages of product development adapted from NASA (2015)

Niazi et al (2006) suggest that early in the design phase, with little information available, qualitative techniques should be applied to understand the rough order magnitude of costs and to inform design decisions (Figure 18). Analogy is often applied early in the design process where little or no data is available for the system. Estimating by analogy uses cost data for a similar or comparable system and makes suitable adjustments representative of differences with the new system. The data is either directly compared to extrapolated relationships or adjusted to generate specific relationships.

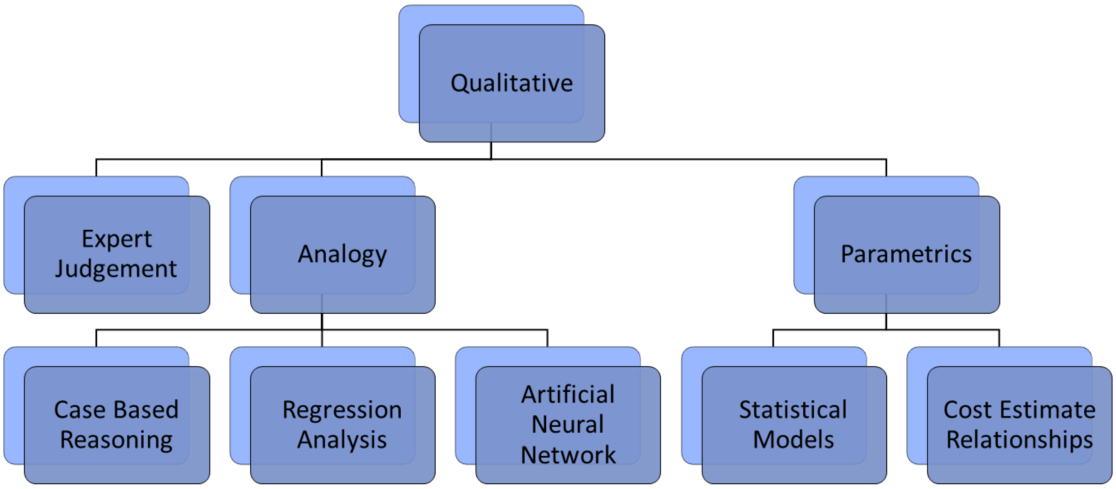


Figure 18: Cost estimating techniques available at the early design stage adapted from Niazi et al (2006)

Case Based Reasoning (CBR) is an example of analogy. CBR uses similar characteristics or requirements between existing products for which cost data is available and the product being developed, to adapt existing data to represent the new solution (Duverlie & Castelain, 1999). Figure 19 presents the basic steps for the CBR approach. The method employed by Ahiaga-Dagbui & Smith (2014) utilised existing knowledge accumulated through data mining techniques to identify correlations or relationships between variables in a representative "reference class."

Figure 19: Case Based Reasoning approach to cost estimating

Eversheim et al (1998) used early design information to estimate the manufacturing cost for a product. The “cost module” was used in conjunction with a Quality Function Deployment (QFD) procedure for a design to cost methodology. Assumptions were made regarding the people (resources), parts and processes required to build up a picture of the cost. For more innovative products and production methods, understanding of each of these 3 cost components is subjective unless significant resources are dedicated to obtaining the required information.

The intention of the statistical analysis of past performance is to develop a model of future expected performance (Attalla & Hegazy, 2003). Multi Regression Analysis (MRA) and Artificial Neural Network (ANN) are forms of predictive cost modelling based on previous performance. Both MRA and ANN require data from previous projects, either in the form of a database (Gunduz & Sahin, 2015) or through the use of data mining (Ahiaga-Dagbui & Smith, 2014).

A parametric cost estimate uses historical project data to develop cost estimating relationships between the physical characteristics of a project and the final cost (Dysert, 2001)**.** Parametric estimating requires a statistically proven set of empirical relationships between characteristics of the product and costs as a basis to estimate the new product costs (Geiger & Dilts, 1996). The data collection and analysis stages require a significant commitment of resources, to obtain and to process. The analysis of data results in the identification of key cost drivers (in some cases the use of hypothesis or expert opinion can identify the likely cost drivers initially). Duverlie & Castelain (1999) identified three approaches to parametric cost estimating:

1. Cost Estimation Relationships (CERs) – simple mathematical relationship, connecting the cost of a product to a set of physical parameters.
2. The method of scales – the most influential parameter is evaluated and used to determine the CER, relying on the assumption of a linear relationship between the parameter and cost.
3. Statistical Models – generating statistically valid mathematical models for each influencing variable.

The use of CERs can also help to reduce the time required to produce early cost estimates. Parametric cost estimates can be applied at the early design phase to identify the main contributors to cost, although they do not identify the cost drivers. Mileham et al (1993) developed a parametric estimating technique which used early concept design information with minimal information regarding the final product. The method is highly reliant on a detailed database of cost information, as well as expert input to understand the likely cost drivers associated with a process. The statistical analysis process used to generate the CER must be validated, something that is usually carried out by subject matter experts (Rush & Roy, 2001).

According to Duverlie & Castelain (1999) the use of one estimating technique in the design phase is not enough to justify the results, and that due to speed of process and the lack of complete information, the two most suitable methods are analogical and parametric. Niazi et al (2006) presented a selection hierarchy based on the availability of data for the cost estimate at the early design stage (Figure 20). Understanding the scope of product costs at the design stage defines the type of cost estimate to be used. Some of the key measures that influence method selection include the relative size of the project, computational aids and skills, user understanding of the technique being applied and the availability of useful data (Boussabaine & Kirkham, 2004). The limit in available techniques present several challenges for early concept design stage cost estimating.

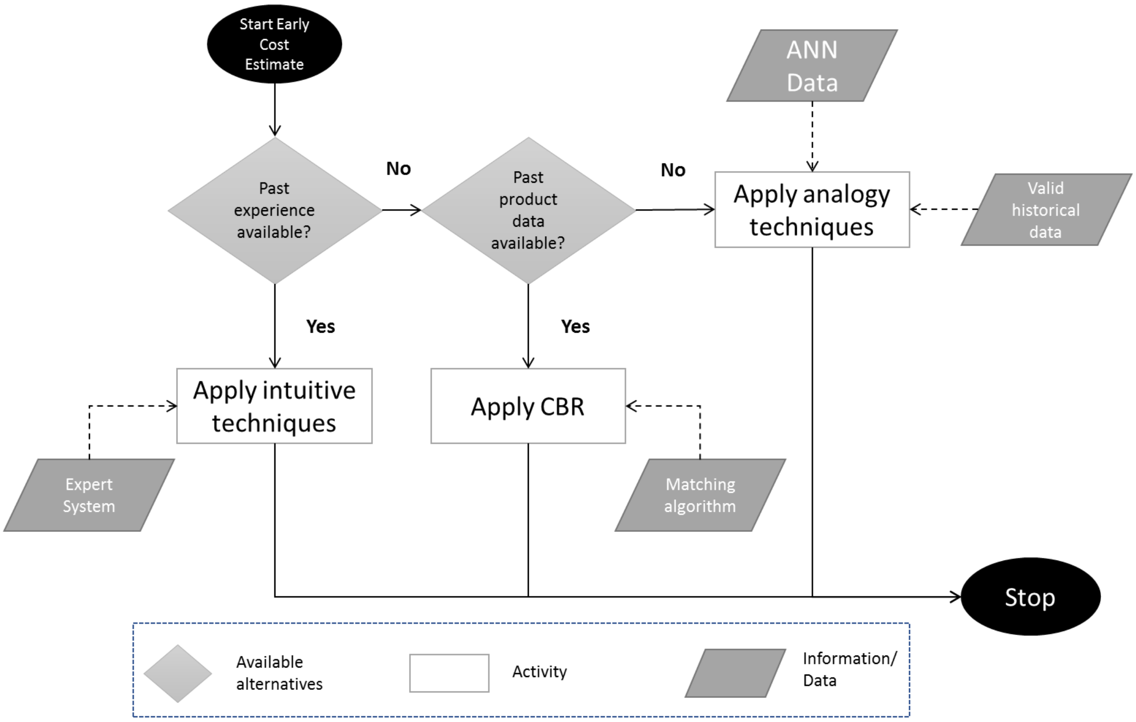


Figure 20: Selecting the right cost estimating technique for the early concept design stage adapted from Niazi et al (2006)

2.5.4 Challenges with Early Design Stage Cost Estimating

Several challenges with early cost estimating have been identified and divided into four categories (Figure 21). Despite the wide number of tools and methods for estimating cost, there will inevitably be a gap in the availability and accuracy of information to support design decisions (Geiger & Dilts, 1996). The accuracy of cost estimates is generally understood to be a function of the level of design detail available (Gardner et al., 2016).

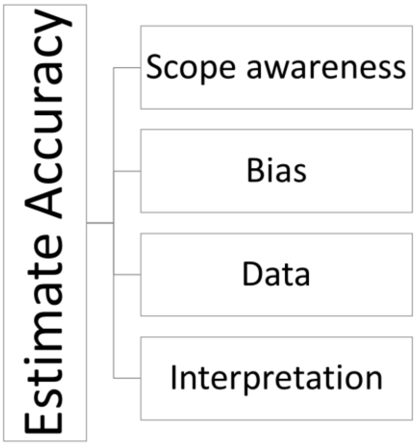


Figure 21: Challenges associated with early concept design stage cost estimates

2.5.4.1 Scope Awareness

Scope awareness refers to the fundamental understanding of what it is that is being estimated (Ahiaga-Dagbui & Smith, 2014). The suggestion is that underestimation should not necessarily be seen as a failure if the intended benefits are delivered. The intended benefit of an early estimate is not then to deliver an accurate cost estimate, but to provide enough information for the required purpose.

2.5.4.2 Data

Detailed cost information is generally not available until the product details are fixed, late in the design process. It can be very costly to change the design later in the development cycle (Elgh & Cederfeldt, 2007). One way of improving confidence in a cost estimate is to provide supporting information to show its validity. Cost models use different methods for validation. Gunduz & Sahin (2015) use a sample of the collected data on previous projects to determine the percentage difference and the mean absolute percentage error between the actual cost and the modelled cost. The validity of these estimates is not only a function of the accuracy of the recording of actual costs from previous projects, but also how closely those past projects represent the new project being undertaken. The lack of historical data for high value, small-batch innovative products justifies the use of detailed financial risk modelling techniques during the design phase (Duffey & Dorp, 1998).

2.5.4.3 Interpretation

As well as academic literature on methods of cost estimating, studies have surveyed how these methods have been used in practice within industry (Akintoye & Fitzgerald, 2000). Design teams have struggled to establish effective tools to support decision rationale. For decision making purposes a point estimate should be provided with an associated risk and uncertainty analysis to show the range of possible future values (Peterman & Anderson, 1999). A lack of sufficient time to carry out cost estimating is a significant cause of poor estimation (Akintoye & Fitzgerald, 2000). The interpretation of such estimates and the resulting decisions could also be a factor influencing the deviation of actual estimates from predicted values. The interpretation of cost estimating information is discussed further in Chapter 5.

2.6 Cost Uncertainty Analysis at the Early Design Stage

An inaccurate estimate of product cost can result in unforeseen cost expenditure (Asiedu & Gu, 1998). Quantifying and assessing the uncertainty associated with a cost estimate is an important factor to consider in decision making (Xu et al., 2012). Cost uncertainty analysis allows the decision maker to take into consideration the level of confidence in the estimate. In this section cost uncertainty analysis at the early design stage is defined. A review of literature is used to categorise sources of cost uncertainty and to describe the drivers of uncertainty at the early design stage.

2.6.1 Definition of Cost Uncertainty Analysis

Estimate uncertainty can be defined as the “degree to which the final cost outcome for a given project could vary from the estimated cost” (AACE, 2011). Uncertainty is inherent at the early design phase, as deviation from the actual cost cannot be truly known until the final cost has been realised. “Mature cost estimates require that the design is fundamentally complete" (Ashley et al., 2013). Early design decisions are made based on imperfect information regarding the actual outcome at a future point in time (Brüggen & Luft, 2016). Cost uncertainty analysis is used to understand the range of possible outcomes based on the impact of cost, schedule and technical influences on the system (CSRUH, 2014). The range of possible final costs presented in an uncertainty analysis is defined as the level of confidence in the estimate generated (Peterman & Anderson, 1999).

2.6.2 Sources of Uncertainty

De Weck, Eckert, & Clarkson (2007) divide the sources of uncertainty into two categories: those which can be influenced by the designer (endogenous) and those which cannot be influenced by the designer (exogenous). Endogenous uncertainties are not always independent of the exogenous uncertainties and vice versa. For example, design decisions are influenced by strategic business decisions, and the constraints placed upon the designer are heavily influenced by the strategic view on the market for the product, key government policy, and changing regulatory requirements.

Figure 22 shows how uncertainty can be divided into two types based on its reducibility (epistemic) or irreducibility (aleatory), and several possible methods of quantifying each type. Aleatory uncertainty is used to describe all sources of uncertainty attributed to randomness including stochastic and extrinsic uncertainties. Aleatory uncertainty thus focuses more on describing the unpredictability of possible future outcomes, i.e. risk. These are irreducible through the direct actions of the design team, although risk analysis can be used to mitigate the probability of occurrence or impact on cost.

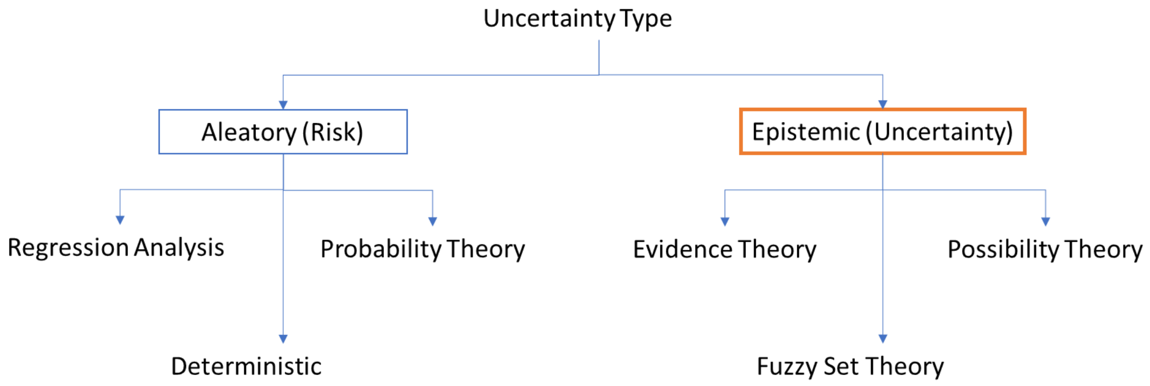


Figure 22: Quantifying sources of uncertainty (adapted Xu et al., 2012)

Cost estimate uncertainty is generally understood to be a function of the level of design detail available (Gardner et al, 2016) which is influenced by the availability of data (GAO, 2009). Epistemic Uncertainty contributes to a lack of knowledge or trust in the knowledge presented (Wynn, Grebici, & Clarkson, 2011). These sources of uncertainty are greatest when the available knowledge is either limited in quantity or is of limited reliability (Yoe, 2011). Epistemic uncertainty can be reduced through the actions of the organisation in acquiring new knowledge (Unal et al, 2011).

2.6.3 Approaches to Modelling Cost Uncertainty

Uncertainty ranges can be defined both deterministically and probabilistically, depending on the level of detailed information available, the cost estimating technique used, and the resources available to carry out the analysis. At the early concept phase the cost estimating techniques used are limited to those generated subjectively or by analogy using power laws, exponential, or factorial estimating (Tsagkari et al., 2016). This inherently limits the type of uncertainty analysis which can be carried out.

Understanding the accuracy of a cost estimate can be described as the need to define how close the model reflects reality (El-Haram, Marenjak, & Horner, 2002). If a model does not provide a sufficiently accurate representation of the situation it is simulating, then it can be said to be uncertain. The adequate selection of data in a model may be the result of selecting benchmark data about the behavior of the system through qualitative analysis. The data upon which the model is based may not be valid, either due to changing conditions or because the data was insufficient to develop an accurate model.

The estimate uncertainty is derived either from analysis of historical data, subjectively through expert elicitation, or by applying generic ranges. Xu et al (2011) noted from an analysis of cost estimating literature that little research has focused on the integration and application of uncertainty modelling into the overall process of cost risk reduction. Much of the literature focuses on the uncertainty modelling techniques themselves, rather than on the application and management of uncertainty in, for example, design decision making. Additionally, there is a need to understand how the cost information is interpreted by the design team, and how the information is used to make decisions. Poor interpretation of the data may lead to the identification of the wrong cost drivers and the generation of incorrect CERs. Even when the availability of data allows a degree of engineering “Bottom-up” analysis to be carried out the hierarchical product breakdown structure (PBS) may oversimplify the relationships between different cost elements. At the early design stage, the limited availability of information may cause the omission of important dependencies between cost elements, limiting the quality and accuracy achievable with the model.

Gardner et al (2016) identified that the objective of early cost estimates is not necessarily to increase the accuracy of understanding the final cost of a potential product or project. There are likely to be diminishing returns related to the amount of effort and expense spent on conducting the conceptual model, and the available information to reduce uncertainty in the estimate.

2.6.4 Uncertainty Propagation

Uncertainty at the early design stage arises, primarily, from a lack of knowledge associated with how a proposed solution will achieve the design requirements. Due to some areas of the design being developed at a greater rate than other areas the requirements of the more developed systems will be better understood than other areas. Uncertainty in these areas is likely to reduce as a result. However, the uncertainty associated with other, less mature areas of the design could be significant. Dependent areas of the design which are not matured at the same rate could lead to unforeseen (and costly) design changes later in the development programme.

Clemen et al (2000) states that the final probability distribution of interest may be impacted by the level of dependency between uncertain variables. A significant problem with cost uncertainty analysis at the early concept phase is the lack of a method to identify and quantify the dependencies between various components in the PBS, and how cost uncertainty propagates from component level to total product cost. Dependencies on cost uncertainty are identified from experts, but purely using cost as a metric. The experts at the early design phase, namely engineers, designers, and technical and commercial analysts, may not have a background in cost estimating, but cost uncertainty needs to be considered as part of the design development process. The subjective nature of cost uncertainty analysis makes it highly susceptible to bias. A knowledge of the interactions between components and sub-systems is required to understand the impact of decisions on the overall uncertainty range. Smaller efforts may then be required to improve the accuracy level of the estimate, limiting the need for more extensive design effort (which may be subject to cost from change later in the design process).

There is a need to establish the overall cost uncertainty range based on quantifying each individual component cost uncertainty metric in the PBS, which can potentially be achieved by establishing the propagation of cost uncertainty to the top level of the PBS. Van der Gaag et al (1999) proposed a probability elicitation method which involved transcribing probabilities for example, presenting conditional probabilities as fragments of text and using scale with both numerical and verbal anchors for marking assessments from domain experts, with an intention to elicit many probabilities in little time. Zimmermann et al (2017) attempts to bridge the gap between systems theory and industrial practice, describing an approach to design a system under uncertainty by supporting the V-model approach to design. They do this by identifying dependencies on information between parts of the system, and quantifying this by looking at how it propagates.

Kishk et al (2003) proposed a procedure for combining the uncertainties calculated via an understanding of how the individual input uncertainty is calculated. The method incorporated whole life cost considerations. Such an approach becomes onerous for any detailed Work Breakdown Structure (WBS) level. However, it can be applied in a form at the very early design phase, where little detail is available, by applying individual probability distributions to the high impact components on a Product Breakdown Structure (PBS), while applying a general probability distribution to the rest of the PBS. Though this method still does not address the interdependencies between sources of uncertainty.

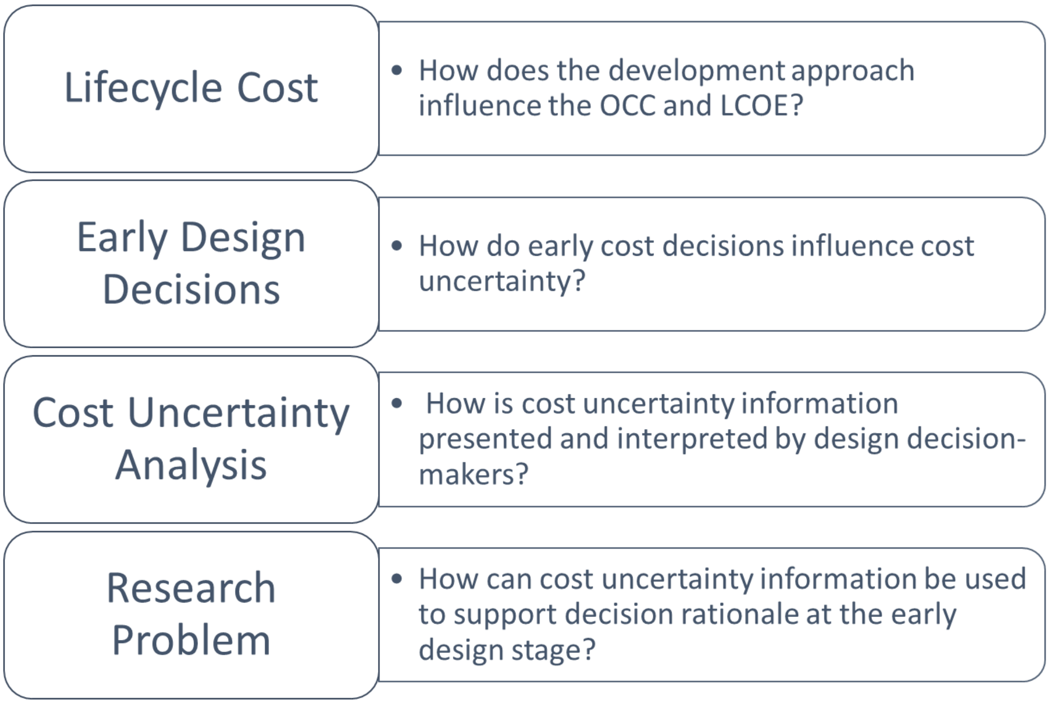
2.6.5 Early Cost Estimate Uncertainty Drivers

During the design phase there is significant uncertainty influenced by the completeness, accuracy, consistency, and quality of the measurements used (de Weck et al., 2007). Information quality is identified as a key factor influencing the accuracy of a cost estimate. Estimate accuracy is dependent on the requirements for the model, and the availability of data to base the cost model on. The accuracy of information is dependent on the reliability (statistical confidence), availability of data and the relevance of the information (the degree of similarity between defining properties of this product and existing or previous products) (NASA, 2015).

Both the AACE and ASTM have developed a classification system for different types of cost estimate. AACE (2011) have mapped the cost estimates against the maturity of a standard project scope defined as those firms involved with the manufacture and production of chemicals, petrochemicals, and hydrocarbon processing. The early stages of product development may lead to significant uncertainty where technology is selected that is unproven or is not at a sufficiently mature stage for the application (NASA, 2015). Changes in procurement approaches, design specifications and manufacturing processes all relate to the risk of employing less mature technology.

2.7 Research Challenges

Several areas of literature associated with cost estimating for NPPs have been reviewed in this chapter, each presenting different challenges which require further investigation. Figure 23 shows how the research problem has been identified through analysis of the existing literature. A summary of the key research gaps identified through the literature review are presented in this section. The research gap this thesis investigates is then presented.


Lifecycle Cost

- How does the development approach influence the OCC and LCOE?

Early Design Decisions

- How do early cost decisions influence cost uncertainty?

Cost Uncertainty Analysis

- How is cost uncertainty information presented and interpreted by design decision-makers?

Research Problem

- How can cost uncertainty information be used to support decision rationale at the early design stage?

Figure 23: Arriving at the research problem

The LCOE is a commonly used investment and policy decision support metric. The lack of a standardised approach to implementing the LCOE render direct comparisons across different studies difficult to validate. Much of the existing literature, therefore, focuses on the economics of NPPs in comparison with other power generation technology. The limitations associated with the LCOE require further investigation, though this is outside the scope of the research presented in this thesis. There is little research, however, into the influence which the development phase of a NPP has on the OCC and the LCOE metrics.

Determining the accuracy of an estimate can be subjective and is generally evaluated on a case by case basis. The point estimate generated at the early concept design phase is based on many assumptions, considering a variety of scenarios. As a result, the estimate is subject to both epistemic and aleatory uncertainty. Historical or analogy-based data is used to provide a verification of the expert judgement analysis. However, these estimates are largely driven by cost uncertainty, and are subjective in their analysis. The innovative nature of the SMR and the lengthy lifecycle of a NPP could make using historical data as the basis of cost estimates difficult and possibly erroneous.

The literature review also identified how early design decisions have a significant influence on the overall LCC of a product. Significant research exists in the field of early design stage cost estimating. Established methods for costing estimating are widely used in industry. Much of the existing literature related to cost estimating focuses on better data acquisition and utilisation, to obtain a more accurate or precise representation of the final product cost. Research has centred on improving the precision of the estimate involving the generation of data, improving estimating techniques or increasing the amount of information available. There is less focus, however, on how early cost uncertainty information is presented and interpreted by the customer of the estimate at the early design stage.

2.8 Next Steps

The research will investigate how early concept development stage cost information can support the design team decision rationale to increase confidence in the cost estimate. Early design stage cost estimates are subject to inherent epistemic uncertainty. This uncertainty is reducible through the collection and interpretation of new information. The key challenge which frames the research focus of this thesis is around cost estimate uncertainty and its application to decision rationale for the SMR.

3 Research Methods

3.1 Chapter Overview

In Chapters 1 and 2 the “why” and “what” questions in relation to the research problem have been discussed. This chapter describes the research methods used to meet the aim and objectives, aligning with the research gap identified within the industrial context. Figure 24 illustrates this chapter as the final part of the preliminary section.

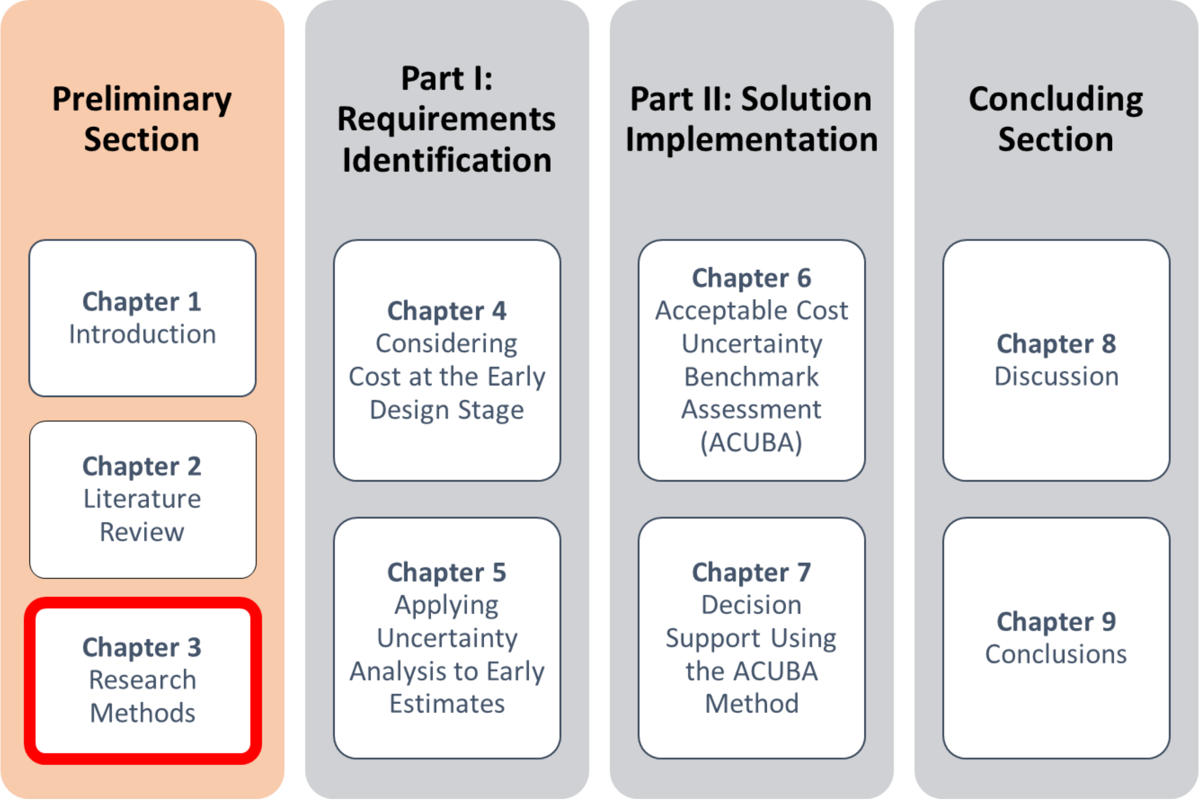


Figure 24: Research methods in the context of the thesis

The methodological perspective is discussed in Section 3.2. Scoping is critical to forming the initial research question, to set the context for the research and to formalise the focus of the study (Remenyi, 1998). The scope of the research is presented within the constraints of the industrial context. Section 3.3 then presents the research strategy, considering both the research gap and the industrial problem that the research is attempting to solve. Section 3.4 provides an overview of the selected research methods used to achieve the research objectives. The data collection and analysis techniques used are described in Section 3.5. The validity of findings based on the research methods employed are discussed in Section 3.6. The ethical considerations of the methods used in the research are summarised in Section 3.7. Finally, a summary overview of the research approach and the structure of this thesis is presented in Section 3.8.

3.2 Research Methodology

A methodology is a way of structuring the way research methods are adopted and are related to an identified problem (Sapsford and Jupp, 2006). An appropriate methodology is required that will provide a robust and rigorous research approach to investigate a possible solution to the identified research problem. In this section the epistemological and ontological stand point of the research is described, informing the strategy of inquiry described in Section 3.3.

3.2.1 Epistemology

Epistemology is a perspective of the nature of knowledge taken by the researcher (Gray, 2009). Adopting a philosophical view for the research informs the adequacy of the knowledge to provide insight into the problem being investigated (Creswell, 2009). Several epistemological positions are described in this section, before the standpoint of this research is presented.

3.2.1.1 Positivistic

Positivism is the traditional view of scientific inquiry in research, identifying the reality of the world being that which can be sensed and, therefore, measured (Sapsford and Jupp, 2006). Forming this view of reality allows the researcher to take an empirical approach to inquiry using scientific observation to logically develop principles (Gray, 2009). The notion of an underlying philosophical truth suggests an absolute and deterministic reality that already exists (Gray, 2009). Positivism emphasises the individual as the sole creator of his or her destiny and the binary notion of self/other is reinforced (Cherryholmes, 1992). The research approach uses quantitative measuring techniques to produce rigorous scientific analysis to identify and verify the nature of the problem (Sapsford and Jupp, 2006).

3.2.1.2 Constructivism

The constructivist attempts to represent the system through modelling or identifying a frame of reference based on historical and social structure (Sapsford and Jupp, 2006). The research is not purely a social construct. The reality of the context is alterable not just through perception or perspective of the individuals engaged within the problem or their contextual experience. Interpretivism is considered similar to constructivism in that, for interpretivists, truth and meaning is created through identifying where interactions occur (Gray, 2009). Even if different subjects are investigating the same phenomenon, they can discover different realities.

3.2.1.3 Interactionist

The interactionist ascribes meaning to particular actions and situations involving social links from multiple perspectives (Sapsford and Jupp, 2006). The interactionist approach requires an awareness of the influence which direct contact could have on the results of the research. Interactionist research attempts to understand the meaning or actions of an observed system while minimising reactive effects of the research procedure on it (Gray, 2009). A view of the social world as a product of the interacting meaning systems and actions of people and groups. Interactionist research is situation-specific, modifies the natural situation and, therefore, minimises the amount of imposed structure.

3.2.1.4 Pragmatic Approach

A pragmatic approach is taken in this research combining elements of the constructivist and interactionist approaches. A Pragmatic approach allows the researcher to implement a variety of quantitative and qualitative methods that may be required to investigate phenomenon, which are outside the purely empirical captured by positivists (Gray, 2009). The mixture of industrial setting and theoretical basis necessitates an approach which attempts to construct a view of the problem from the perspective of those involved in the system. The person and the social context act as co-constructors of reality (Cherryholmes, 1992). The applied nature of the research and the level of interaction with the “real-world” promotes a pragmatic approach, allowing both the theoretical development of the research and the practical implementation into the real-world. A pragmatic approach enables the researcher to expand on the ‘what’ questions of human existence asked by positivism to include the ‘why’ and ‘how’ questions asked by constructivism (Cherryholmes, 1992).

3.2.1.5 Action Research Approach

Action Research (AR) is a collaborative approach to the development of new knowledge that can be practically applied to a specific case or context (Ripamonti et al. 2015). AR is often considered a practical approach to relate the realities experienced in the industrial setting with the researchers approach to creating new knowledge (Coughlan and Coghlan 2002). The application of AR provides insight and actionable learning on practical issues (Ivankova and Wingo, 2018). These can be identified as AR when the output is a way of changing actions.

AR is closely developed with the identification of a problem which is representative of the understanding of both the researcher and the participants in the organisation. Key to its application is that it involves participation from the observed group and the researcher acting as either an embedded member of the observed group or becoming integrated into the group. Coghlan (2001) describe Action research as involving the planning and studying of interventions in real situations which then inform further interventions. In this way, AR develops a solution that is “of practical solutions to issues of pressing concern to people” (Reason and Bradbury, 2008). It is participatory and simultaneous to the action (Dresch, Lacerda, Miguel 2015).

3.2.2 Ontology

Ontology is the view taken on the nature of reality (Gray, 2006). A spectrum of the perceived reality can be described as the extreme objectivist (a realist) at one end and the relativist (subjectivist) on the other (Coghlan & Brannick, 2014). Action research is interpretivist from an ontological perspective, with the researcher and participants involved in the production of contextual knowledge through planned interventions in real-world practice (Abrahamsen et al 2016). The research takes on a primarily interactionist approach, although the frame of research is developed through a pragmatic construction of the system. By developing an understanding of reality through subjective enquiry this research can be considered more closely related to the relativist viewpoint.

3.3 Research Strategy

"Strategies for inquiry provide a specific direction for procedures in a research design" (Creswell, 2003). An important aspect of the research strategy is informed by the need for practical application to industry. This section begins with a summary of the industrial problem which informs the research strategy. The research aim and objectives are then stated. The research strategy is then described.

3.3.1 Industrial Problem

The research was carried out from the perspective of the Rolls-Royce Plc SMR development team. The purpose of research applied to the real world is to improve the understanding of an organisation-specific problem, creating solutions to that problem through carrying out research activities (Saunders, Lewis, & Thornhill, 2009). Thus, the research methods, developed solution, and findings need to be of relevance to industry. A significant driver for this research is the context of the development of the SMR. The early design development stage for the SMR bounds the scope of the research presented in this thesis.

3.3.2 Research Aim and Objectives

The research aim and objectives are formalised based on the challenges presented in Chapter 2 and the bounded scope of the industrial problem. The aim of this research is:

> **"to develop a method which uses cost uncertainty information to support decision rationale at the early development stage for the UK Small Modular Reactor".**

To achieve the research aim, a set of objectives are defined as follows:

- To define the design decision making process and how cost is used to support design decision making;
- To ascertain the appropriate uncertainty levels at each stage of the design phase;
- To identify the key influences on the cost uncertainty (cost uncertainty drivers);

- To create rules to determine the acceptable uncertainty range and whether estimate generated at the defined stage is acceptable;
- To validate the developed method.

3.3.3 Selecting an Appropriate Strategy

Figure 25 shows how the research strategy is driven by the identified research problem and is then shaped by the methodological framing of the research. The resources considered are time, cost and the skill of the researcher as well as appropriate access to data to carry out the research.

Figure 25: Factors influencing the research approach (Remenyi, 1998)

Having identified the research problem in the previous section, the next step is to identify the reasoning approach. There are two types of reasoning approach described here: Deductive and Inductive. Deductive reasoning relies on the identification of a theory, testing that theory and either corroborating or rejecting it, then modifying the theoretical standpoint based on the examination of the research analysis (Gray, 2009). An inductive research approach involves collecting appropriate data to form relationships that may suggest a general theory, possibly inferring a new theory.

AR is applied in situations involving system improvement, organisational learning, managing change, or other “issues of organisational concern” (Coghlan, 2001). Touboulic and Walker (2016) apply action research to discuss the challenges around sustainable supply chain management. The core argument in applying action research is the need to develop a real world basis for theory, upon which to challenge supply chain management to become more innovative, particularly in the inclusion of social aspects to management. Marshall, Coleman and Reason (2011) present action research in the context of accountability of infrastructure project stakeholders using a discursive approach. The opportunity to carry out action research as a First person retrospective assessment of the research during the “frenzy” (i.e. uncertainty) of project execution is identified as a key positive. Combining with an inquisitive viewpoint when receiving feedback from participants increases the depth of inquiry as the researcher implements a process and receives feedback from promoters of infrastructure projects to improve through iteration the project communication process.

An AR approach is taken focussing on the single case study application to the SMR development program. “Case studies emphasize the rich, real-world context in which the phenomena occur” (Eisenhardt and Graebner, 2007). Case studies provide an in depth understanding of a particular phenomenon (Dresch, Lacerda, Miguel, 2015). Even when a single case study is selected, this may be because they are a unique opportunity or an outlier to the norm, thereby providing the opportunity for unique insight (Yin, 2013). Dey et al (2015) presented a case study, utilised action research by carrying out focus groups and statistical analysis within a UK manufacturing organisation. The main output was an AHP and QFD evaluation and ranking tool for supplier performance. Eisenhardt and Graebner (2007) also state that case studies are not carried out to produce generalisable results, more that they involve the development of theory, with theoretical sampling shinging a light on relationships and the theoretical constructs.

A combination of inductive and deductive methods was pursued in this research. Figure 26 shows that in the combined approach the identification of a related theory is based on first gathering data which can be used to reason and formulate a generalisation or hypothesis (Gray, 2009). The next stage investigates whether the hypothesis or generalisation holds true, based on experimental design and the data gathered in the research.

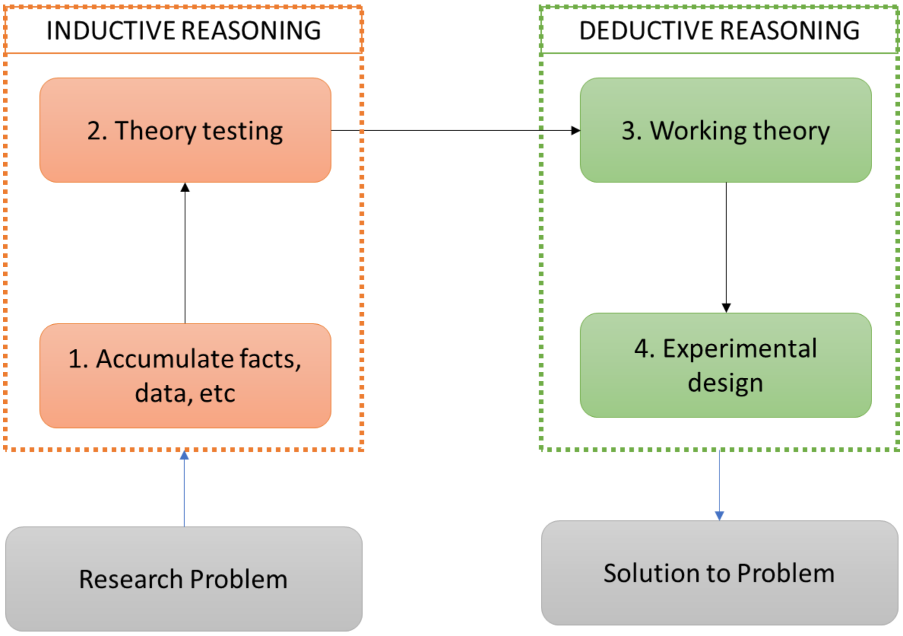


Figure 26: Combining inductive and deductive reasoning

3.4 Research Methods

This section outlines the research methods used to meet each of the objectives identified in Section 3.3.2. Given the wide variety of methods to choose from, the criteria for selecting the appropriate method is discussed. AR is suitable where real events of interest are investigated in real time, and where the study provides the researcher with the ability for action and learning (Coghlan, 2001). The research output provides practical solutions as well as contribute to the body of knowledge in research (Coghlan, 2001). A summary of the selected methods used in this research is then presented.

3.4.1 Available Research Methods

The two overarching approaches to research can be described as quantitative and qualitative (Creswell, 2009). Table 3 presents an overview comparison of qualitative and quantitative approaches (Gray, 2009). A combination of the two approaches is described as mixed methods research. Ivankova and Wingo (2008) identify that the pragmatic approach of action research (which combines empirical data to identify a problem with qualitative procedures for resolving the problem) aligns with the mixed methods philosophy of rejecting the theory of incompatibility between quantitative and qualitative methods.

Table 3: Comparison of Qualitative and Quantitative Research Methods

Consideration	Quantitative	Qualitative
Strategy of Inquiry	Highly structured Theory testing	Semi-structured, unstructured, Exploratory
Purpose of study	Measure of phenomenon based on existing theory	Ascertain/ describe theoretical basis for phenomenon
Benefit of approach	Objective, pre-defined methods, statistically valid findings	Subjective and difficult to measure phenomenon are identified and structured
Data analysis Considerations	Descriptive statistics, statistical tests, analytical approach	Thematic descriptions, narrative approach

Quantitative studies involve the generation of numerical data (Sapsford & Jupp, 2006). The collection and analysis of statistically valid data are used to confirm or redefine a theory (Blaxter, Hughes, & Tight, 2010). It is possible to choose the same research methods for different methodological approaches.

Conversely, the qualitative approach is a way to analyse and understand the world of human experience (Creswell, 2009). Qualitative studies involve the collection of large and diverse data sets using less structured methods, attempting to seek a deeper understanding that may not available through quantification (Sapsford & Jupp, 2006). In qualitative research data is collected in a natural setting and analysed inductively to identify patterns or themes. In the organisational context, access to data or sources of data, particularly in the identification and recruitment of experts, is a challenge. Verification and validation of the data collected through qualitative research methods is crucial to justifying the conclusions drawn by the researcher (Sapsford & Jupp, 2006).

Choosing appropriate methods is based primarily on identifying the type and form of data to be collected and analysed (Fellows & Liu, 2003). The framing of the action research study can be driven by understanding the key issues from organisational participants who will draw attention to their key issues at the time of the study.

A mixed methods approach has been applied in an action research framework. Ivankova and Wingo (2018) presented the advantages of applying mixed methods, aligning qualitative and quantitative techniques with stages of action research. Some key advantages of applying action research relate to the enhanced benefits the research can have in being translated into practice. By maintaining stakeholder involvement throughout the various action research stages, participant stakeholders have a level of ownership to the research, and also help to optimise the developed solution, increasing the effectiveness of the research.

At a high level the steps for action research are shown in Figure 27, and involve cycling through the following four steps to generate solutions to real world problems (Ivankova and Wingo, 2018):

1. Reflection – critical assessment of identified problem
2. Planning
3. Acting
4. Observing

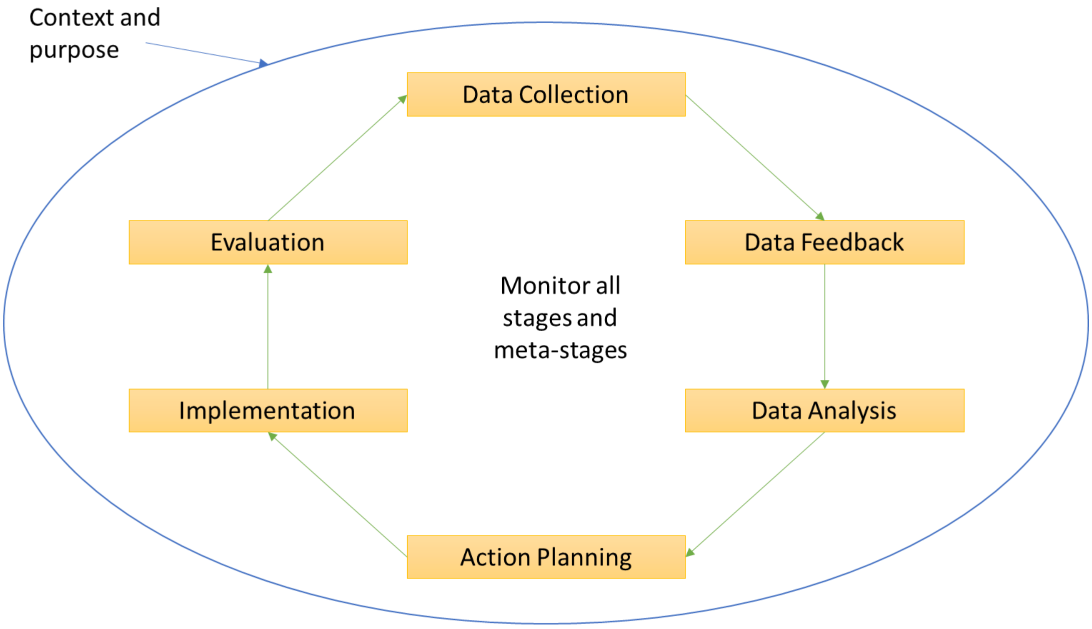


Figure 27: Stages of the Action Research Approach adapted from Dresch, Lacerda, Miguel (2015)

Research innovation and knowledge is sometimes identified as difficult to integrate or communicate directly (Ripamonti et al 2015; Kieser and Leiner 2012). Action research can be a bridge to this communication gap, supporting both the practical need of the case study organisation in this research as well as the academic contribution to knowledge. AR also supports the researcher to systematically investigate a complex practical solution which may be qualitative in nature (Ivankova and Wingo, 2008).

In planning the selection of research methods for collecting and analysing the right data the researcher first considers the purpose of the study. The need to collect primary or secondary data should then be considered. Primary data includes both quantitative and qualitative data generated through research. Depending on how accessible and resource intensive the collection and analysis of primary data is, there may be a need to collect secondary data. Data sources available from the organisation can be classed as secondary sources of data. These could be existing documents, guidelines or publications.

Table 4 presents the selected research methods employed to collect data and the type of data that is collected. The approach taken in the research has been to align as closely as possible the requirements for cost information and cost estimating of the case study organisation with the research activities. The research is divided into two phases. The purpose of this two-phase approach was to explore participant views and to refine the problem identified in literature with a focus on the application to the case study organisation.

Table 4: Linking the research approach to the key objectives

Epistemological Position	Pragmatism				
Ontological Position	Relativist (subjectivist)				
Research Strategy	Inductive reasoning			Deductive Reasoning	
Research Approach	Qualitative	Qualitative	Qualitative	Qualitative	Quantitative
Research Objective	1	2	3	4	5

The results of the first phase informed the research methods used to develop and test a solution to the problem in the second phase. The researcher was embedded in the case study organisation design team for much of the research period. The availability of useful data sources was limited for two reasons. Firstly, the early design stage of the design process inherently involves a lack of data. Secondly, the sensitivity around cost data in any organisation restricts access and dissemination through publicly available documentation.

Secondary sources of data were also available in the organisation, primarily through existing documentation in the form of guidelines and procedures associated with cost estimating. These documents were identified as useful to provide validation for several research studies carried out (See Section 3.6). Additional data was sought externally to the case study team from the wider organisation. Again, access was restricted, either through the lack of synergy or direct relevance with the case study or for security and commercial sensitivity reasons.

3.5 Data Collection and Analysis

Based on the research strategy identified in Section 3.3 there are two phases to data collection. The first phase involves an exploration of the use of cost information to inform early decisions by collecting data from participants at the research site. The research methods used to achieve objectives 1,2 and 3 seek to explain the use of cost by the design development team, the requirements of cost and the limitations of different applications of cost at the early concept stage. The results of the first phase form the requirements of the second phase. The second phase then uses a different set of research methods to develop and test the developed solution, meeting objectives 4 and 5.

There are a range of data collection methods which can be used in Action Research studies (Table 5). Action research incorporates the analysis of existing documentation, interviews, self-assessment surveys and statistical analyses (Takey and Carvalho, 2015).

Table 5: Data collection methods associated with research method

Characteristics	**Case Study**	**Action Research**	**Design Science Research**
Achievable Objectives	Support to understand complex phenomena	Practical and theoretical explanation of systems	Development of solutions to identified problems
Main Activities to conduct research	Plan Case Collect Data Analyse Data (Isenhardt, 2007)	Plan Action Collect Data Analyse Data (Plan more actions) Implement Action Evaluate Results Monitor (Coughlan and Coghlan 2002)	Define problem Propose solution Develop, evaluate conclude solution Communicate output (March & Storey, 2008)
Results	Descriptions Explanations	Descriptions Explanations Actions	Constructs/ models Methods
Researcher role	Observer	Dual role	Constructor/ evaluator
Context of conclusions	Specific Situation	Specific Situation	Generalisable to certain class of problem

Argyris, Putnam and Smith (1985) identified a set of central tenets of action research, which have been listed by Coghlan (2001) as research that:

1. Focuses on a problem, seeking to support the client system
2. Involves an iterative process of identifying a problem, planning a resolution, acting and evaluating the resolution
3. Involves changing ways of working through modifying actions or patterns of thinking that are the norm for the organisations, or individuals within the organisation and as a result…
4. “Challenges the status quo from a participant perspective”
5. Contributes to knowledge (in research) and provides a solution applicable to industry (everyday life).

These tenets provide the structural basis for each data collection method presented in the following subsections along with some key limitations in their application and the results that can be achieved through their implementation to the case study.

3.5.1 Document Analysis

In this research document analysis is carried out for two different purposes. Document analysis is used to review existing literature and to specify the gap in knowledge to meet Objective 1. In addition, document analysis is used as part of a triangulation method to meet Objective 2.

For Objective 1 the focus of document analysis is on text and the message being conveyed. Formal documents e.g. peer-reviewed journal papers and government reports described the problems and approaches taken to resolve these in the research domain, giving an explanation of the problem and the currently preferred solution (Sapsford & Jupp, 2006).

For objective 2 a review of existing documents within the case study organisation to establish the use of cost estimates and cost information to support the design decision-making process. The data obtained include secondary sources i.e. from a review of existing documents within the case study organisation to establish the use of cost estimates and cost information to support the design decision-making process. Document analysis in this application provides an unobstrusive means of analysing a research problem which are not directly influenced through investigative techniques carried out by the researcher (Sapsford & Jupp, 2006). The framing of the interviews (see Section 3.5.2) is created by the understanding of the company procedures within which the participants operate. By using existing process guidelines as a baseline to understand the questions to be asked of the interview participants some internal validity can be achieved.

3.5.2 Semi-structured Interviews

The study for objective 2 involved in-depth interviews and secondary data analysis to triangulate the use of cost information in the design decision making process for the SMR case study. The use of interviews combined with document analysis has been applied in previous AR studies. For example, Abrahamsen et al (2016) use discursive action research to produce a conceptual network picture showing the decision-making boundaries of the case study organisation. In the action research methodology three planned interventions involving group discussions, group interviews, observations and more in depth reviews where participants ranged from between 4 and 20 managers in each study. Ripamonti et al (2015) surmise that action research is effective when the researcher and participants are engaged in “a dialogue that emphasises the dynamic, multifaceted, and multi-vocal nature either of their stories, discourses, or of their culturally informed practices.”

Semi-structured interviews within the case study organisation were used to establish understanding of cost requirements for the SMR. In-depth evidence was collected through a series of interviews carried out with the design development team senior decision makers. The output from the interviews is a concept model to establish the approach to early design stage decision making in the industrial case study.

Specifically, the following activities were carried out:

1. A review of company process information to provide a baseline understanding of the design decision process.
2. The elicitation of the design decision process used by the design team for the case study
3. Interpretation of the design decision process into two different types of model. Firstly, individual functional block diagrams of the processes used by each study participant. Then into an IDEF0 Diagram to represent the overall design decision process used by the case study design team.

Words and their meaning are specific to the context, institutional setting, and person who used them, and, as a result, lack universality (Sapsford & Jupp, 2006). It is possible that in the course of conducting an elicitation study, that researchers might be given “what they’re asking for” (Laurel, 2003). There is also the potential that the researcher incorporates their own bias into the understanding of the process. To mitigate these situations the research activity also involved a triangulation approach, where existing processes and confirmation from the participants were used to clarify that the model represented the real situation (or at least approximated it sensibly). The experience of the design process is much more extensive than is described by the model. There are many informal communication channels, development of data and input of information not formally captured in process. These shortcomings limit the granularity of the model produced from carrying out the interviews.

3.5.3 Surveys/ Questionnaires

The purpose of the study for objective 3 was to identify the usefulness of existing cost uncertainty analysis approaches on the design decision-making process. Identifying existing approaches to cost uncertainty analysis and the effect of information presentation on design decisions. Evidencing the limitations of applying existing cost uncertainty analysis methods to support early design decisions in the case study.

A scenario-based survey was carried out with the design team to understand how cost information is interpreted. A case example was presented on the application of cost uncertainty analysis to available data at the early concept design stage. An elicitation study was then carried out to investigate how different members of the team interpret cost uncertainty information. The useful outcome is the opinion of the experts obtained and the insight this has on the perception of cost given the information presentation.

3.5.4 Design Research

To achieve objective 4 requires an approach to resolving a design problem. There are four different types of design problem for which different methodological approaches to solving them have been proposed (Muratovski, 2015). Three of the design problem types identified relate to quantitative and linear approaches to technical problem solving in design. These highly structured and linear approaches to problem solving require minimal group or participant involvement and are based on technical reference information. The subjective and interdisciplinary nature of the research problem makes a highly quantitative and rigidly structured approach to a design solution infeasible. Information is highly uncertain as is the cause of the phenomenological basis of the research problem. The research described in this thesis aligns with a type 4 design problem, involving a complex-closed research problem, where an investigation is carried out to detail the content of the problem “revealing” the complexity (Muratovski, 2015).

AR is an established method within the fields of business management and information systems involving participation within the research (Naoum, 2007). Action research aligns with an early iterative stage of design development (Figure 28)

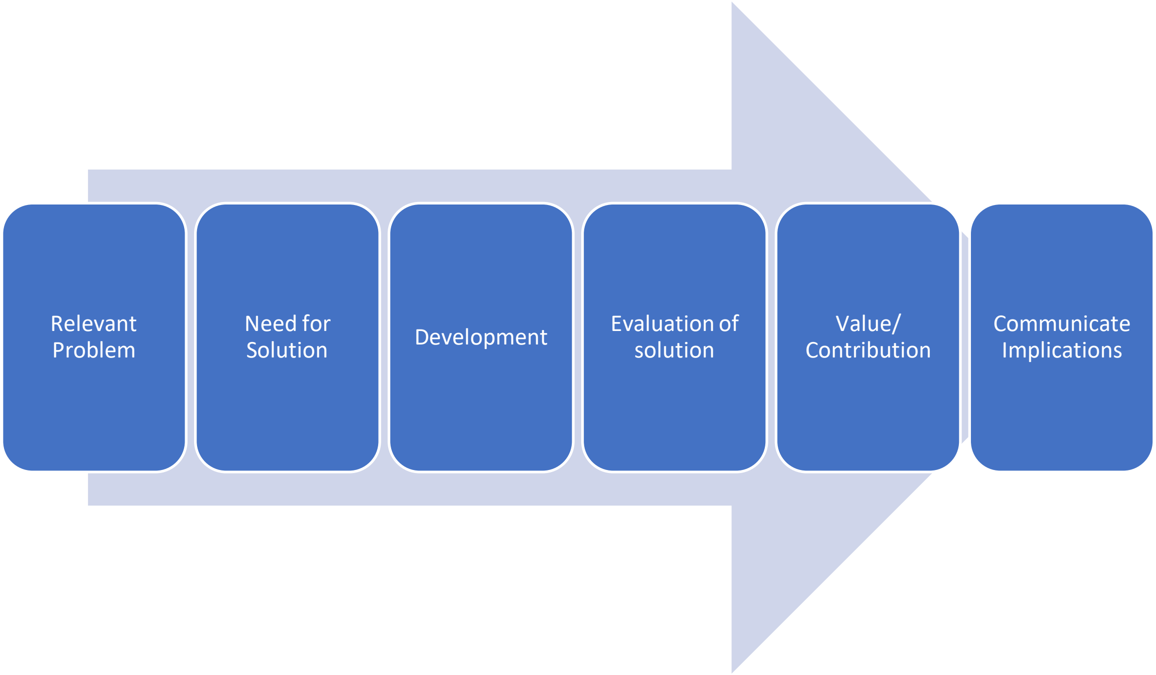


Figure 28: Steps for the AR approach with Design Research adapted from March & Storey (2008)

Dresch, Lacerda and Miguel (2015) illustrate how Design Science Research in conjunction with Action research provides a systematic, structure process to resolve problems in practice. Takey and Carvalho (2015) analysed organisational competencies using case-based analysis combined with action research. Action research is a vehicle for direct involvement of the researcher with the research object. Design science research can be used to develop a solution for an identified problem.

Using the requirements defined by carrying out the research activities described in Sections 3.5.1 and 3.5.2 a method was developed to support design for cost maturity applied specifically to the SMR case study. The method developed through action research approach, identifying the requirements for the case study organisation and by informal and regular meetings with the case study project team.

3.5.5 Observation

The purpose of the final research objective is to confirm that the user requirements identified for the need of a method are justified. Validation of the method was sought through case study application of the method to an early design decision and focus group analysis. Using a focus group approach an iterative game technique can be applied (Laurel, 2003). Observation research was carried out to record the decision-making thought process for each individual participant, and to compare this with the group finding.

There are underlying assumptions to the developed method which can only be substantiated by further investigation. One assumption applied in this research is that the way the developed method will be used is already understood by the designer. Another assumption is that the user requirements for the method have been addressed and are well understood. To confirm the assumed user requirements have been achieved the method was validated using expert focus groups, essentially seeking expert advice on the developed method.

Data collection was carried out by combining questionnaires and observation studies. Structured questionnaire is used prior to observations (preliminary questionnaire), during observations (main questions around interpretation and decisions), and after observations (usability related questions). This was carried out to reduce reactivity to observation research being carried out with the participants.

The method adapted from Laurel (2003) can be outlined as follows:

- Establish the experts
- Develop a set of hypotheses about the expected needs of the experts for the method, where they will be applied, and how they will be applied
- Develop a “game” approach to using the method
- Using exploratory questioning (what, in what way, tell me about, why) identify whether the hypothesis set out have been confirmed
- Review the developed method against the outcome from step 4.

Two mini focus groups were set up to test the interpretation of cost information using the new developed method. Mini focus groups provide for more detailed responses deeper questioning and questioning more specifically tailored to each person in the group (Muratovski, 2015). One focus group were asked questions having been presented with traditional forms of data. A second focus group, independent from the first, were presented with traditional information as well as the data output from the new method. This allowed the researcher to collect observations on the ability to communicate and make decisions based on the available information. The presence of two comparative groups acts to draw a boundary around the conclusions, enabling the researcher to say what is true with regards to the usefulness of the developed method.

3.5.6 Ethical Considerations

Ensuring that research is conducted in an ethical manner is critical to legitimate research (Ritchie et al, 2013). The highly commercial nature of the case study project, and the high profile of the organisation made it vital that the research was executed in a trustworthy way. In all interactions with interviewees or during focus groups everyone was informed of the purpose of the research and they were all given a brief description of the research project. They were informed that the process was going to be recorded and that they will remain anonymous and findings of this research may be published or presented in an academic context.

A significant issue described by Coghlan (2001) is the researchers role duality, whereby the researcher is also an active member of the organisation or team in which they are carrying out the research. In carrying out action research, the researcher must overcome the following challenges identified by Coghlan (2001):

- Preunderstanding – The ability to inquire within the organisation using language and experience which are understood by the participants during e.g. questionnaires or interviews. The level of preunderstanding of the organisation will influence how much the researcher may assume about responses from the participants, which had not been stated. Access to data or information may be difficult depending on the political and organisational structure
- Role Duality – Organisation and research role – the impact on other organisational members through relationships – seen as a researcher or as a team member? These ties can impact upon the level of openness or restriction to research participation. Sensitivity of the data around estimating, performance management, and the decision-making process.
- Managing organisational politics – Research within an organisation could be perceived internally and externally as a controversial, especially when inciting reflection from the participants. Requires management of both the participants expectations and allaying fears of use of the research material, and managing

stakeholder expectations i.e. sponsors of the research to reduce resistance and continue to receive backing and participation in the projects.

3.6 Validity of Findings

Research validity can be described as the extent to which assurances can be given that the data produced and results interpreted from carrying out the research activities are representative of the conclusion drawn and the knowledge claims made by the author (Sapsford & Jupp, 2006). In this section the term validation refers to the confirmation of the belief about will be learnt by carrying out the research methods.

Different types of validity can be described. Construct validity through establishing the required data to be collected and to evaluate and categorise the information from participants. To establish the approach to early design decision making in the industrial case study organisation. Ensuring the validity and reliability of the data obtained was carried out through triangulation – that is, using multiple sources of data or multiple methods to interpret the situation (Remenyi, 1998).

“Knowledge claims arise out of actions, situations, and consequences rather than antecedent conditions” (Cherryholmes, 1992). A pragmatic approach is taken to arrive at the knowledge claim. The case study focuses on one specific development programme. The contribution to knowledge that is claimed is based on an awareness of wider practice that is presented in literature.

Case studies are interpretive, based on the evidence provided and are less empirical than other methods. Case studies can, therefore, be subject to the bias based on the collection methods and analysis techniques employed by the researcher, which can lead to determinations based on incomplete information. Takey & Carvalho (2015) identified that the key limitation of action research is the inability to generalise the findings. This is primarily because the method is usually applied in a case study, but also because of the deep insight provided by focusing on the characteristics for the specific organisation in the context of the research. Ivankova and Wingo (2008) state that “the pragmatic nature of mixed methods and action research makes it advantageous in illuminating and assessing change over time without sacrificing credibility and validity standards”.

The aim of action research, therefore is to merge theoretical with practical implementation, which is achievable for the specific case study at hand. As stated by Abrahamsen et al (2016) "we are interested in how our respondents interpret their environment, and what actions they take based on their understanding". Given that the results are not generalisable, they are also difficult to verify, thought this is not necessarily key when carrying out action research.

The goal of case studies is to "expand and generalise theories and not to enumerate theories" (Remenyi, 1998). By verifying the conclusions drawn from the collected data from multiple sources of evidence, for example through triangulation with experts, the findings are presented as representative of the specified case rather than an overall representation of a wider population or phenomenon. One of the strengths of case study investigation is the exploration of the wider research space through one-off case investigations. Detailed case studies can investigate complex ideas which address very specific issues. Ivankova and Wingo (2008) discuss the enhanced translation of research findings into practical applications that result of the combination of action and mixed methods research. Table 6 presents a summary of the applicability of different approaches in the research together with the defining requirements and characteristics of the research context.

Table 6: Characteristics of applicable data collection methods (adapted from Dresch, Lacerda and Miguel 2015)

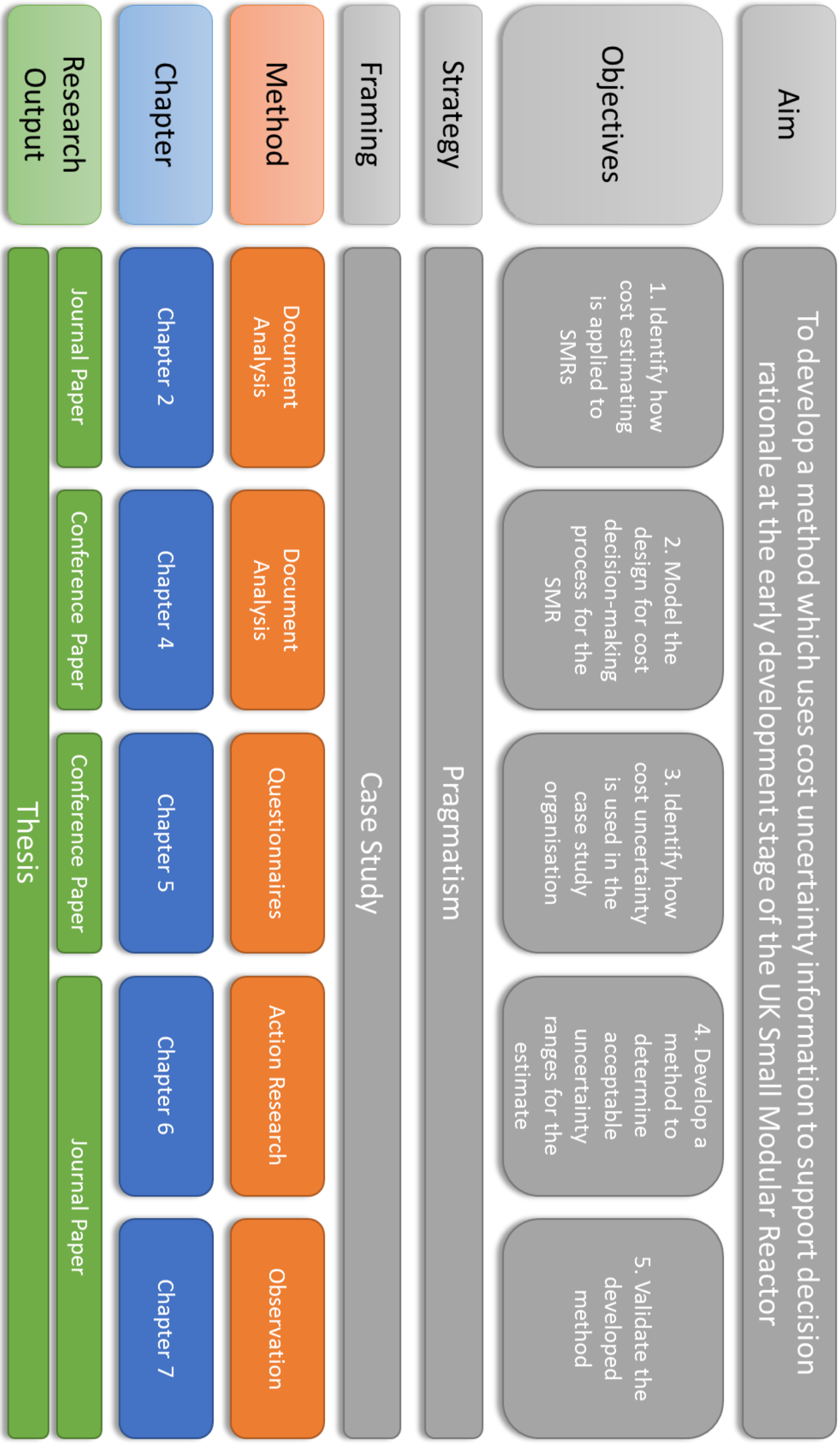
Requirements/ characteristic	**Experiment**	**Survey**	**Case Study**	**Action Research**
Presence of the researcher in data collection	Possible	Unusual	Usual	Usual
Small sample size	Possible	Possible	Usual	Usual
Difficult to quantify variables	Possible	Possible	Possible	Possible
Requires deep understanding of the decision-making process	Difficult	Difficult	Appropriate	Possible

To define the design decision-making process a triangulation approach is taken using interviews and observations together with documentation. The research strategy was informed by the Industrial need (context) as well as the identified gap in knowledge. Some of the key challenges associated with validating a new process using cost for decision support (Cai & Tyagi, 2014). The long product lifecycle, and lack of data are the clear challenges of a direct comparison with actual data. The uniqueness of design tasks and project do make it difficult to replicate the exact environment for two different design decisions. A key output of action research is its contribution to organisational learning. However, the project can evolve over time, and “researchers need to go with the story as it evolves” (Coghlan, 2001). This was certainly observed throughout the course of this research.

The research applied at the early design phase of development is contextual, in that the data generated and analysed is to help understand the specific business, sector, or project context (Laurel, 2003). Through evaluation within the context of the early concept design process for the case study team the construct validity can be assessed. Applying the scientific method to design research can have different levels of success. On the one hand it should lead to reproducible results, when given the same set of conditions. However, the design of products is unique from project to project, meaning that applying the scientific method to generate a solution which produces exactly the same result will likely fail. It is the change of context which could cause this to happen (Laurel, 2003). The results and findings are not generalised outside of the case application. External validity cannot be claimed by this research as it is case specific and is not typical or representative of a wider population.

3.7 Summary

Figure 29 shows each of the research objectives, the application of the research methods to resolve each objective and the data that will be produced from carrying out each research activity. There is a point of view taken with regards to cost for NPPs. Narrowing the field of research to consider how decisions are made using cost information, and the development of a process to rationalise the timing of design decisions has necessitated a mixed methods approach. This research focuses on the use of cost information in the design decision making process by the SMR development team.



Aim	To develop a method which uses cost uncertainty information to support decision rationale at the early development stage of the UK Small Modular Reactor				
Objectives	1. Identify how cost estimating is applied to SMRs	2. Model the design for cost decision-making process for the SMR	3. Identify how cost uncertainty is used in the case study organisation	4. Develop a method to determine acceptable uncertainty ranges for the estimate	5. Validate the developed method
Strategy	Pragmatism				
Framing	Case Study				
Method	Document Analysis	Document Analysis	Questionnaires	Action Research	Observation
Chapter	Chapter 2	Chapter 4	Chapter 5	Chapter 6	Chapter 7
Research Output	Journal Paper	Conference Paper	Conference Paper	Journal Paper	
	Thesis				

Figure 29: Summary of research aims, strategy and outputs

4 Considering Cost at the Early Design Stage

4.1 Chapter Overview

This chapter forms the first part of the requirements identification stage of the research as shown in Figure 30. In this chapter a model representing the product development process followed by the case study organisation is developed. Expert elicitation is used to model how cost information used by the case study design team. This chapter aligns with research objective 2:

"To conceptualise the use of cost information at the early design stage for the SMR."

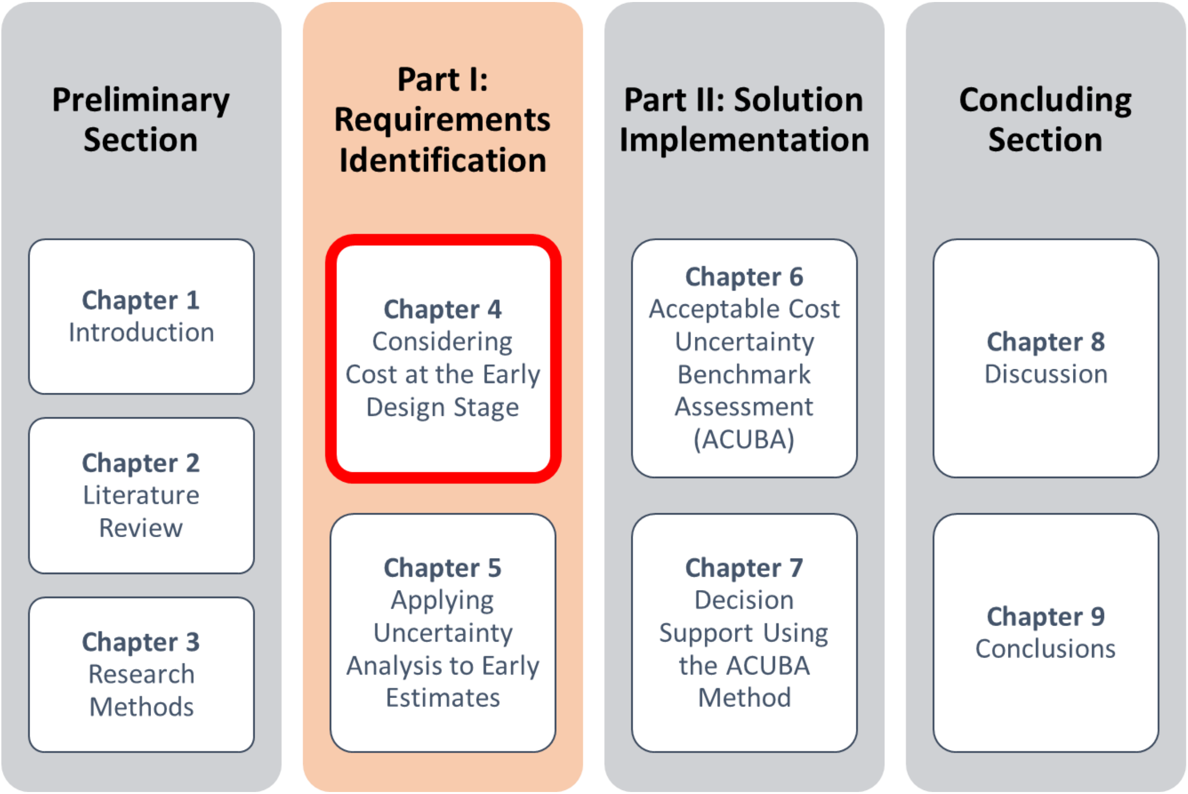


Figure 30: Chapter 4 as part of the research requirements identification stage

Section 4.2 provides an outline description of the New Product Development (NPD) process. Section 4.3 presents the elicitation study carried out within the SMR development team investigating how cost information is used in the NPD process. The organisation-specific processes and guidelines are the basis for understanding the NPD process. The identified process documents represent standard practice for the overall organisation. Given that a case-specific perspective is required for the process used by the SMR development team, Section 4.2.2 describes the method used to produce a model of the early NPD process. Section 4.4 presents an analysis of the results of the transcripts produced from the elicitation study. In Section 4.5 a model is developed through the analysis of NPD process documentation and the expert elicitation study carried out with senior-decision makers. The key cost requirements of the SMR, from the perspective of the case study design team are analysed in Section 4.5. Section 4.6 presents the key challenges with early design stage cost estimating, aligning these with the early cost estimating challenges identified in Chapter 2. The summary presented in Section 4.7 frames the study within the overall scope of the research identifying some of the requirements for a decision support method which utilises cost information at the early design stage.

4.2 The New Product Development Process

The NPD process is a structured and systematic approach to the design, manufacture and launch a new product. NPD involves carrying out a number of interrelated tasks to create a new product which meets customer requirements (Collins, Yassine, & Borgatti, 2009). Traditional NPD involves identifying a customer needs, requirements then generating concepts, selecting one or several concept, designing a product, testing then finally launching (Relich & Pawlewski, 2018).

The case study organisation uses a Stage-gate© approach for NPD. Stage-gates provide a traceable process to progress from concept into a final product (Cooper, 2008). Phillips et al (1999) describe this as “an aid to keeping the risk associated with new product development to a minimum.” Each gate serves as a check point. Figure 31 shows how each stage is divided by decision points which act as gateways to ensure the product is matured in a systematic manner.

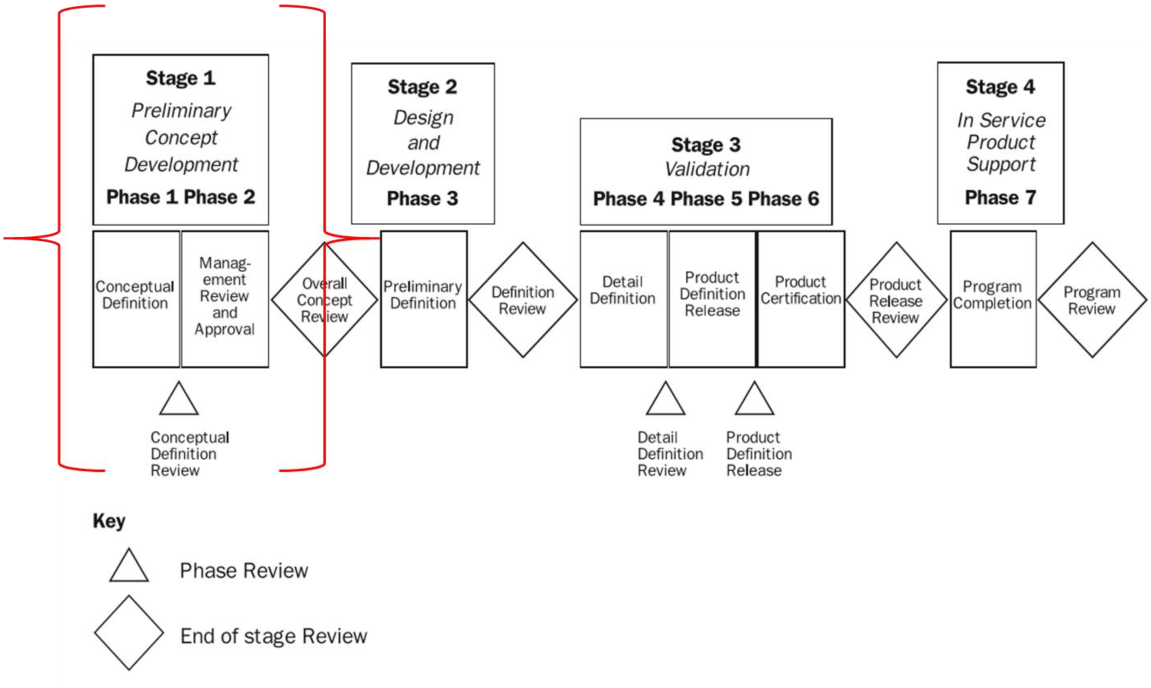


Figure 31: Focus of the analysis at Stage Gate 1 of the new product development process

This research focuses on Stage 1 of the gated process. The key decision points for Stage 1 are the “Conceptual Definition Review” and the “Overall Concept Review”. The activities in Stage 1 involve creating a baseline concept along with a product specification and a business justification. As the concept is developed further the design team generate information which is used as the basis for the decision review gate (overall concept review). Between each Stage-gate a planned development process is structured around several primary tasks as shown in Figure 32.

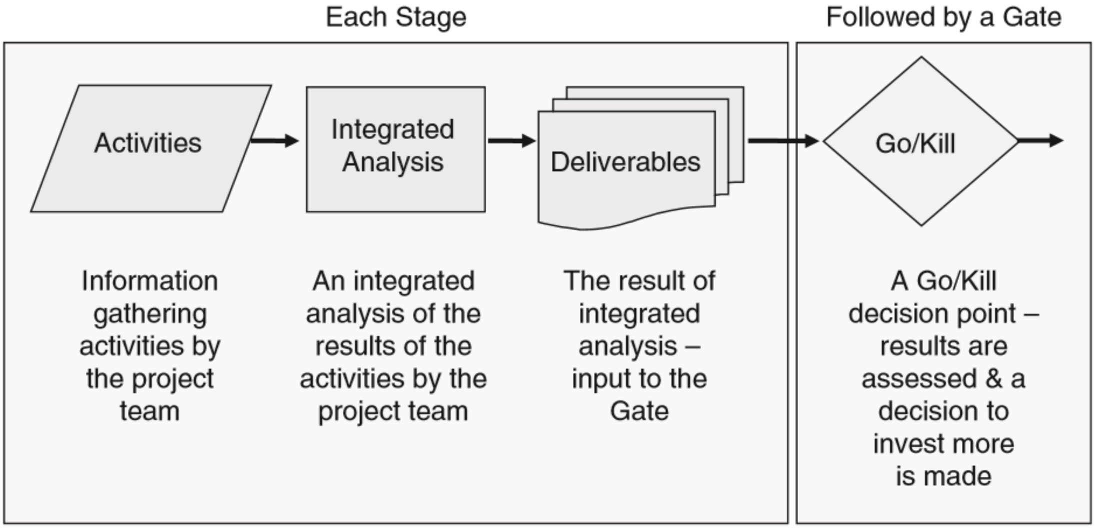


Figure 32: Stage-gates with information gathering, analysis and decision points (Cooper, 2008)

The ability to progress through the review gate successfully is based on an assessment of the design solution developed against a set of customer requirements as well as a commercial analysis. The review ensures that the concept aligns with to the strategic goals of the organisation. The information gathered to progress through the gate must, therefore, be of sufficient quality and integrity to prove the concept meets both the organisation-specific goals as well as providing a solution that meets the needs of the customer.

4.3 Method

This section describes the method used to model the NPD approach used by the case study organisation. The triangulation method was applied in this study to understand the SMR team-specific approach to concept design stage decision making. The steps involving the combination of analysing existing processes and expert elicitation are explained.

The study is centred on the technical decision making process at the preliminary concept development stage which directly influence the design solution. A combination of information analysis, expert elicitation, and systems modelling was used to create a concept model of the design decision making process (Figure 33).

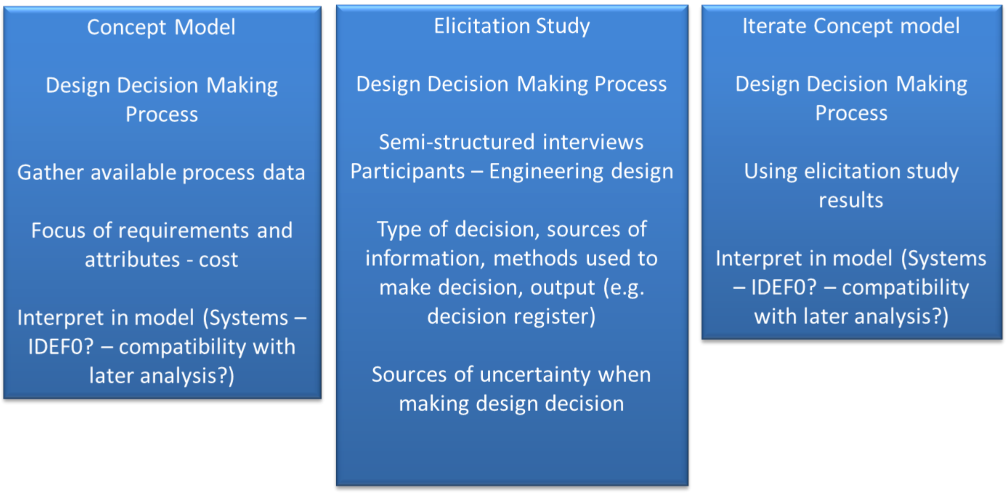


Figure 33: Developing the Concept Model of the Design Decision Making Process

4.3.1 Review of Company Processes

The process documentation related to the early concept design stage of the NPD process used by the case study organisation was reviewed. The documents provides a standard, idealised process which is expected to vary when applied to each development programme within the organisation. The aim of the review was to identify the formalised processes and procedures used to support early design development. The review of company processes also provided a baseline for the elicitation study, allowing general themes to provide structure to the interview questions.

The tasks involved in developing the preliminary study include:

1. Identifying formal processes and procedures defined by the organisation to support technical design decision making
2. Review design principles and assessment criteria related to cost for the project
3. Review decision registers to establish current practice being used to make design decisions, specifically on cost

The specific decisions made and technical information about the design are not revealed by the model. However, it will be important to identify which system(s) are being designed.

4.3.2 Participant Information

Semi-structured interviews were used to elicit the actual NPD process used by the case study design team. The aim of the interviews was to explore the design decision-making process and how cost information is used at the early concept phase from the perspective of the case study team.

The study was carried out with key decision makers in the team who have a direct influence on the development of the design solution. A total of 11 participants were identified as suitable for the elicitation study, each holding the responsibility of making decisions which directly impact the design of the SMR. For the purposes of the study each individual participant was anonymised. The role of each participant in the team was recorded to understand any differences in perspective between each of the functions represented (Table 7). Eight participants were interviewed during the early concept design phase. 3 participants were not available for interview during the study, namely the Lead Engineers for Civil Engineering, Safety and Performance, and Control and Instrumentation.

Table 7: Senior Roles within the SMR Design Team

Participant Reference	SMR Role	Design Team Responsibilities
WP01	Research & Development Lead	Lead for verification and validation
WP02	Component Design Lead	Leading the design of the mechanical components
WP03	Chief Design Engineer	Chief Design Engineer
WP04	Supply Chain and Development Lead	Lead responsible for supply chain and development
WP05	Head of Programme	Head of Project Management Function
WP06	Supply Chain Manager	Supply Chain Manager
WP07	Core Design Lead	Leading the reactor core design
WP08	Materials and Chemistry Design Manager	Lead for Materials and Chemistry

A question guide was used to maintain a general structure for each interview and to support the coding of responses at the analysis stage of the study (See Appendix C). Specifically, the questions were focused on identifying:

1. The design area being considered (i.e. understanding the scope of design),
2. how design decisions which influence the design and cost of the design were categorised,
3. which information sources are used to make the decision, with a focus on cost information,
4. the assumptions and uncertainties which the designer incorporates into the decision-making process,
5. the outcome of a decision and to what extent the designer understands (or can quantify) the cost impact of a decision on the system level and total product cost level.

Each interview ranged in duration from 30 minutes to one hour. The interviews were conducted individually and recorded using a digital audio recording device. The audio files were transcribed into Microsoft Word documents. The transcriptions were then returned to the participant to confirm that the interpretation was correct, and to suggest clarifications for unclear areas of recording. The updates from participants were then incorporated into a redrafted transcription in a format suitable for analysis and uploaded into NVivo 11 Pro software.

4.3.3 Interview Data Analysis

The output from the elicitation study is a model representing the early concept design process used by the SMR development team. The process used to analyse the transcriptions is described in this section and is illustrated in Figure 30.

The research relied on a variety of modelling, data capture and analysis techniques. A Systems Modelling (SM) approach was taken. SM is a method of describing the real world through simplification and interpretation of properties which represent that system (Haveman & Bonnema, 2015). Several studies have attempted to categorise System Modelling techniques to provide a framework for selecting the right technique for the right application. Haveman & Bonnema (2015) provided a summary of system modelling approaches focusing on those techniques which are most applicable to the concept stage of a project. More detailed and rigid methods, such as SysML are were identified as more suitable for modelling the detailed design stages, and for formal structuring within a systems engineering context with technical stakeholders. Methods such as Soft Systems Analysis enable the views of participants to be conceptualized and verified against established procedures (Mingers & Rosenhead, 2004).

The framework developed by Giaglis (2001) (see Table 8) was used as the basis for identifying a suitable modelling technique employed during this research. According to Giaglis, the appropriate modelling technique should represent at least one of the following (Giaglis, 2001):

1. **Functional perspective:** Identify the process elements that define the key activities being performed.
2. **Behavioural perspective:** the flow and order of activities carried out, and how activities are performed such as the decision-making conditions, exit criteria, etc.
3. **Organisational perspective:** The technique should define where activities are performed, and the resources required to carry them out. It should also can represent the information transfer and storage mechanisms.
4. **Information perspective:** The ability to represent the interrelationships within a process, and the changes to "informational entities" i.e. data, in the system.

Table 8: Framework for Evaluating Process and System Modelling Techniques (Giaglis, 2001)

Fit					
Informational perspective	Systems documentation	Systems analysis & design	Systems project management	Software re-engineering/ systems development	Systems O&M
Organisational perspective	Organisational structure representation	Rule redesign	Human resource management	Workplace design	*No purpose identified*
Behavioural perspective	Business process documentation	Business process re-engineering	BPR project management	Work flow design	Work flow execution
Functional perspective	Task documentation	Task redesign	CPI/TQM project management	Quality assurance/ control	Automated task execution
	Understanding & communication	***Process Improvement***	***Process Management***	***Process Development***	***Process Execution***

The main output of this study was a model of the early design stage decision-making process. The elicitation study also identified key areas of uncertainty and the metrics used to understand these uncertainties at the early design phase. The focus of the analysis was then on how cost is measured, the requirements of cost information to support decision-making at the early design phase. The model perspective, project goals, and where in the project the model fits, can all be used as criteria to categorise project characteristics.

The IDEF0 model structure was used to present the information structure of the early design decision making process using cost estimating. Thematic analysis was used to understand cost requirements and use of cost information in a system, using the IDEF0 model to provide a template structure. An IDEF0 model is composed of a hierarchical series of diagrams that display increasing levels of detail describing functions and their interfaces within the context of a system (Dorador & Young, 2010). The two primary modelling components are functions (represented on a diagram by boxes) and the data and objects that interrelate those functions (represented by arrows). Within the diagram each individual box represents the activity or function, with the interfacing arrows left to right representing an input and output, respectively (Figure 34).

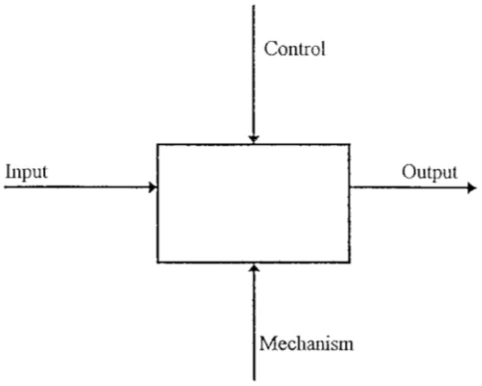


Figure 1. IDEF0 function box.

Figure 34: An IDEF0 function box with standard notation (NIST, 1993)

The control and mechanism are constraints on the activity. The input may arrive from a connected activity which determines how the function is activated. Likewise, the output of the function determines how the proceeding activity operates.

A standard set of rules for producing the IDEF0 diagram were followed (NIST, 1993):

1. The model begins with a stated purpose and viewpoint
2. The top page is the context diagram, defining the inputs, controls, outputs and mechanisms for the single, top-level function from external systems. In this study, the top-level function is the design decision process at the early concept development phase.
3. Each subsequent page represents the next level of detail down for the system.
4. The number of sub-functions for any IDEF0 function is limited to six, for the purposes of a readable display on a page.
5. Each page and diagram interface is defined using Node numbers, Box numbers, C-numbers, and a Detail Reference Expression

The first stage of the analysis involved categorising key sections of the responses related to each nodal theme representing the process. The question guide supported the development of the IDEF0 diagrams, based on a set of themes derived from the review of company process documentation. The interview data was analysed manually to select the aspects of the response which related to each node. The nodes were then populated with selected data obtained from the transcriptions.

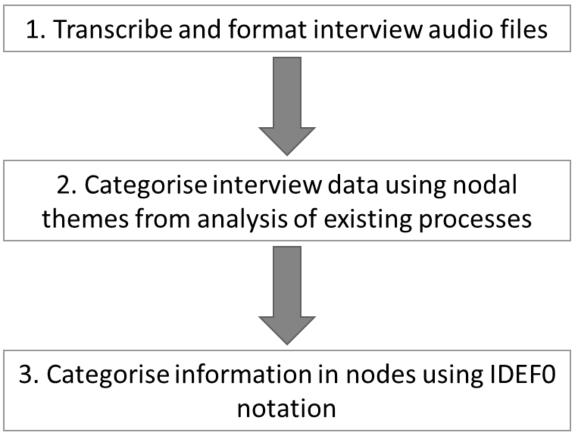


Figure 35: Method of analysing interview data

Once the initial text categorisation was complete, the selected data were then clustered and renamed to singular phrases which could then be used in the IDEF0 notation (IDEF0 is described further in Section 4.4). Each phrase was related to a specific IDEF0 notation as either an Activity, Input, Output, Control, or Mechanism. Each of the control, input, output, and mechanism line items were then reviewed to identify similar themes and duplications. The activity-related descriptions were analysed, firstly to identify and combine similar activities described by different participants, and then to order each activity in the NPD process. The nodal categories were then used to produce several hierarchical levels of IDEF0 diagrams. The line items were then assigned to the relevant activities for the Level 2 diagrams. A set of preliminary IDEF0 diagrams were then generated for the verification of the model.

4.3.4 Verifying the Model

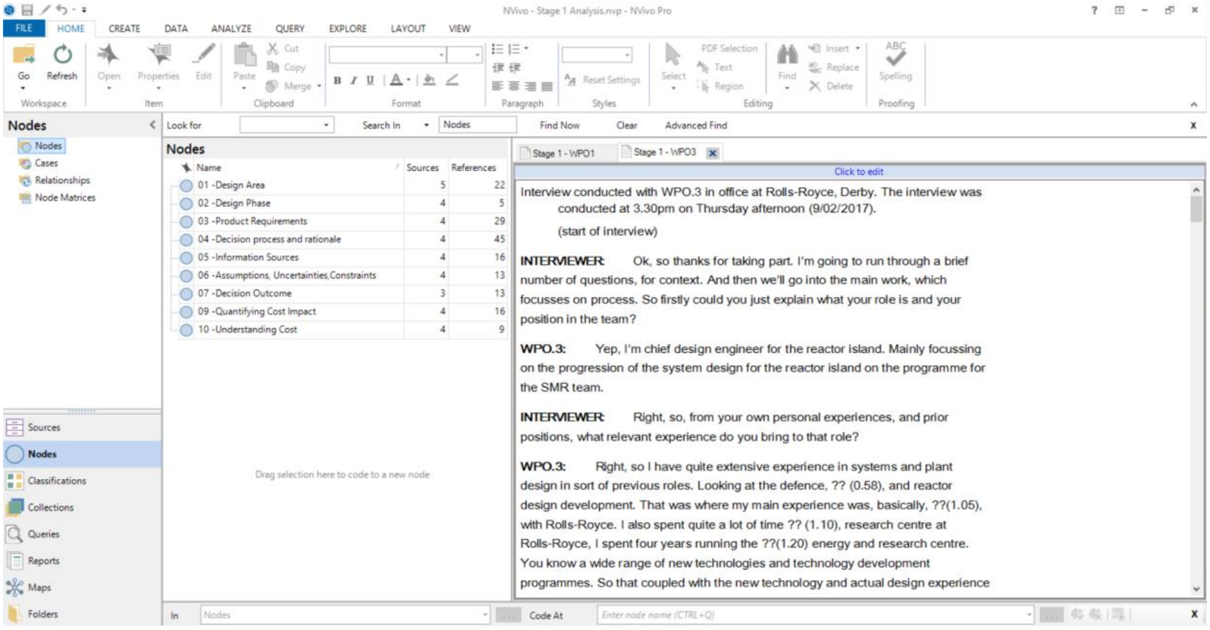
A follow up elicitation was conducted with each individual participant to verify the model. The study participants have different levels of expertise and experience in relation to understanding system modelling. A benefit of the IDEF0 notation is its simple format structure, which can be easily understood and analysed by those with less experience in system modelling (Giaglis, 2001). The model was used to guide the verification process, while also allowing the model to be edited in real-time. The final step required each participant to agree that the iterated diagram provided a reasonable interpretation of the NPD process.

4.4 Data Analysis

The question guide for the interview also helped to shape the systems diagram, with a clear starting point being the identification of requirements, and the theme of cost being central to the discussion. This bounded the discussion without restricting or biasing the responses. An example transcript is shown in Appendix D.

The development of the system model is dependent on the ability of the researcher to effectively translate the interview transcripts into codes, and to visualise these in a simple, informative, and correct way. There is a need to formalise a method for converting the transcripts recorded from the interviews into a representative model.

The nodes were defined using the question guide. The text was then analysed manually to select the aspects of the response which related to each node (Figure 36). Once the text analysis was complete, each individual node was reviewed to identify the activities, the interfaces, external interactions, and the key start and end points of the process.



Nodes

Name	Sources	References
01 -Design Area	5	22
02 -Design Phase	4	5
03 -Product Requirements	4	29
04 -Decision process and rationale	4	45
05 -Information Sources	4	16
06 -Assumptions, Uncertainties,Constraints	4	13
07 -Decision Outcome	3	13
09 -Quantifying Cost Impact	4	16
10 -Understanding Cost	4	9

Interview conducted with WPO.3 in office at Rolls-Royce, Derby. The interview was conducted at 3.30pm on Thursday afternoon (9/02/2017).

(start of interview)

INTERVIEWER: Ok, so thanks for taking part. I'm going to run through a brief number of questions, for context. And then we'll go into the main work, which focusses on process. So firstly could you just explain what your role is and your position in the team?

WPO.3: Yep, I'm chief design engineer for the reactor island. Mainly focussing on the progression of the system design for the reactor island on the programme for the SMR team.

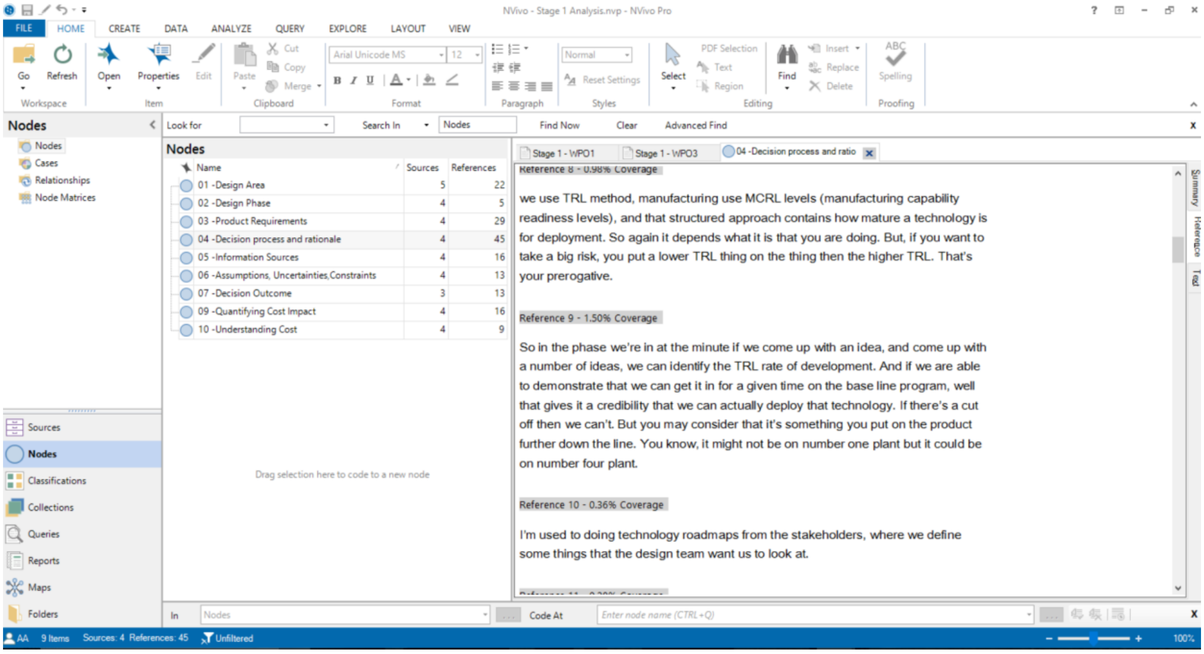
INTERVIEWER: Right, so, from your own personal experiences, and prior positions, what relevant experience do you bring to that role?

WPO.3: Right, so I have quite extensive experience in systems and plant design in sort of previous roles. Looking at the defence, ?? (0.58), and reactor design development. That was where my main experience was, basically, ??(1.05), with Rolls-Royce. I also spent quite a lot of time ?? (1.10), research centre at Rolls-Royce, I spent four years running the ??(1.20) energy and research centre. You know a wide range of new technologies and technology development programmes. So that coupled with the new technology and actual design experience

Figure 36: Transcripts analysed to identify information which can be categorised into "nodes" representing the semi-structured questions in NVivo 11

Several nodes were used to interpret the decision-making process. Other nodes were also used to understand the use of cost information, the need for cost information in supporting the design team to make technical decisions, and an outline understanding of uncertainty and the metrics used to define the design progress (Figure 37).

The participant responses were coded into a format suitable for producing a conceptual representation using simple functional block diagrams. This was achieved by grouping information obtained from the interviews into a higher-level description. The individual transcripts were coded based on the semi-structured questions used during the interview. These were then used to produce individual systems diagram to interpret the design process undertaken by each participant, described in the following section.



Nodes

Name	Sources	References
01 -Design Area	5	22
02 -Design Phase	4	5
03 -Product Requirements	4	29
04 -Decision process and rationale	4	45
05 -Information Sources	4	16
06 -Assumptions, Uncertainties,Constraints	4	13
07 -Decision Outcome	3	13
09 -Quantifying Cost Impact	4	16
10 -Understanding Cost	4	9

Reference 8 - 0.98% Coverage

we use TRL method, manufacturing use MCRL levels (manufacturing capability readiness levels), and that structured approach contains how mature a technology is for deployment. So again it depends what it is that you are doing. But, if you want to take a big risk, you put a lower TRL thing on the thing then the higher TRL. That's your prerogative.

Reference 9 - 1.50% Coverage

So in the phase we're in at the minute if we come up with an idea, and come up with a number of ideas, we can identify the TRL rate of development. And if we are able to demonstrate that we can get it in for a given time on the base line program, well that gives it a credibility that we can actually deploy that technology. If there's a cut off then we can't. But you may consider that it's something you put on the product further down the line. You know, it might not be on number one plant but it could be on number four plant.

Reference 10 - 0.36% Coverage

I'm used to doing technology roadmaps from the stakeholders, where we define some things that the design team want us to look at.

Figure 37: Example where metrics were identified which are used to support the design decision process and rationale

4.5 Case Study Development Process Model

In this section the IDEF0 models are presented and described. IDEF0 models are presented as a hierarchy of diagrams representing different levels of detail described for each activity. The hierarchies are consistent in the use of notation in each level with clear cross-referencing. The activities are categorised into Level 1 and Level 2 representative of the detail available from the interview data for each hierarchy of the IDEF0 Diagram. The level 1 activities are ordered in terms of process dependency. Level 2 activities are then assigned to each level 1 activity for the generated IDEF0 model. Figure 38 illustrates the hierarchical nature of the IDEF0 diagrams generated. The top level of the IDEF0 represents the scope of the analysis usually defined as the "Top Level Context Diagram." Each subsequent ("child") level of the Context Diagram represents a more detailed breakdown of activities within the scope of the IDEF0 analysis.

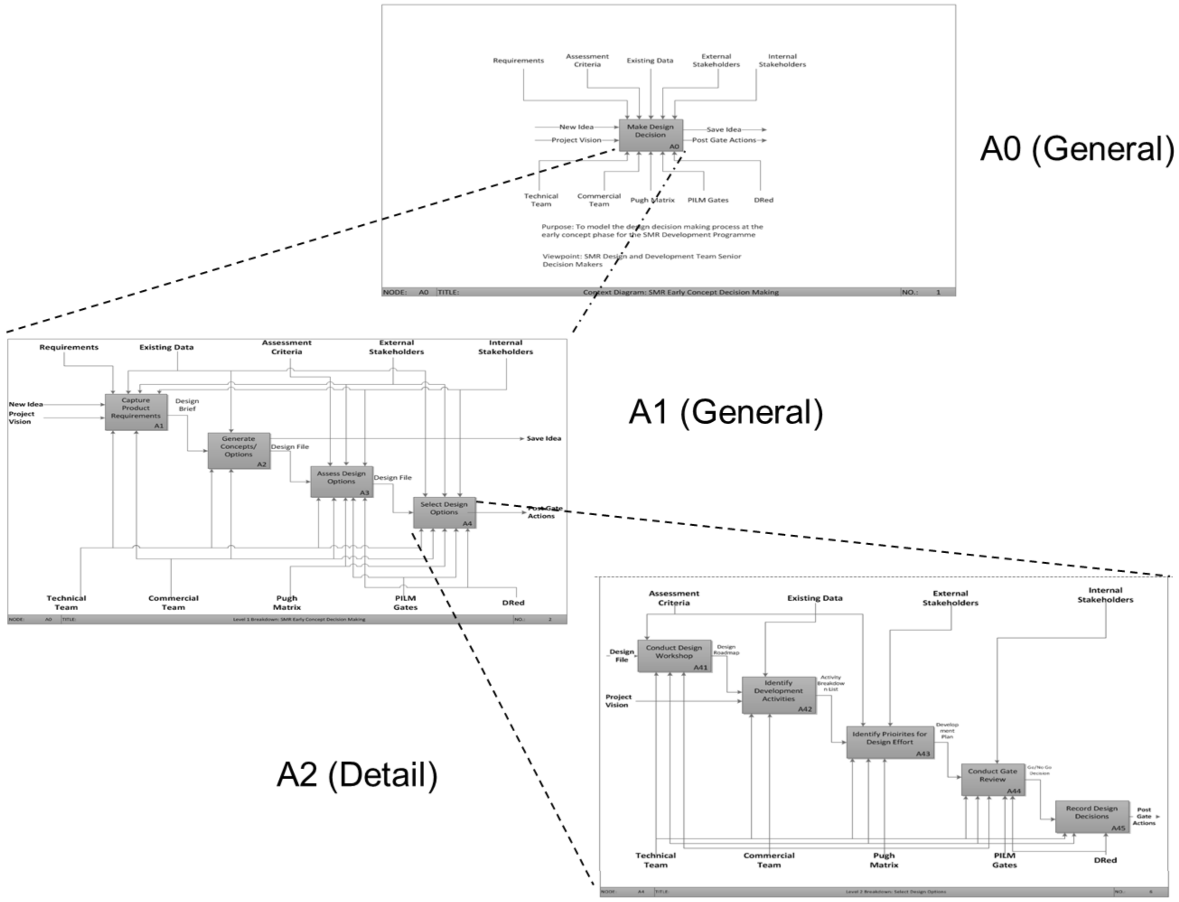


Figure 38: Hierarchical structure of IDEF0 diagrams from A0 general to A2 detail level

The context for the IDEF0 model shown in Figure 32 is the early concept design (Stage 1) of the NPD process. Generating ideas and defining the initial set of requirements for the product solution are outside the scope of the model. The output point of the model is defined as the gate review which, for the early concept definition phase, is defined as the “Overall Concept Review” decision point. The process described in the IDEF0 model describes the steps to take the design requirements, produce several options, selecting the options to carry out additional development work and the selection of the refined design options.

4.5.1 Detailed Breakdown of Level 1 Process Steps

This subsection provides some further description of the Level 1 IDEF0 diagrams shown in Figures 39, 40, 41, 42 and 43 below. Step A11 involves detailing the requirements for the product. Requirements are divided into functional and non-functional types. These requirements are refined when additional information is obtained and are verified using existing data or through engagement with key stakeholders. Existing data refers to historical data, documentation, standards and codes of practice used which are not generated through design activities directly associated with the NPD process. The design team works together to produce the business requirements document derived from the product requirements document. Stakeholders external to the organisation and stakeholders internal to the organisation but not part of the design team are also identified. The requirements are detailed to product or component specific levels, including how these requirements are to be measured.

Developing key ideas through innovation sessions is described in activity A12. A12 forms a sense check as well as idea generation. Ideas to be developed are selected for additional design work, while those which are rejected are recorded for possible future consideration. Assessing design options, shown as activity A13, involves formal and informal reviews. The technical and commercial feasibility of design options are assessed against the requirements criteria. From the review of ideas, design options are selected based on the attributes assigned. The requirements are validated by defining a set of attributes which measure the performance of each design option against a set of measurable criteria. The review outcomes are then recorded in decision files.

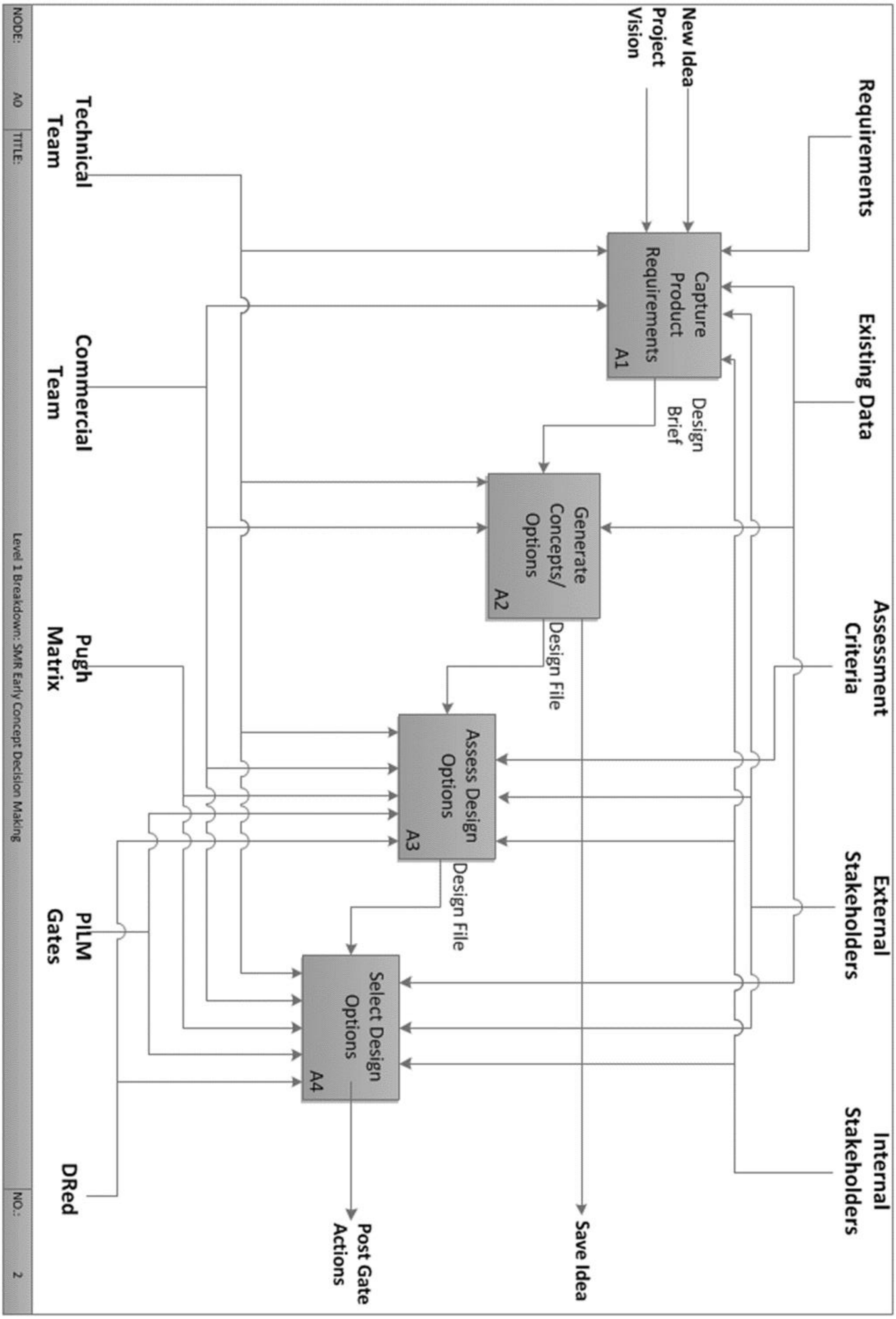


Figure 39: Top-level IDEF0 model of the new product development process

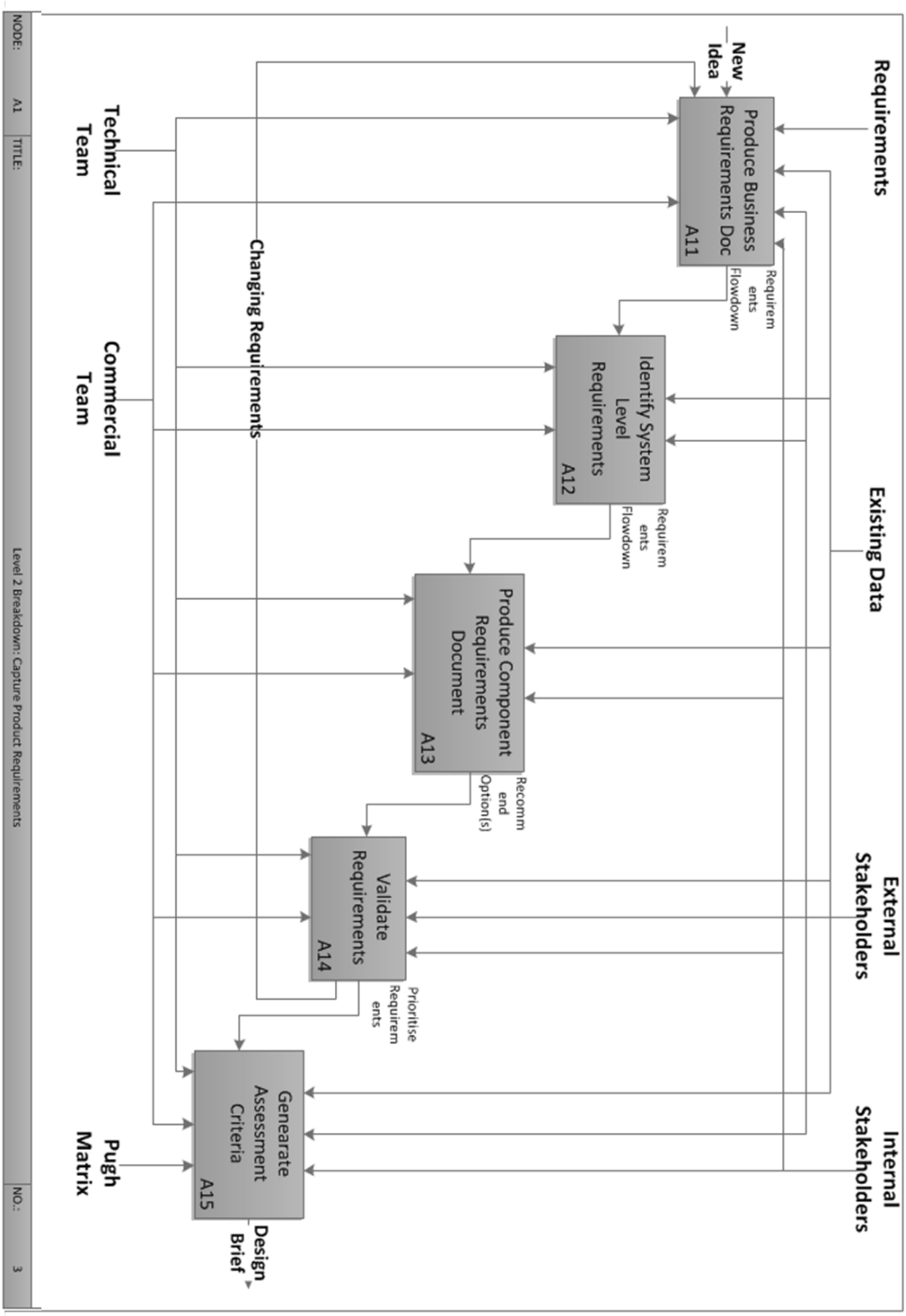


Figure 40: Level 2 IDEF0 model representing requirements capture

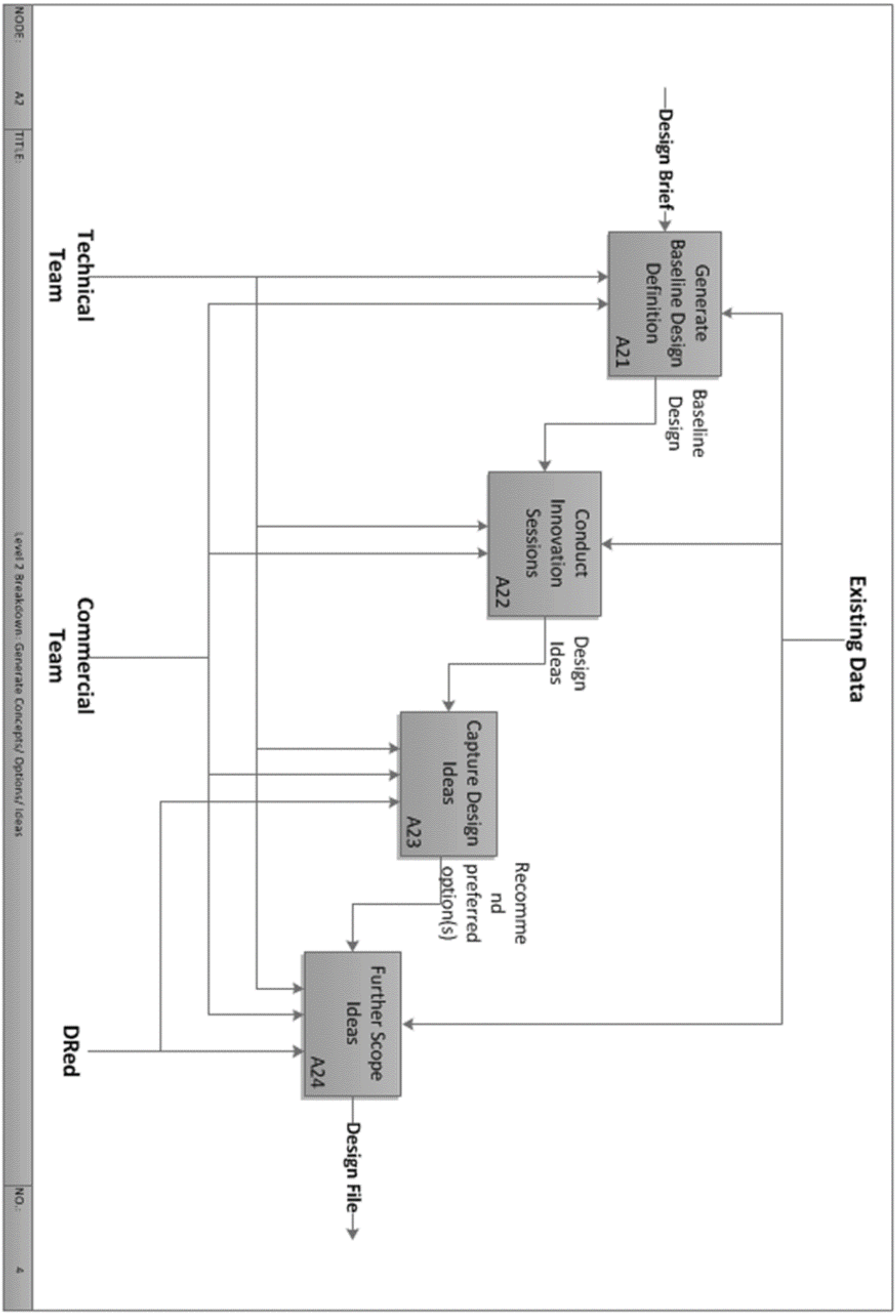


Figure 41: Level 2 IDEF0 model representing concept development

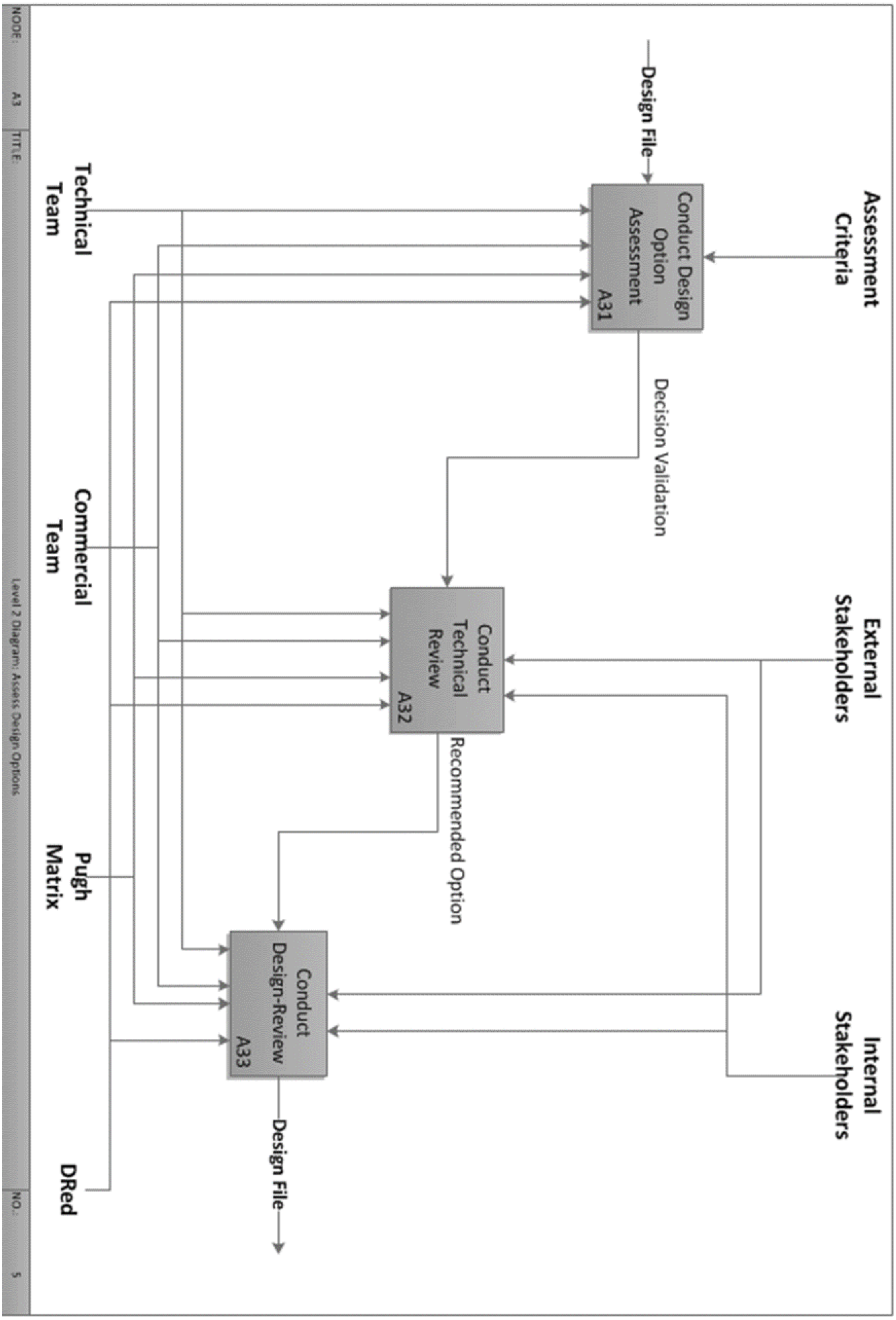


Figure 42: Level 2 IDEF0 model representing design option assessment

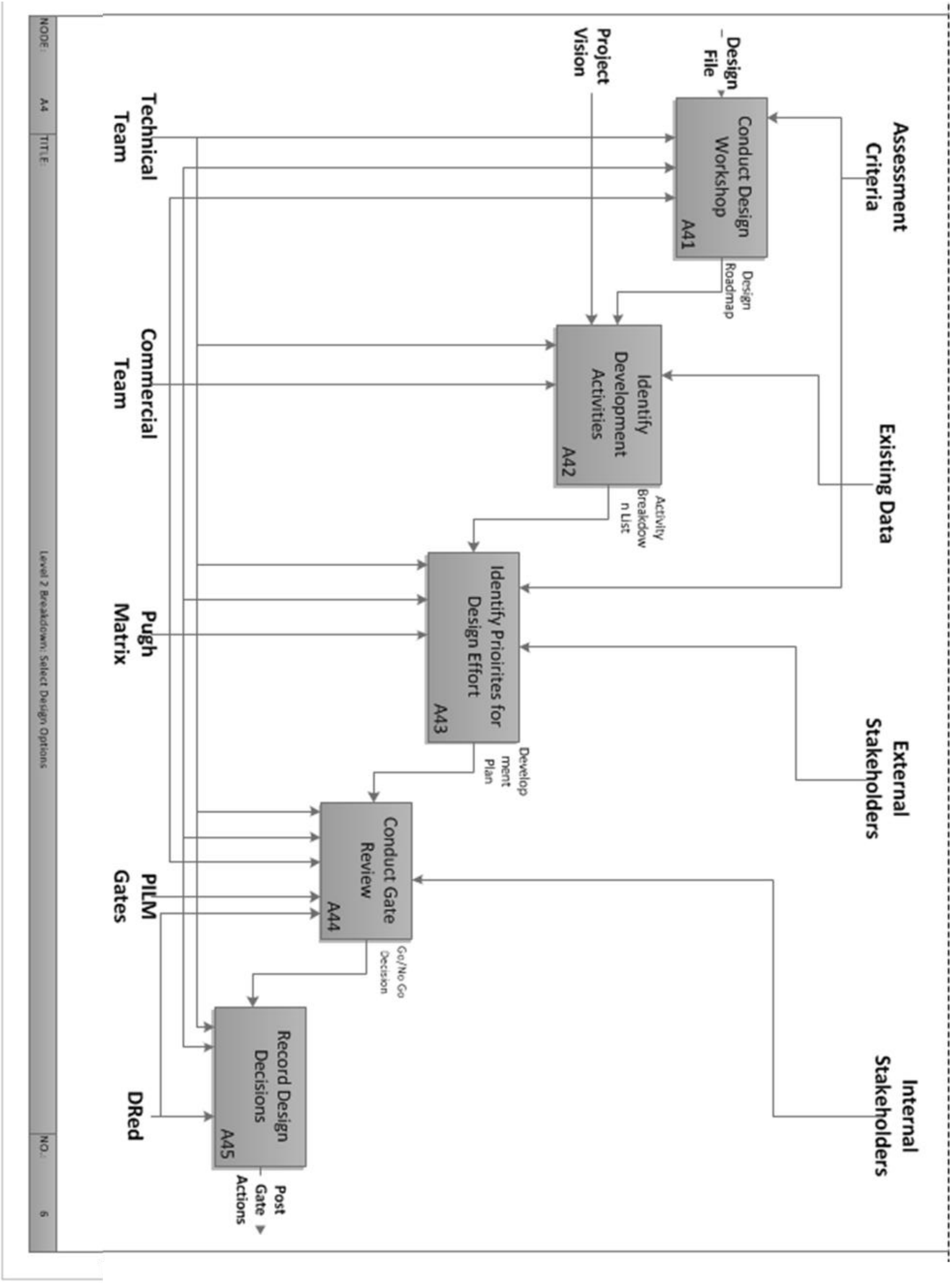


Figure 43: Level 2 IDEF0 model representing design option selection

4.6 Cost Requirements for Early Design Development

The elicitation study is also used to understand the use of cost information to support design decision and to identify the cost metrics used to assess design options. Supporting information from the elicitation study is used in this section to support the outline definition of cost information requirements at the early design stage of the NPD process.

4.6.1 Interpreting Cost Requirements

Different aspects of product cost are mentioned by each of the participants. There is an awareness that a balance is required between the product cost to the customer and the cost to develop the produce (Figure 44). WP02 separated two areas of costs, one associated with the product cost describing the initial unit or capital cost, and the other describing the design and development cost. WP04 determined that the cost requirement of the SMR is to have a competitive cost of generating electricity, and that this was related to the cost of the original equipment, financing the construction, build time and operating costWP04 also divided the cost into two “lenses”: that of the vendor relating this to the cost of supplying and building the site. The other lense was the unit and operating cost for the utility owner.

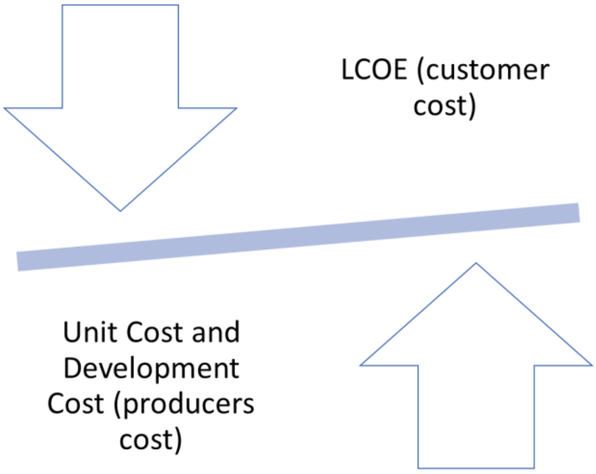


Figure 44: Costs considered by design-decision makers at the early development stage

LCOE was mentioned by all participants during the interview sessions. WP05 focused on the LCOE, defining capital costs, operating costs, and the electrical output of the station. WP01 described a whole lifecycle approach to product cost, from design to decommissioning, as well as understanding different “manifestations of cost” e.g. time. WP04 specified that the long lead time items and materials influenced the site build phase and, therefore, the lifecycle cost. WP06 stated that LCOE drives design decisions, maximising the power obtained for the lowest cost possible. WP07, by contrast, showed that the LCOE was useful as a way of generating a common currency for comparing the costs and benefits of different design options. WP07 also stated that producing as much power for as low a cost as possible was the key driver of design decisions. The viability of the design related to achieving the lowest LCOE and the ability to show confidence in a short build duration.

Schedule is identified as a key cost driver, and that these programmatic costs are interlinked with product cost estimates. For example, if product cost reduction is a key requirement then greater effort may be required to reduce product cost through innovation and design effort incurring a greater development cost.

At the project initiation phase the estimate is used to generate a business case for the project. Design information is gathered and is used to develop cost attributes. Cost is then benchmarked for attribute comparison at each proceeding design decision gate.

4.6.2 Design Optioneering

The participants described design decisions as involving trading costs across different phases of the product lifecycle. Trade studies incorporate multiple criteria, including cost, to determine the most optimal design solution which meets all product requirements as closely as possible. Trade studies support assessments in a logical and rationale way, where little data may be available. WP02 provided some insight into how design decisions could impact on lifecycle costs, presenting a link between the cost of meeting functional requirements of components and the O&M cost:

> *“So sometimes you may consider spending a bit more money up front because it has a through-life cost benefit… you might get a really good back-end cost, but it costs you a lot up-front, or vice-versa. It might be a false economy.”* – WP02

WP04 defined a specific process to rank the design using an impact measure. Similarly, WP05 described a multi-criteria decision analysis tool with the capability of capturing decisions and justifying the selection of an option. WP06 supplemented the understanding of the process by describing how it is a qualitative measure using a set of high, medium and low impact scores which are assigned to each major decision area.

WP04 identified the need to balance the design solution, the manufacturing method and the supply chain in terms of cost, lead time, capability level, and production rates. Another approach, used by WP08, is a sensitivity analysis to identify step changes in cost for high level changes to functional requirements. Sensitivity analysis, where system parameters are changed to observe the effect on system cost. It can provide decision makers with the rationale to prioritise design effort on those areas which are likely to drive the overall cost, or to support the case for a lower cost alternative.

4.6.3 Design Decision Rationale

The rationale for design decisions in this context relate to the review and selection of options for further development. Where several options are presented there is a need to present a rationale based on cost alongside other selection criteria. The intent to establish a rough order magnitude cost as a benchmark was stressed by WP03 to begin target costing for key components. A preliminary Bill of Materials (BoM) is populated with the available information and judgements from the design, manufacturing, and supply chain team members is used to verify the data.

The participants described some of the limitations to what cost estimating methods could be applied at the concept design stage. WP01 and WP02 defined the approach to cost estimating as more subjective, using judgement to determine if a potential option was the lowest cost (using relativistic terms). Understanding of through-life cost presented a major challenge:

> *“So, in the absence of a mature cost model, is A more expensive than B? Not necessarily ‘it’ll be X million’ but ‘we think it’s going to be 10% or 20% more’...”* – WP08

The use of analogy to determine the likely future cost of an option was subject to a degree of uncertainty:

> *“As you go further forward... decisions are made based on relative assessments. You can’t cost accurately until you get at least a level of definition… you’re hoping that you start with that bounding and you get a target value from your cost model… you refine it and if it starts to deviate significantly you get the red alarm bell and you need to understand why.” – WP03*

> *“The design is immature, but also the cost model is immature because this is the first time we’ve done a project exactly like this.” – WP05*

> *“When you get down to the detail of individual decisions, on some levels it’s almost impossible to quantify what cost impact that will have.”* – WP07

The realistic nature of cost (from the perspective of the development organisation) lends credibility to the estimate and becomes a significant aspect of achieving acceptability when compared with the business case. However, there are limitations to quantifying the impact of design decisions.

4.7 Early Cost Estimating Challenges

In this section the challenges and limitations associated with the use of cost information in the early concept design stage are discussed. The challenges identified through the elicitation study are compared against the findings from the literature review identified in Chapter 2 (summarised in Figure 45).

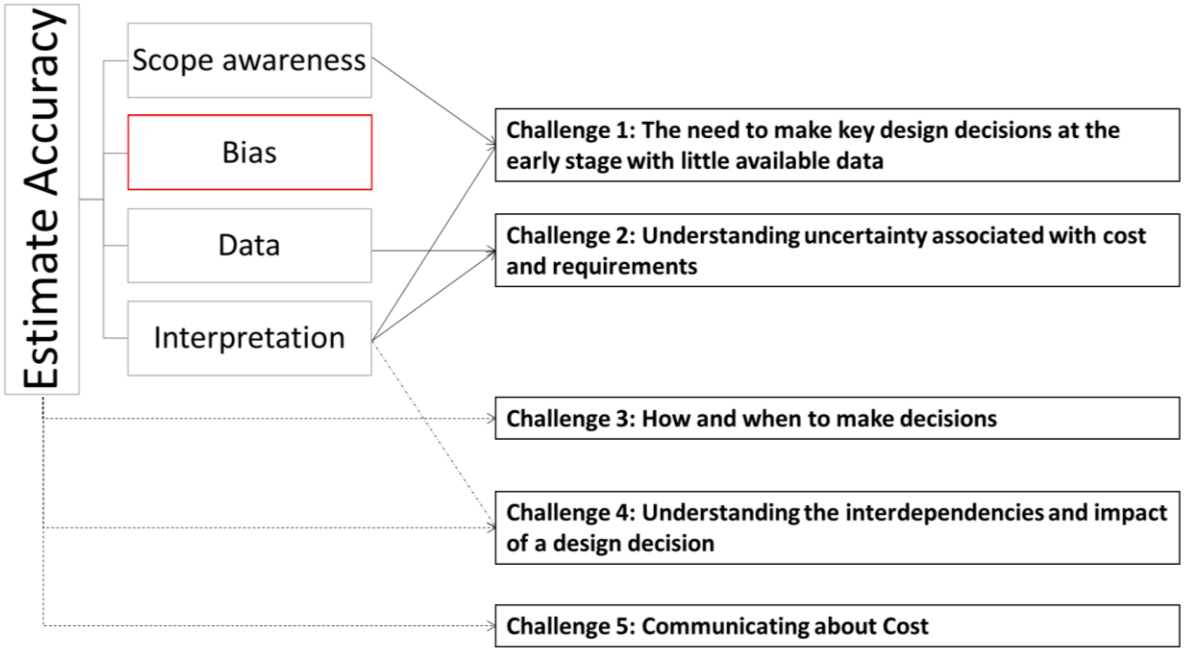


Figure 45: Gaps and challenges with early cost estimating for the SMR case study

In the elicitation study there is no discussion about the potential bias introduced through subjective estimating at the early design stage. The first two challenges discussed in this section relate to three of the main challenges identified with early design cost estimating in literature (See Chapter 2). Additional challenges have been identified that do not directly relate to the literature findings. Challenges 3, 4 and 5 relate most directly to the understanding of accuracy and confidence associated with estimating at the early design stage, and the impact of design decisions in a complex project. Each of the challenges are now discussed.

Challenge 1: The need to make key design decisions at the early stage with little available data

The cost paradox at the early concept design stage (described in Chapter 2) is understood by the SMR design team as a limitation to cost estimating. WP08 identified that the design decisions made, although leading to a more mature idea of the design, were not necessarily final decisions. The potential for change in the design remains high for as long as possible. Judgement is often used with a heavy reliance on assumptions to understand cost requirements. The ability to engage actual experts is restricted both due to the low maturity of the design and the commercial sensitivity of the design development programme.

Challenge 2: Understanding uncertainty associated with cost and requirements

The need for an improved basis of decision-making is related to the knowledge available. Better knowledge leads to greater design certainty, enabling greater clarity for decisions.

> *"It's inherent uncertainty... how you manage it (so that) you can turn on your power station when you said you would… and how much you said it would cost."* – WP01

One way of managing uncertainty was identified as clearly understanding requirements:

> *"if we define our requirements, then you can more closely align costs and your tolerances start to narrow down… we can narrow our efforts then. And that's when the tolerance starts to go down… certainty of the design, it funnels in. You're making decisions, and each decision gets you into a more defined position."*

Collecting and analysing useful data can also be resource consuming, and expensive to conduct. At the same time, the participants state that it is difficult to quantify the accuracy needed. A question develops around what level of accuracy is achievable at the early stages of the design process for an innovative product, and how this is viewed by decision makers in the context of what is acceptable information upon which to make a decision.

Challenge 3: How and when to make decisions

The participants identify that the most significant challenge is the ability to make a decision when the cost model was immature. The scope of the cost model, cost requirements, as well as understanding of the cost drivers influence the decision outcome.

> *"It's identifying the key areas where you really need to progress that certainty… those are the areas you really want to focus your design effort to reduce the cost."* – WP03

There is a need to keep options open as possible at the early design stage until the risks and uncertainty are better understood. Decisions need to be taken such that different options are still available that may link directly to cost and time certainty requirements, but that may also be related to higher uncertainty.

> *"although innovation is not a requirement, delivering cost savings often requires you changing the way you do things today… and for some people that creates uneasiness about how to resolve them,"* – WP08

> "But it's always a balance between making a process that then becomes onerous, because that kills ideas." – WP01

Challenge 4: Understanding the interdependencies and impact of a design decision

The impact of a design decision on cost and time certainty is a significant challenge identified by the participants. Understanding how decisions affect different areas of the design is identified as a key question associated with the quality of the cost information generated at the early design stage. One approach used by the design team is a Pareto method to establish where the greatest benefit would be realised by focusing costing and design efforts on the "high impact" parts.

> "to identify bigger cost items, to identify where the big cost items are, and they're the ones that you really need to focus on

> and understand and get more defined because if you're out on those then your costs will grow significantly." – WP03

The assumption here is that the biggest cost items are also the biggest cost drivers. There was some awareness that the aggregation of smaller cost items could lead to significant and as yet, unquantifiable cost drivers:

> *"The cumulative effect of many small cost increases can catch you out."* – WP08

However, the uncertainty associated with the impact of a design decision on different interfacing parts of the design is difficult to quantify at the early design stage. Design decisions may have far reaching, indirect interfaces, not defined by early cost estimate and models.

Challenge 5: Communicating about Cost

Cost estimating is carried out to support an array of activities and functional requirements associated with different aspects of the design. Generally, the team consists of manufacturing engineers, supply chain management, project management and design engineers.

> *"If we have that vision, and we're clear about the key goals of that vision, and the objectives, then a decision may be attached to the strategy. But if it's not communicated then people struggle to [understand and accept the decision]."* – WP05

> "We need to get to the right stage at the right time, and not too early, because we'll be knocking on the door saying oh I want a drawing now. But we're not going to get a drawing until 6 months' time." – WP06

Clear communication of cost information and the impact of cost across the design is limited. It is not necessarily more cost information which is required by the team, but better ways of using cost information to inform decisions to influence the acceptability of the design.

4.8 Summary

In this chapter a model has been generated which represents the early concept design decision-making process used by the case study design team. Cost can provide a supporting rationale for making design decisions. The types of decisions, basis of these decisions, and how different options are assessed at different decision points have been defined by the case study team.

The Stage-Gate© method is used to structure the design development process by understanding which questions about the design need answering at a point in the development cycle. Design optioneering involves trading different criteria to generate a solution that meets requirements. The criteria for non-functional requirements and functional requirements can be fuzzy at the early design stage. The long duration of NPD, limited accessibility of information, and the need to make significant lifecycle affecting decisions at the early stage is a major challenge in the NPD process.

There are multiple viewpoints on the cost requirements to meet customer requirements, showing inconsistencies in how key cost requirements are understood. The general approach is to observe cost from the perspective of the customer, in this case the LCOE.

The level of knowledge of cost is generally understood to be the main limitation of more accurate early cost estimates. The cost information, by the very nature of the early concept design phase, is immature. Fuzzy or relativistic information is used to trade through design options. The main downside to sensitivity analysis is the inability to assess the impact of dependencies between cost elements, and the combined impact of cost uncertainty.

Cost uncertainty information is not described by any of the elicitation study participants as an area considered in the analysis of cost in design optioneering studies. However, confidence in the estimate is described by several participants as something which can support design decisions at the early development stage. The next chapter addresses the production and use of cost uncertainty information in the early design phase of the case study.

5 Applying Uncertainty Analysis to Early Estimates

5.1 Chapter Overview

In Chapter 4 the interpretation of subjectivity and uncertainty associated with early cost estimating were identified as major gaps in that affect the design decision making. The purpose of this chapter is to understand how cost uncertainty information is interpreted by the design team. Figure 46 shows that this chapter forms the last chapter in which the requirements for a new method are identified. This chapter aligns with research objective 3:

To identify how cost uncertainty information is used in the case study organisation to support design decision-making

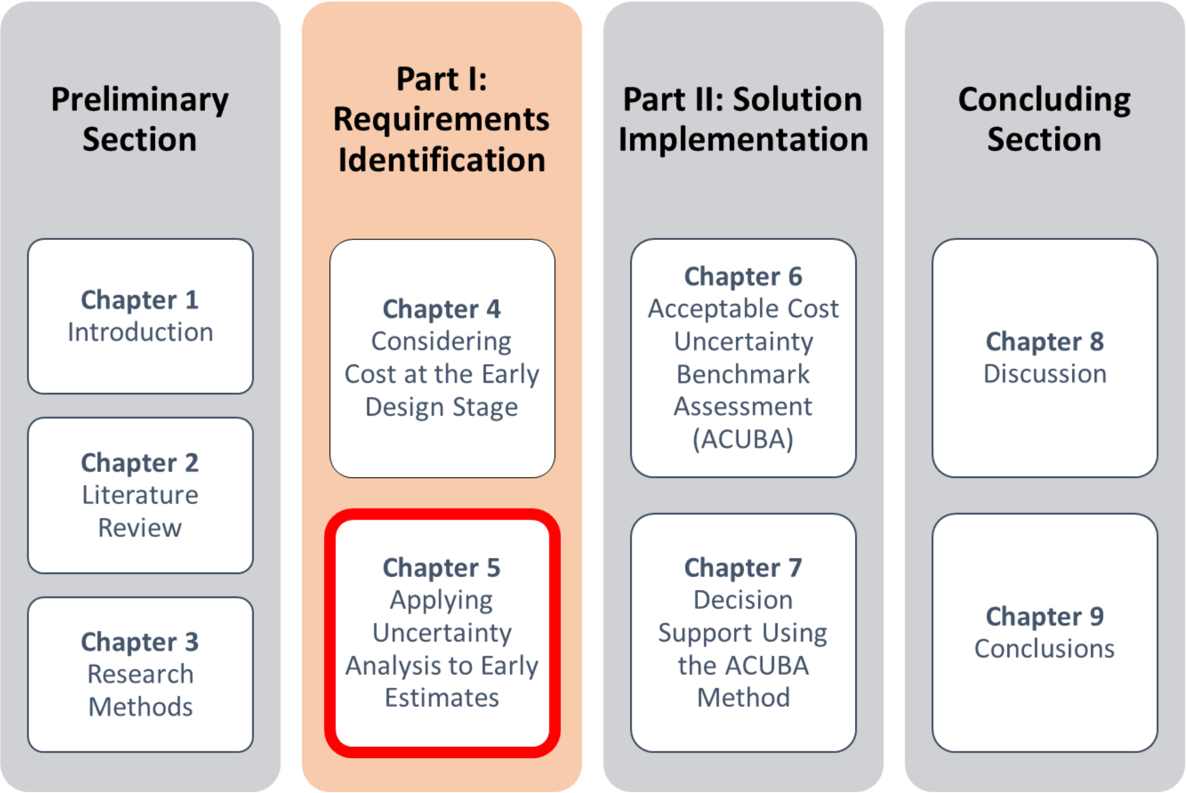


Figure 46: Chapter 5 in the context of the thesis

By understanding the limitations of early design stage uncertainty analysis, as applied to the case study, the requirements for a new method are identified. Section 5.2 describes the two ways the case study organisation currently present cost uncertainty information. Section 5.3 then presents a survey carried out with the case study organisation to investigate how cost uncertainty information is interpreted. The limitations of the existing approaches to cost uncertainty analysis are discussed in Section 5.4. The requirements to improve cost uncertainty analysis are provided in Section 5.5. Section 5.6 summarises the key findings from the investigation into applying cost uncertainty at the early design stage.

5.2 Presenting Cost Uncertainty Information

A major challenge identified in chapter 2 is the lack of consistency in the application of cost uncertainty analysis at the early design stage due to its subjectivity. Cost estimates are used to support the rationale for early design decisions and to prioritize the design effort on those areas which are likely to drive the overall cost. At the early design stage there will inevitably be a gap in the availability and accuracy of information to support design decisions. The cost uncertainty range at the early design stage is defined here as the level of confidence which the estimator has in the inputs used to produce the estimate and the realistic nature of the result. Presenting the accuracy range for the estimate should provide the stakeholder with a better understand of the confidence in an estimate.

This section concentrates on the output of the uncertainty analysis. Two types of cost uncertainty information presentation are shown. The uncertainty describing the confidence in the estimate from the perspective of the cost estimator are shown and is based on the availability of information within the case study organisation and the method of analysis. The first method is an uncertainty distribution based on subjective assessment. The second method described is a cost maturity metric which uses an ordinal scale to describe the confidence in a cost estimate.

5.2.1 Uncertainty Distribution

The most widely used assessments for probability distributions are central measure (a mean, median or mode) and the assessment of quantiles (O’Hagan et.al. 2006; Devilee and Knol, 2012). For early cost estimates the 3-point estimate can be used to define a distribution of possible costs associated with that estimate. Typically, the lower and upper bounds estimated by experts represent the 15 percent and 85 percent levels, respectively, of all possible outcomes to account for skew (GAO, 2009). The specific type of distribution (e.g. normal, triangular, etc) is not discsused in this chapter. At the early design phase it could be acceptable to simply apply a normal distribution to the point estimate (GAO, 2009). An example of cost uncertainty data presented as a distribution can be seen in Agar et al (2018).

5.2.2 Qualitative Cost Maturity Metrics

In the previous chapter the case study design team identify the use of a trade matrix to investigate and optimise the design for different attributes including cost. The trade matrix approach requires the input of cost information generated using historic data or expert judgement. As historic data is limited in the case study there is a tendency to use available data supported by qualitative metrics. One such technique is the cost Estimate Maturity Level (EML), a new method developed by the case study organisation. The EML provides a single metric which defines the overall uncertainty of the cost estimate from different sources of uncertainty. The maturity describes the confidence of the estimator in the estimate they have generated. Assigning ordinal values from 1-9 for each of these sub-categories of the estimate the EML generates an overall cost confidence rating. The sub-categories of the EML metric is shown in Figure 47.

The metric requires some detailed bottom-up estimates for components of a product, which limits the application to the latter stages of the design process. When there is sufficient detail, i.e. at the detailed design stage, the design team employ a cost maturity metric to individual components. Prior to this study the EML had not been applied to the case design project given that the case study was at the early concept stage (See Chapter 4).

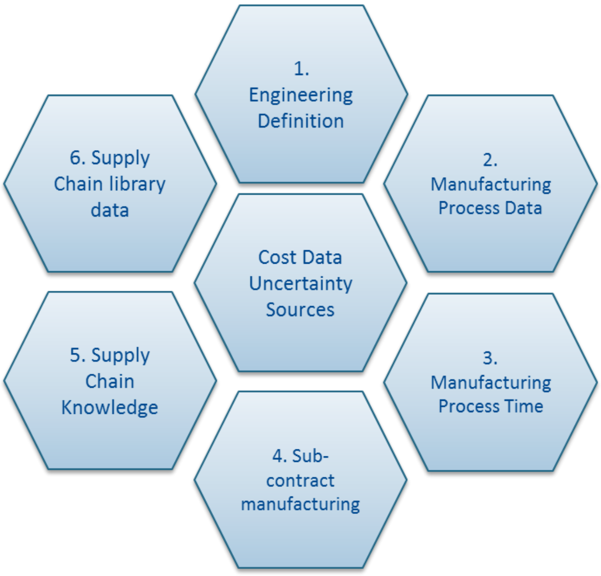


Figure 47: Sources of epistemic uncertainty considered within the maturity metric

Engineering definition relates to the type of information such as a detailed drawing or outline drawing used to generate the estimate. The manufacturing data sources are associated with the manufacturing operations used to produce the component from raw material to finish goods. The Supply Chain Definition Data Metric is associated with the level of internal and external manufacturing supply chain definition. The Cost Model Data Metric is primarily based on the logic which identifies the uncertainty associated with mistakes within the model. At the early design stage, the model is considerably simpler than at the detailed design stage.

5.3 Interpreting Cost Uncertainty Information

The way a cost estimate is communicated can influence a decision outcome (Fischhoff, 2015). In this section a survey of the case study design team is presented in which different methods of presenting cost information and the resulting influence on decision-making is investigated. The purpose of the study is to identify whether differences in the presentation of cost uncertainty influences the team decision rationale.

5.3.1 Method

A survey was carried out in the form of a presentation workshop held in the case study office. The workshop participants were recruited on a voluntary basis and consisted of different members of the case study design team (Figure 48). The participants were made aware of the purpose of the workshop and were requested to individually select one of a discrete number of options based on the cost information that was presented. 20 participants were involved in the workshop, representing 40% of the design team.

Prior to the presentation of each scenario the participants did not have access to the cost information, or the scenario details. An accompanying questionnaire was completed by each participant during the workshop. The questionnaires were anonymised with only the individual function within the design team being recorded. An example component was selected as the basis of the cost analysis. Three methods of presenting cost data were then shown to the participants.

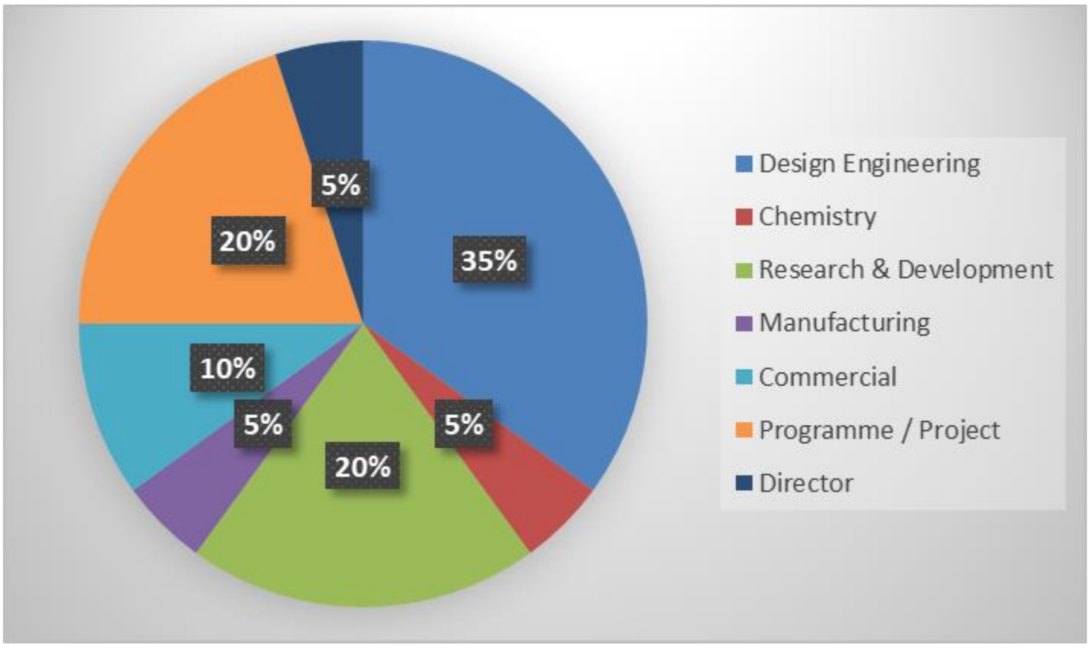


Figure 48: Composition of participants involved in the survey

After each scenario was presented the participants were asked whether they were familiar with the method of presenting cost information. For each of the scenarios the participants were then asked to record on the questionnaire "**best cost option**" from the 3 available choices. The wording was purposefully chosen so as not bias the personal opinions of each participant regarding the meaning of "best cost option". The cost requirements of the SMR described in Chapter 4 show that, in addition to the need for a lowest cost option, cost certainty also plays a key role in the commercial success of the product.

5.3.1.1 Generating Cost Estimate Information

Each of the scenarios presented cost information in different ways. Three estimates were developed using different methods and sources of data (Table 9).

Table 9: Estimates generated for the component

	INFORMATION USED	UNCERTAINTY
ESTIMATE A	1. Dimensioned engineering drawing; 2. Manufacturing process defined; 3. Supply chain engaged.	Low
ESTIMATE B	1. Sketch drawing; 2. Manufacturing process not defined; 3. Supply chain not engaged.	High
ESTIMATE C	1. Dimensioned engineering drawing; 2. Manufacturing process not defined; 3. Supply chain not engaged.	Medium

Estimate A involved the most detailed analysis where direct contact was made with supply chain and manufacturing process engineers to estimate cost inputs. An engineering drawing was available including dimensions and material composition. A partial bottom-up cost estimating approach using the Bill of Materials for the component was then verified by engaging with the supply chain.

Estimate B is the least detailed analysis, using subjective knowledge to estimate the cost. A sketch drawing was used to understand the rough dimensions and material properties of the component. Some research was conducted into the manufacturing processes used and the potential supply chain available, but the analysis was not validated or verified. The cost estimate was a top-down Rough Order of Magnitude (ROM) assessment using the expert judgement of the estimator.

For Estimate C an engineering drawing was available, however the estimator did not have time to directly engage suppliers or manufacturing process engineers to develop an estimate. The estimator used existing knowledge in the form of a Microsoft Excel spreadsheet with labour and material cost rates based on previous projects. The supply chain was not engaged and so the estimating method was not verified against another estimating method.

5.3.1.2 Scenario 1 - Point Estimate

In the first scenario presented to the participants a single point estimate for each option was presented (Figure 49). Estimate A was the highest cost, Estimate C was the lowest cost, and Estimate B was in between.

Estimate A = £ 10,500k
Estimate B = £ 8,000k
Estimate C = £ 5,000k

Figure 49: Point Estimates presented to participants

5.3.1.3 Scenario 2 - Distribution of 3-point Estimates

The second scenario presented to participants was a triangular distribution for each option (Figure 50). The estimates presented the most likely costs for each option to be the same as the point estimates presented in Scenario 1. Additionally, the distribution widths of Estimate A and C were approximately the same, showing a similar level of uncertainty for each option. Option B was the least certain, showing a broad range incorporating almost all the uncertainty range of option A and C.

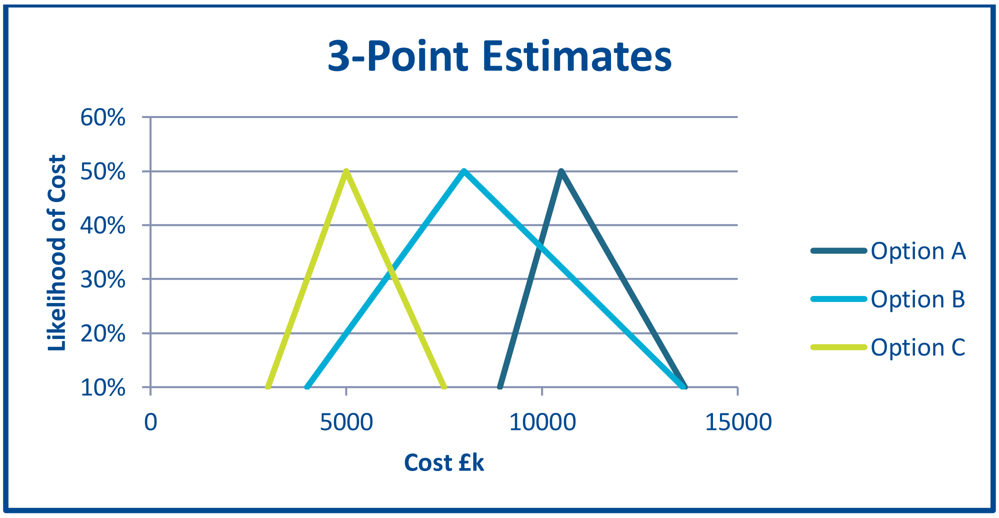


Figure 50: 3-Point Estimate Distribution presented to participants

5.3.1.4 Scenario 3 – Cost Estimate Maturity Rating

For Scenario 3 a brief overview of the EML described in Section 5.2 was provided. The researcher was careful not to discuss how to interpret the diagram during the workshop but described the components of the EML. Figure 51 was presented at the workshop for the final scenario to interpret the EML associated with each estimate.

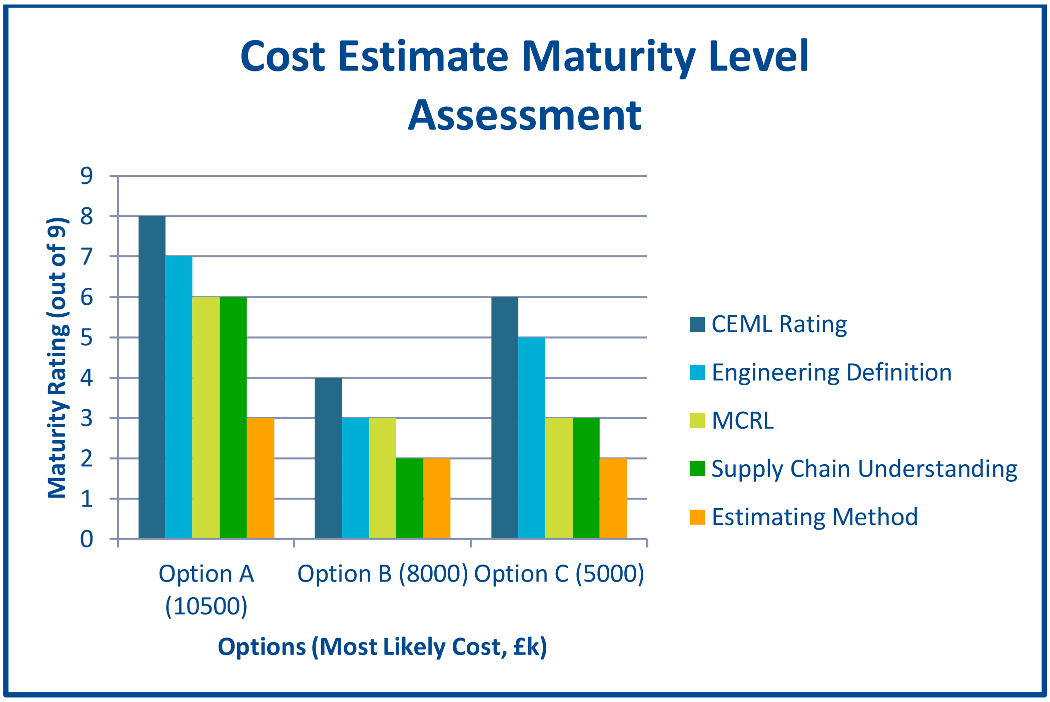


Figure 51: EML ratings presented to participants

Finally, the participants were asked to rank each method of presenting cost information "in terms of which format gives the most confidence that they had chosen the **best cost** option," and their reasoning for selecting that order.

5.3.2 Results

In this section the results of the uncertainty information presentation workshop are presented. The survey results are supplemented with additional questions that identified the reasoning for selecting the option in each scenario.

5.3.2.1 Scenario 1

When presented with point estimates in Scenario 1 50% of the participants identified Estimate C as the best cost option (Figure 52). C was selected on the basis that it was the cheapest or lowest cost option, and since no further information is available to inform the decision. Estimate B was also a popular choice selected by 43% of participants. Primarily, Estimate B was identified as a “mid-range” value, where A and C were potentially over or under estimated. B was also identified as the most realistic option based on the complexity and perceived expense of the component. One participant suggested that estimate B was selected because of a lack of basis upon which to select an option, “shooting for the middle”.

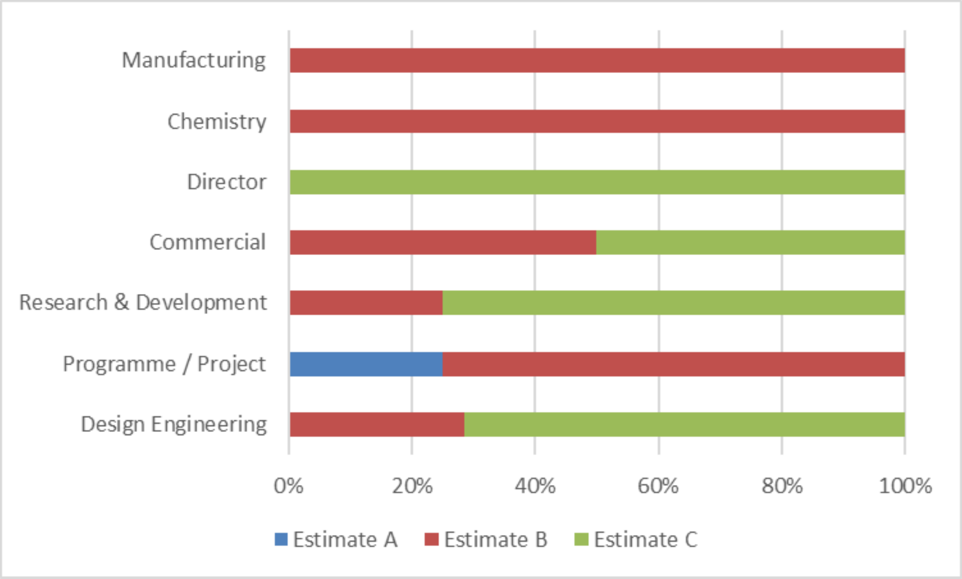


Figure 52: Selection of Preferred Estimate Based on Information Presented in Scenario 1

The design engineering and R&D functions participants placed more emphasis on the “cheapest” option as the reason for choosing C, while the programme and project team members tended to select the perceived mid-range value of Estimate B. One project team member chose the highest cost option (Estimate A) stating that they would not have chosen any of the estimates if that option was available.

5.3.2.2 Scenario 2

11 of the participants had familiarity with the presentation of cost uncertainty in Scenario 2. Again, Estimate C was identified as the best cost option by the majority of the design engineers, 50% of the R&D and commercial team members, as well as the director and chemistry team members (Figure 53). As well as being the lowest cost option, the narrower distribution when compared with estimate B and similarity compared with Estimate A improved confidence in the selection of Estimate C.

Estimate B was less popular than in Scenario 1. However, most of the programme and project team members selected Estimate B. The main reason B was selected is due to it being interpreted as the average likely cost, or most likely to be correct when compared with the other options. One participant also identified that option B covered the entire range of possible costs for all the options so that the actual cost would lie in the range estimated by B.

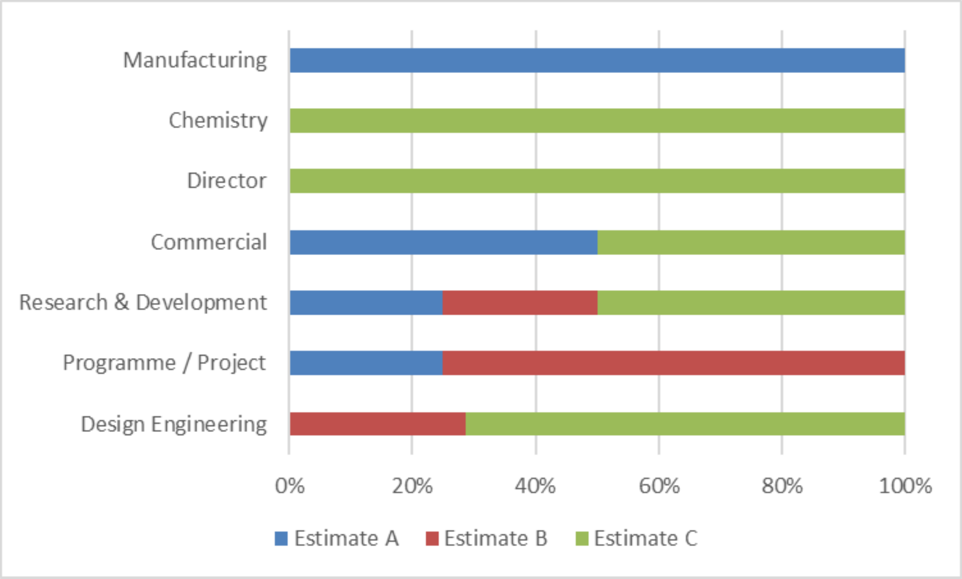


Figure 53: Selection of Preferred Estimate Based on Information Presented in Scenario 2

Estimate A was selected by an increasing number of the participants compared with Scenario 1, as it provided a narrower range than Estimate B. Two of the participants appeared to have misread or misunderstood the diagram, providing the reason for selection option A as due to it being the cheapest option or having the same likelihood of being the cost of option B.

5.3.2.3 Scenario 3

13 of the 20 participants had not previously seen the EML presented in Scenario 3, and so they had no knowledge of how to interpret the information based on training or experience. All of the programme and project team participants noted that they had some familiarity with the metric, while the majority of design engineers and R&D participants had no familiarity.

Based on the estimate presented, the most popular choice became Estimate A which was identified by participants as having the lowest risk due to the higher maturity rating

(Figure 54). More than half of the design engineers selected A, while 75% of the programme and project participants also selected A. Participants related this lower risk to a greater understanding of engineering definition, and the lower chance of unexpected costs arising. Greater certainty, more trustworthy, greater confidence in the underpinning data and the best chance of success are statements assigned by participants to the higher maturity rating, and the main reasons for selecting A. One participant stated that the greater confidence "justified" the higher cost.

Estimate B was selected by just one participant, who had also selected B in both the previous 2 scenarios. Estimate C was still popular with 8 participants, being identified as only slightly less mature than A but still being the cheapest overall. Participants who were previously aware of the EML all selected Estimate A, with 4 out of the 6 participants changing from selecting Estimate B to selecting A. The main decision change was related to those who had selected Estimate B previously in Scenario 2, changing to A in scenario 3. These participants had consistently selected the mid-range or were more conservative based on the lack of knowledge in previous scenarios. With the additional information they described having increased confidence and greater certainty in the estimate.

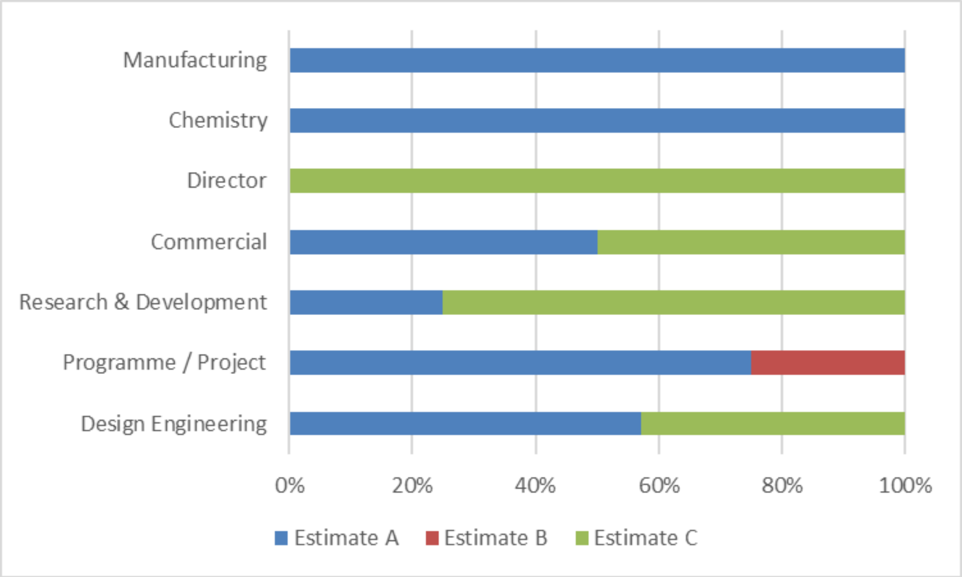


Figure 54: Selection of Preferred Estimate Based on Information Presented in Scenario 3

Participants selected either estimate A based on the greater certainty of cost provided by this option, or C based on a significantly lower cost compared with the other options. Those who had no previous experience of the EML but had selected Estimate C in

Scenario 2 still selected Estimate C in Scenario 3. Those who selected C suggested that, despite it being less mature and having a slightly higher risk than Estimate A, C provided a potentially large cost saving over Estimate A.

5.3.2.4 Preferred Method of Presenting Information

19 of the 20 participants selected the Scenario 3 method of presenting data (EML) as the preferred method over Scenario 1 (point estimates) and Scenario 2 (uncertainty distributions). The point estimate was identified as the least informative and so was considered immature, although one participant who had selected the cheapest overall cost consistently for each scenario preferred the point estimate as a simpler method. Rather than discussing in terms uncertainty ranges or purely based on lowest cost, the basis of decisions from Scenario 3 were related to estimate maturity, an awareness of where data had come from in the estimate, and more granularity on the sources of data related to Supply Chain, Engineering definition and Manufacturing Process knowledge. The EML presentation added confidence in the quality of the estimate.

When presented with a point estimate or a 3-point estimate, participants tended towards the lowest cost option. The result of providing additional information is a shifting of the decision from the lowest cost option to a more reasoned discussion regarding the confidence in the estimate (Figure 55).

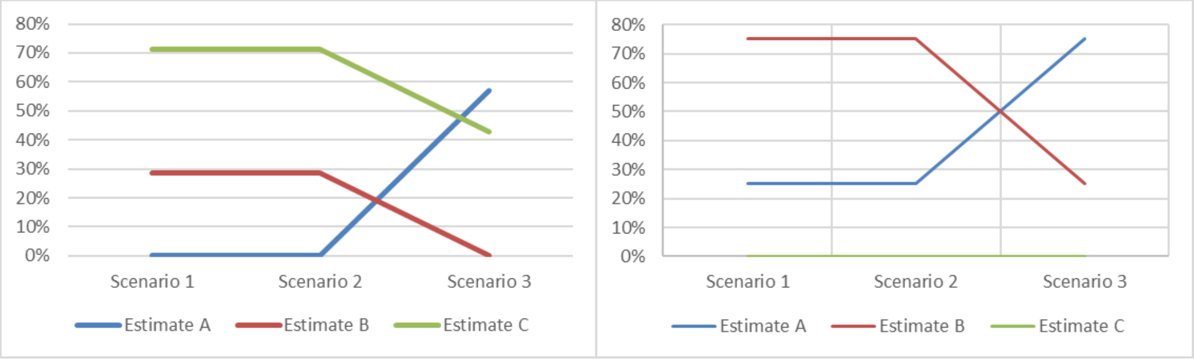


Figure 55: Design Engineers (Graph A) and Programme/ Project Team (Graph B) Change Decision When EML Presented

Programme and project function team members consistently selected the more certain but higher cost option when presented with a distribution of possible costs. Whereas, Design Engineers consistently selected the lowest cost option in each of the scenarios.

5.4 Discussion

The accuracy of a cost estimate generated at the early design stage for the case study is quantified deterministically using expert judgement. At the early concept phase, a complete design definition is not available. The PBS is incomplete, with only partial cost information available about the identified components. Simply applying uncertainty ranges subjectively to high levels in the PBS may not be an effective method for supporting design decisions at the early concept development phase.

There are two schools of thought which relate the term “best cost option” to the SMR product cost. That is the notion of cheapest option, and the notion of greatest certainty of cost. The results of this study suggest that these two cost requirements were better understood using Scenario 3, where there was a clear choice between a lower maturity but also lower cost option and a higher cost but higher maturity estimate. Scenario 3 appeared to provide a more consistent rationale for the selection of an option based on cost.

The case study design team require an analysis technique to provide information showing which design options will present the greatest certainty of cost. By only presenting design options which are certain, innovation could be stifled. The design team are aware of the inherent uncertainty associated with early design stage decisions, and so there is a tolerability for the risk associated with making early design decisions based on limited cost information (See Chapter 4). A “suitably accurate” estimate is required that accounts for the uncertainty associated with early design stage cost estimates.

When presented with additional information regarding the uncertainty of different data sources within the cost model, the design team is able to present a more reasoned rationale for the decision. Presenting cost uncertainty in the form of a maturity metric could be used to demonstrate to the decision maker the effort required to increase the maturity to a level which allows a more reasoned decision to be made. Using a maturity metric may present the design team with a standard measure of the confidence in an estimate that is complimentary with existing processes.

The case study organisation has developed a component-level method for presenting the cost estimate confidence in the form of a qualitative maturity metric. The ability to differentiate between sources of uncertainty associated with the estimate is shown to present a useful source of additional granularity of information for the decision maker. Uncertainty ranges are defined subjectively based on the level of detailed information, and the cost estimating techniques available at a specified maturity level of the design phase. The maturity metric is currently only suitable for component-level assessment of cost models based on information available at the detailed design stage. In the design phase until full maturity is achieved, the product is never completely defined and will therefore not be suitable for use with the current cost estimate maturity assessment method.

The interpretation and presentation of cost uncertainty data varies from person to person suggesting that there is a need for a standard protocol to be employed to quantify and communicate cost uncertainty information. Although more confidence is placed in a higher maturity estimate the EML ratings are based on expert judgement. The importance of each component of the EML have not been weighted using a verifiable process. In different scenarios the relative importance of each uncertainty component to the confidence in the estimate is likely to change. For innovative products at the early concept design phase, it is expected that the level of engineering definition would be low.

After generating the PBS a total product cost estimate can be established. The propagation of uncertainty across different levels of the PBS becomes important, not only in providing a reasonable representation of the overall cost uncertainty, but also to understand the effort required to reduce cost uncertainty.

5.5 Summary

The question of how cost uncertainty information is interpreted in the case study is addressed in this chapter. Several approaches to interpreting the overall cost uncertainty for a product estimate at the early design phase have already been described in this chapter. These have been found to be unable to account for the complex interdependencies between sources of cost uncertainty when there is little design information available. There is no standard approach for analysing cost uncertainty and risk at the early design stage. Assigning accuracy ranges generically across projects is difficult, because of the number of potential variations in project conditions. A clear definition and separation of uncertainty and risk considerations is required for the design team to understand the impact of decisions on cost, to ensure risks which are not already captured in the uncertainty model are incorporated into the risk analysis.

The product development process involves managing uncertainty and risk to create a design which meets customer requirements. Designing for cost certainty is a requirement which influences design decisions. All cost estimates are subject to a degree of risk and uncertainty. The decisions made at each stage of the design process are often interlinked, where strategic decisions influence the technical design and vice versa. For the early design development stage understanding the uncertainty around the point estimate can inform key technical decisions, and therefore influence the entire product Life Cycle Cost (LCC). How to integrate the impact of decisions on the LCC cost, unit cost, and development cost associated is still a key limitation.

Once an estimate has been generated an understanding of the level of certainty associated with the cost is required by the design team. Cost uncertainty analysis should provide decision makers with an understanding of the level of confidence associated with the estimate. However, this chapter has identified that cost uncertainty analysis at the early design stage is limited in its usefulness to support early concept design decision making in the case study design team. Providing more granular information related to the sources of uncertainty associated with the cost estimate using the EML is shown to influence decision-making rationale. Presenting cost information with a maturity rating, therefore, forms the basis of the decision support method presented in Chapter 6.

6 Acceptable Cost Uncertainty Benchmark Analysis (ACUBA)

6.1 Chapter Overview

This chapter presents and describes the Acceptable Cost Uncertainty Benchmark Analysis (ACUBA) method. The ACUBA method has been developed based on the requirements for cost information support to early decisions identified in Part I of the thesis (Figure 56). This chapter aligns with research objective 4:

> *Develop a method to determine the acceptable uncertainty range for the defined stage of the design process.*

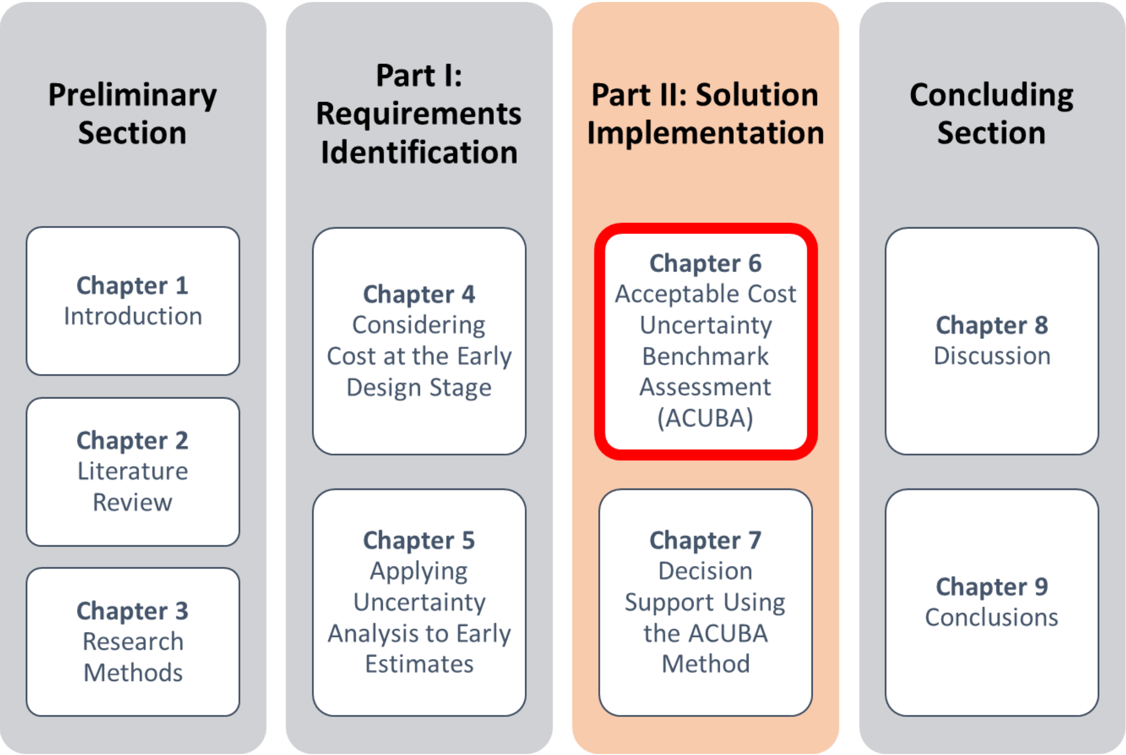


Figure 56: Chapter 6 in the context of the thesis

Section 6.2 presents the requirements of the decision support method developed. The assumptions used to develop the ACUBA method are presented in Section 6.3. The main steps to executing the ACUBA method are described in detail in Section 6.4, including proposed approaches for practically implementing each step. Section 6.5

discusses the expected benefits of the method and the current limitations on its application. A summary of the method and next steps are presented in Section 6.6.

6.2 Requirements of a Design for Cost Maturity Support Method

Two questions arise which are used to drive the development of a method to manage design for cost uncertainty:

1. What information does the design team have?
2. What information is available at each particular stage of design?

For the early design stages there is no clear indication of what would be deemed an acceptable level of cost maturity by the design team. This leads to the risk that a design team will over or under design, not meeting the expectation of gate keepers, and those that control the fate of the project. The maturity metric will need to be able to translate the level of cost uncertainty attributed with each stage gate, to support the acceptability of the decision against what is possible from using the available techniques.

Understanding the dependencies between cost elements can identify the drivers of cost uncertainty changes particularly the direction of dependency and magnitude of the change in uncertainty. Uncertainty can be under or overestimated if the consideration of dependency is not included. More work may be carried out than is necessary to reduce uncertainty to an acceptable level. Using the components of the maturity metric the cost uncertainty drivers and the influence on uncertainty for other items in the PBS will need to be identified. Presenting cost maturity may support more meaningful cost uncertainty analysis at the early design phase.

A suitable definition of “Acceptable Cost Uncertainty Range” is required to provide a consistent basis for the analysis. By identifying what is classed as expected at each stage of the design process, this can be compared with the current cost uncertainty range, to identify if the actual uncertainty is within the expected range. Naturally the question then becomes “is the expected uncertainty, and the actual uncertainty, acceptable?”

The use of the maturity metric must be considered within the multi-criteria nature of the decision-making process where the designer must also consider:

- Customer requirements – functional and non-functional (often interrelated, interdependent and involving trade-offs);
- Company profits;
- Best decision for all life cycle phases;
- Design process (progress and rate of maturity increase).

6.3 Assumptions

This section presents the key assumptions that are the basis for applying the ACUBA method. The assumptions are listed in Table 10. Each of the assumptions are described in more detail below.

Table 10: Assumptions and related steps in the ACUBA method

Number	Assumption
1	**Decisions are discrete events.**
2	**Cost information is generated to support design decisions.**
3	**Transfer of cost information is standardised.**
4	**Cost uncertainty information is used to support unit cost estimating.**
5	**ACUBA method aligns with existing processes.**

6.3.1 Assumption 1: Decisions are discrete events

At the point where the design is fully mature, there is no knowledge uncertainty associated with the product in line with the definition of epistemic uncertainty presented in Chapter 2. Knowledge uncertainty can be said to go from 100% at the start of the concept design phase to 0% at the point where the design is fully mature.

The ACUBA method is applied at the early concept design phase between Stage Gate 0 and Stage Gate 1 (See chapter 4 for a description of the Stage-Gate© process). The decision events are planned prior to the commencement of the concept definition stage. A discrete number of decisions occur between stage gate 0 and stage gate 1 to increase product maturity. Figure 57 shows how each decision is designed to increase the knowledge about the product. With each design decision there is an increase in the product maturity and an associated change in the cost estimate uncertainty. The decisions relate to Engineering Definition, Supply Chain Strategy or Manufacturing Process knowledge.

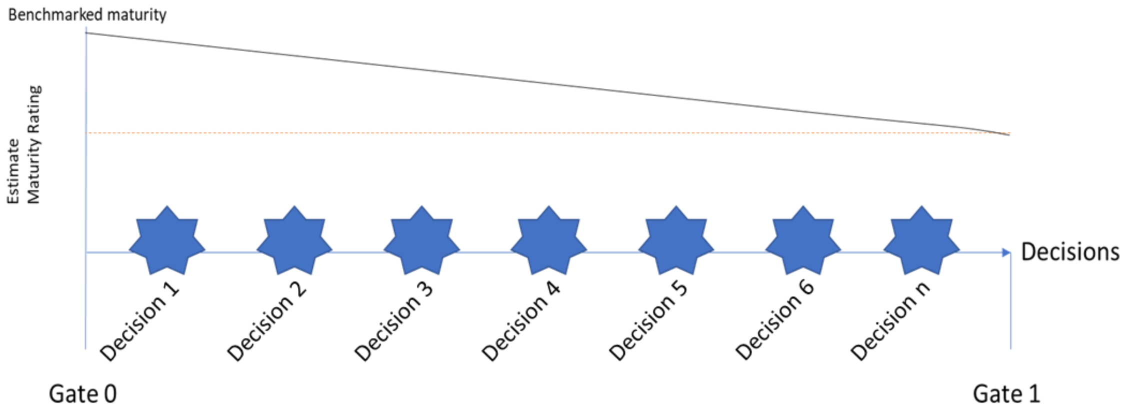


Figure 57: Each design decision leads to an incremental increase in product maturity

To make a decision, a set of design activities are carried out to understand the impact of various options on key attributes. The dependencies between each of the planned design decisions forms the basis for quantifying the interdependencies between the knowledge uncertainties of the cost elements in the PBS. This assumption is explained further in Section 6.3.3.

6.3.2 Assumption 2: Cost information supports design decisions

At the early design stage, cost information is generated to support the design decisions. Additional cost information may be available to support decisions or to investigate the continued business case feasibility. The ACUBA method is applied where information is generated specifically to support design decisions. The decisions that are made require cost information from the estimator. The information may be used to support trade studies, for lifecycle cost analysis and for development cost analysis (discussed in Chapter 2). Where the cost information generated is related to a particular component or set of components the estimator develops a bottom up, or semi-bottom up estimate. The additional cost information is not accounted for in the ACUBA method unless the data has been processed previously and is, as a result, already defined in the PBS.

The cost estimate available at the start of the design stage is used as a benchmark to generate the current baseline estimate maturity. The benchmark estimate is assumed to have been developed using analogy or simple parametrics supported by expert judgment.

6.3.3 Assumption 3: Transfer of cost information is standardised

The ACUBA method assumes there is a standardised approach to generating cost estimates. The design team request cost information related to specific elements of the design to which the decision is related. The estimator may, on occasion, receive requests for cost information that are communicated informally via verbal dialogue or email. The estimator then has to request additional information to clarify the requirements (scope of the estimate) or to obtain more information about the design. Alternatively, the estimator may derive cost requirements from the design team carrying out the decision (formally through a request for information). The estimate is then generated using a standardised method. The estimate, or range of estimates based on different input criteria are then presented to the design team to support decision analysis.

6.3.4 Assumption 4: Cost uncertainty is used for unit cost estimating

At the early design phase, uncertainty analysis is carried out for each cost estimate generated. In the ACUBA method the focus is on understanding the level of epistemic uncertainty, which can be used to represent the confidence the estimator has in the estimate produced. The derived importance weightings for each source of uncertainty (described in Section 6.3.1) are related to design decisions which influence the product maturity. These are treated as dynamic values that can change depending on the type of decision being made.

6.3.5 Assumption 5: ACUBA aligns with existing processes

The steps carried out to generate the product cost maturity metric using the ACUBA method rely on cost estimate information that is presented in a standardised format. A key assumption, therefore, is that the information used to generate the maturity metric is done so using existing company processes. Further, the results of the maturity assessment lead to actions which can be carried out within the bounds of existing design development processes.

6.4 ACUBA Method

This section describes the key steps involved in carrying out the ACUBA method. Figure 58 illustrates each step in a flow diagram. Some of the activities on the diagram are already carried out by the case study organisation and are not described further in this section.

Several steps are preliminary activities involving the generation of information that is then used to support the ACUBA method steps. These include the need to weight the importance of different sources of cost uncertainty and the need to provide an acceptable cost maturity benchmark. The component cost estimate is generated using existing processes. The cost maturity of the component is based on the relative importance of each source of uncertainty and the magnitude of cost associated with each input to the estimate (component maturity is further described in Section 6.4.3. The propagation of component cost maturity to an overall product cost maturity is then considered based on the interdependencies between design decisions. Depending on whether the product cost maturity has reached an acceptable maturity threshold, the next action is either to accept the estimate for the decision, or to conduct additional design work to improve the cost maturity. Additional design tasks are then proposed that could improve the quality of information that is used to produce the estimate, increasing the confidence in the estimate.

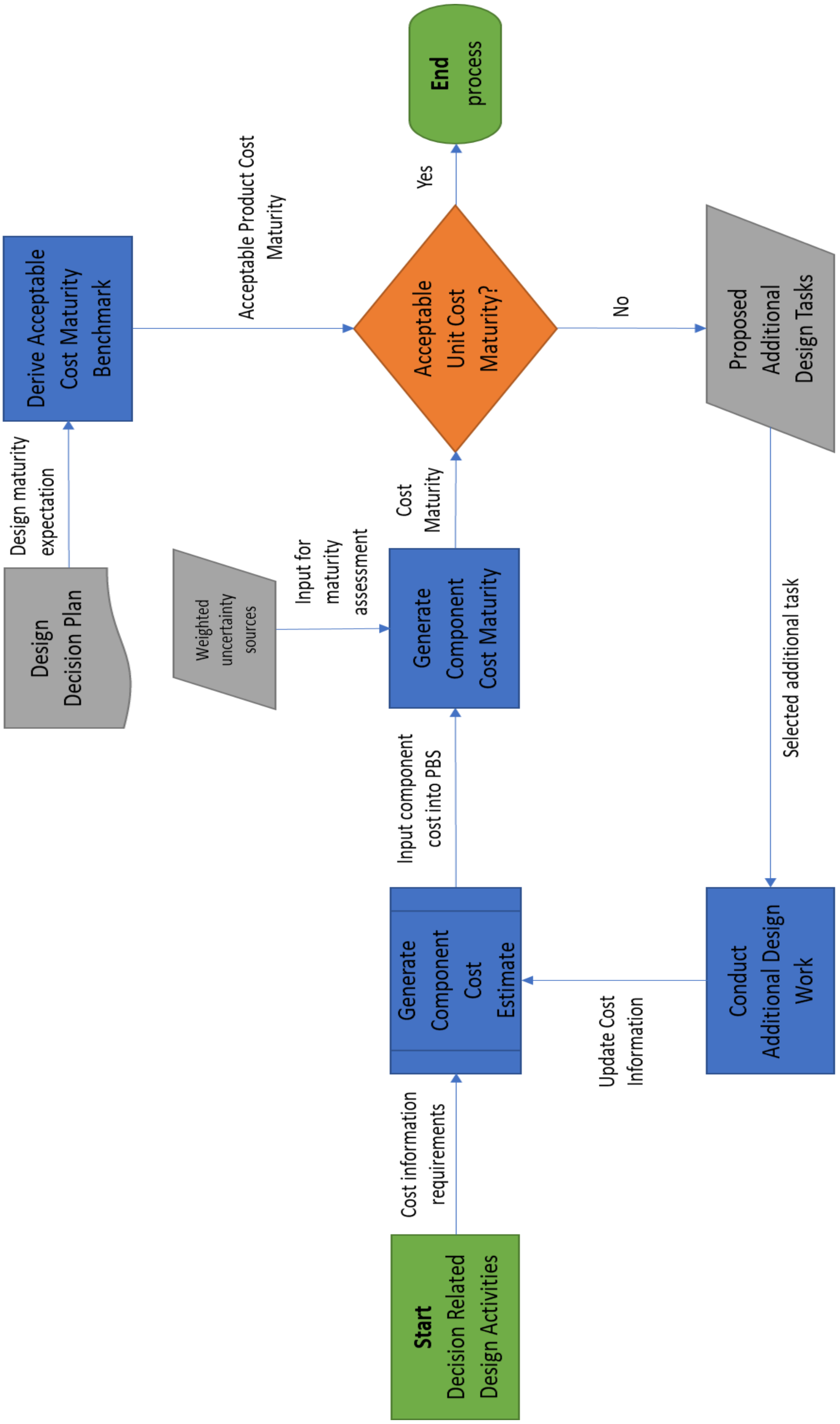


Figure 58: Flow diagram illustrating the steps for the ACUBA method

6.4.1 Cost Uncertainty Identification and Importance Weighting

In this section, the sources of cost uncertainty are defined. The proposed method for weighting the sources of uncertainty is the Analytical Network Process (ANP). The ANP method is described further in this section.

6.4.1.1 Sources of Cost Uncertainty

The sources of epistemic uncertainty in the design space can be related to the complexity of the product (Malmiry et al, 2016). The complexity derives from the uncertainty associated with a lack of information at the early design stage, in knowing the system behaviour and the underlying relationships between different design parameters.

To make the method as useful as possible to the design team the sources of uncertainty align with existing definitions used by the case study organisation for component cost estimating (Figure 59). The basis of these sources of uncertainty is a standard process used by the Cost Estimator.

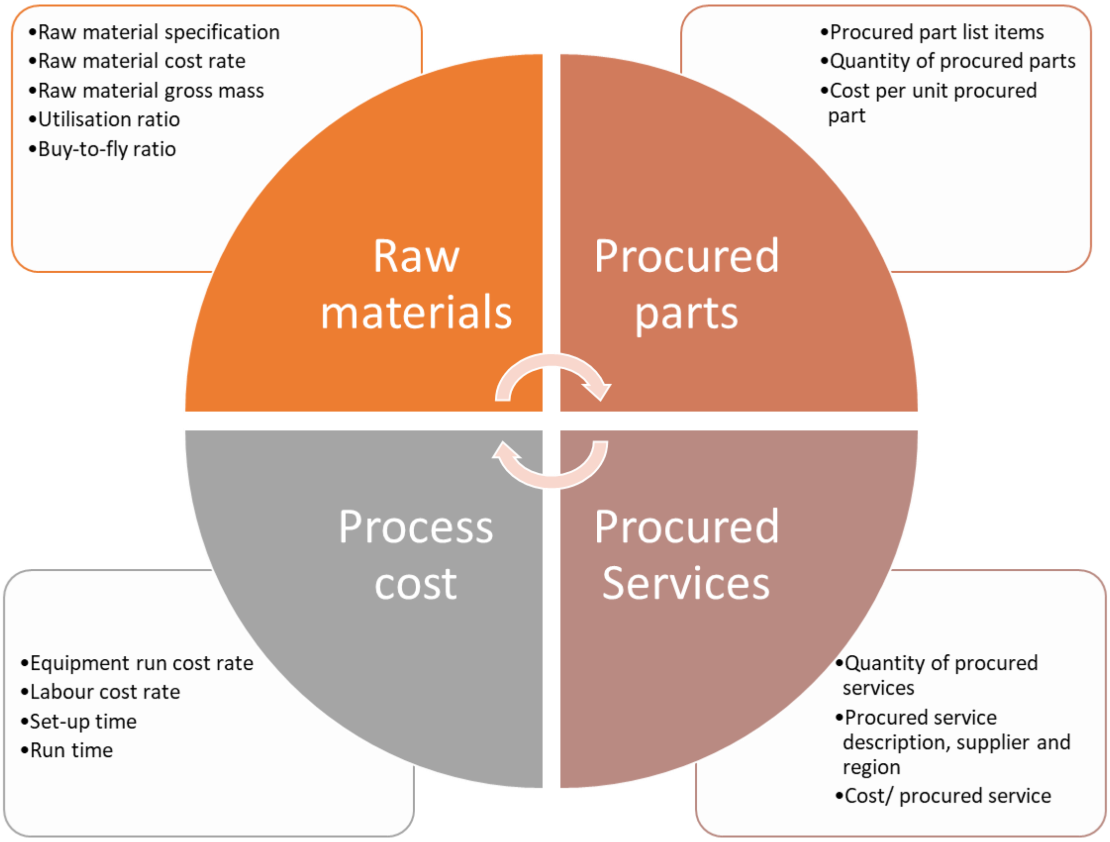


Figure 59: Cost inputs used as basis for component cost estimates

The different sources of epistemic uncertainty that influence the cost estimate maturity relate to the engineering definition, supply chain definition, and the manufacturing process knowledge associated with the estimate. The weightings of each source of uncertainty on the product cost maturity has not been formalised in any previous literature. The data required to produce such weightings does not exist. Therefore, formal elicitation of experts is required to understand the relative importance of each source of uncertainty on the confidence associated with the cost estimate.

6.4.1.2 ANP to Rank Importance of Cost Uncertainty Sources

ANP is a generalised approach based on the Analytical Hierarchy Process (AHP) which is a well-known method for assigning and ranking different, intangible but relational criteria (Saaty, 2001). AHP assumes the relationships between various interacting levels is uni-directional (Meade & Presley, 2002). The criteria for pair-wise comparison must not be linked to the characteristics. The AHP method has been applied to achieve consensus on the ranking of various criteria for multi-criteria decision analysis, particularly where there are conflicting, or subjective criteria (Franek & Kresta, 2014). It allows for the direct comparison of qualitative and quantitative information through scaling, meaning that the participant does not need to produce a numerical response. This is particularly useful at the early design phase of a project, where the requirements may be more descriptive, based on the subjective responses of experts.

The ANP presents the relationships between different levels as a network rather than as a hierarchy (Figure 60). This allows for more complex interactions to be interpreted by decomposing the dependencies of a hierarchical structure (Lee et al, 2010). The ANP has been identified as a potentially useful technique to gain a more representative set of weightings for use in establishing the component maturity rating. The use of ANP to support early concept design decision making is a relatively new approach. It has been used in concept selection with the goal of identifying the best conceptual design, i.e. the option which meets the requirements of the customer and the design team based on multi-criteria (Ayağ, 2007). The ANP can be applied to the opinion of experts to establish relative importance weightings for each of the sources of uncertainty. The interrelated nature of these sources of knowledge uncertainty are investigated and quantified into weightings to support the production of a component cost estimate maturity measure. The ANP approach relies on mathematics to organize pair-wise comparisons of decision components and to prioritise the results to arrive at a stable outcome.

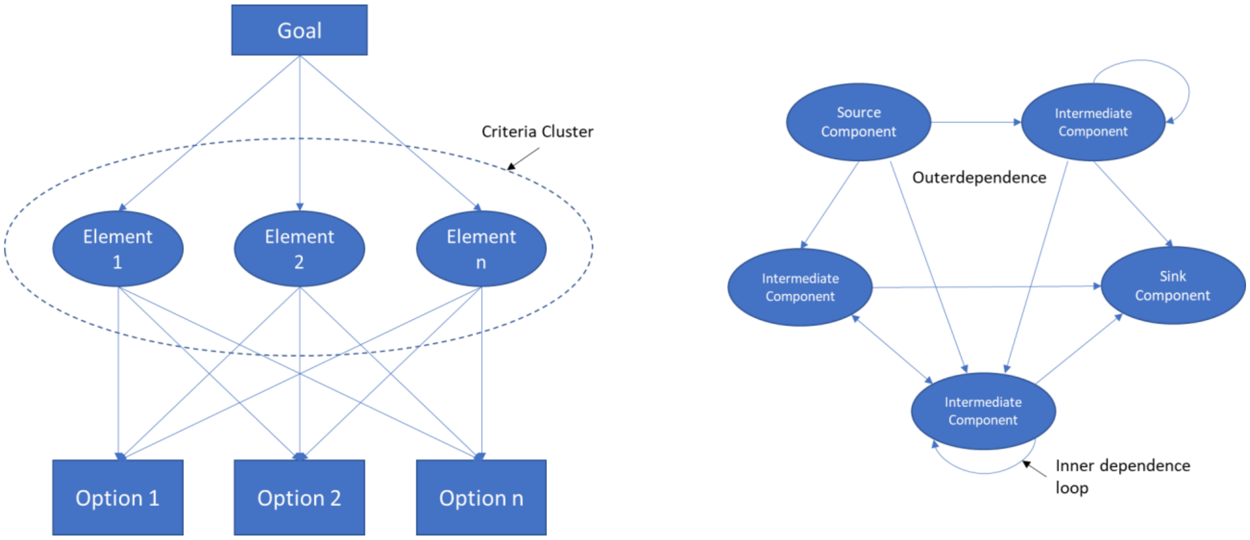


Figure 60: AHP and ANP approaches to establishing weights of importance for different criteria

6.4.2 Component Cost Maturity Assessment

To generate the cost estimate maturity for a component the estimator is required to input cost data and to identify the sources of information which are used to generate the estimate. The reliance on judgement to assign numerical maturity values is likely to be just as subjective as assigning numerical uncertainty ranges. To reduce the variability of response from the different estimators and to give consistency to the component cost maturity metric a set of standardised qualitative responses is generated. Rather than presenting the estimator with the option of selection a maturity rating, (e.g. from a scale of 1 to 9), the estimator is asked to identify from semantics next to each input the information that was used. The Maturity assessment and the uncertainty weightings are then used to calculate the component cost maturity assessment.

6.4.2.1 Semantic Levels for the Sources of Cost Estimate Maturity

Each decision is assumed to lead to an incremental improvement in the cost maturity. In the ACUBA method the proposed approach for eliciting the confidence ranges is to use qualitative statements based on a standard set of semantics. A 1 to 9 scale is then assigned to each semantic statement, with the lowest quality information having the lowest number. When populating the PBS with cost information, the estimator will select from a set of options the engineering definition, manufacturing knowledge and supply chain knowledge used to generate the estimate.

6.4.2.2 Generating a Component Cost Estimate Maturity

For each cost component, a maturity rating is assigned. The cost maturity is a weighted sum of the source of knowledge uncertainty and the importance weighting for the source of uncertainty. The maturity rating is generated for that component from the assigned weightings:

$$Maturity\ Rating = \left(E_{Def} \times E_{Weight}\right) + \left(M_{Def} \times M_{Weight}\right) + \left(S_{Def} \times S_{Weight}\right)$$

Where:

E_{Def} – Engineering definition rating

M_{Def} – Manufacturing knowledge rating

S_{Def} – Supply chain knowledge rating

And E_{weight}, M_{weight} and S_{weight} are established weightings of importance for engineering definition, manufacturing knowledge and supply chain knowledge respectively, obtained using the ANP method. To obtain a relative maturity impact, the component maturity metric is normalised based on the relative cost of the component to the total product unit cost estimate. The relative maturity is obtained by first calculating the cost magnitude of each component and then summing based on the dependency criteria (the dependency structure is described in Section 6.4.3).

$$Relative\ Maturity = \sum [(\frac{element\ cost}{total\ cost}) \times Component\ C\ EML]$$

6.4.3 Propagating Component Maturity in the PBS

So far, the estimator has produced the component cost estimate(s) required by the design team to support decision-making activities. Given the limited detail associated with component cost estimates at the early concept stage this information may not provide sufficient support to design-decisions.

As well as a component cost estimate, however, the design team will need to understand the impact of the decision on the product unit cost and the LCOE. Although the ACUBA method does not include within its scope the entire lifecycle cost impact, a key cost driver is the unit cost of construction (defined as the OCC in Chapter 2). There is a need, therefore, to generate an overall product cost maturity. In the ACUBA method, the product cost maturity is based on the propogation of component cost maturity using the following steps.

6.4.3.1 Establishing the PBS

The PBS for the previous design stage provides the baseline for comparison for the PBS that is developed in the current stage gate. The component cost information required for each decision in the current stage contributes to the development of the PBS. Therefore, any product cost changes in maturity are the direct result of the design decisions that are being made in the current development stage.

The PBS is traditionally presented as a hierarchy, with dependency relationships represented as a single, non-feedback parent and dependent as shown in Figure 61. It can be assumed that each of the product subsystems will mature at different rates. The cost estimates generated for each system, subsystem and component are likely to have different levels of detail and maturity. In the hierarchical structure of the PBS the overall cost is simply the sum of each component identified, a so-called “Bottom-up estimate.” If there is more cost information available for a sub-system then that part of the PBS is more detailed but may not necessarily have a greater cost maturity. Interpreting the impact of new information on the uncertainty associated with the total product cost will then produce invalid results, as the dependencies are not identified.

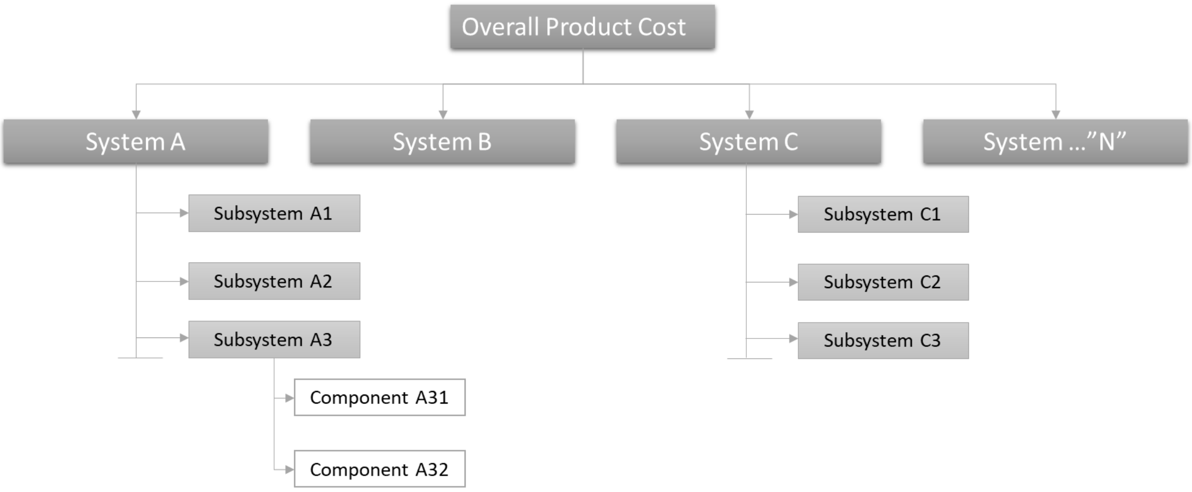


Figure 61: Traditional hierarchical representation of the PBS

To account for the interdependencies on cost uncertainty between different cost elements the Dependency Structure Matrix (DSM) is employed. The information flow dependencies between the design decisions are modelled in DSM in terms of engineering definition, manufacturing knowledge, and supply chain knowledge. The result is a PBS which is more of a network, although the overall product cost (Level 0) remains as the top of a semi-hierarchy (Figure 62).

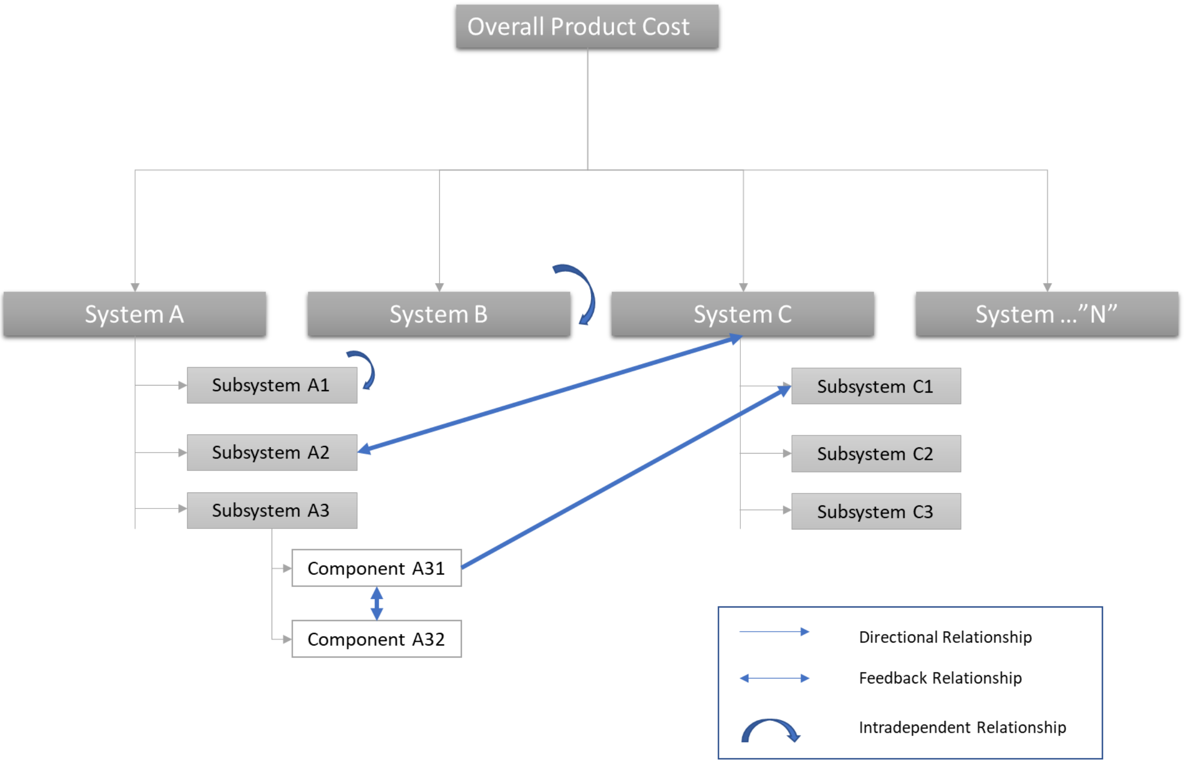


Figure 62: Network representation of the PBS illustrating interdependencies of epistemic cost uncertainty

The detail associated with the PBS used in the ACUBA process is dependent on the components or subsystems for which cost information has been generated. The more detailed the PBS, the more possible ways there are of influencing cost uncertainty. The interdependencies will then show how some decisions can lead to a greater influence on product cost maturity then would be expected in a single hierarchical structure. In the case of a dependent network PBS the sum of the dependent network becomes the total product cost and the sum of the relative component cost maturities becomes the total product cost estimate maturity.

6.4.4 Benchmarking the Acceptable Cost Estimate Maturity

This sub-section defines how the acceptable cost estimate maturity benchmark is obtained. Prior to the start of the concept development stage the achievable and expected cost maturity that is required at the end of the stage is agreed by the gate keepers (i.e. those who decide the progress of the design at the gate stage). It is not straight forward to encompass what is "expected" and what is "achievable", to then interpret what is "acceptable." The expected maturity is a notional acceptable maturity threshold. A suitable definition of "Acceptable Cost Uncertainty Range" is required to provide a consistent basis for the analysis. A cost estimate may be deemed to be acceptable if the expected accuracy meets the specified quality requirements (Rothwell, 2004). In this case the specified quality requirements relate to the expected information available to make a design decision at the early concept design stage.

The expected product maturity could be inferred from the information available in the generic process guidelines for the design development process. The stage gate expectations are defined in the process guidelines set out for the case study organisation. The acceptable cost maturity for each design stage is expected to be specific to each individual project. Therefore, a calibration would be required to make the generic expected maturity project-specific.

As noted in Section 6.3, a key assumption of the ACUBA process is that the design decisions lead to a more mature understanding of the product. Organisations use project planning to organise and resource effectively the work that will be carried out in a project. It is possible to chart the expected product cost maturity at the end of the development phase based on the information that is expected to be generated based on an analysis of the project planned activities at the start of the design stage. Aligning the expected information generated to each source of uncertainty leads to an expected product cost maturity rating for the planned phase of work. The required product cost maturity can then be translated from the semantic definition to the related maturity score from 1-9. To carry out this step the following activities are carried out:

1. Confirm that a plan has been produced for the concept development phase;
2. Refine the expected product maturity at the end of the gate phase, using semantics developed for assessing the cost estimate maturity;
3. Produce the expected maturity rating for the end of the stage gate;
4. Verify the acceptability of the uncertainty range with the gate keepers and confirm the threshold minimum acceptable maturity.

The uncertainty ranges are not quantitatively discussed with the decision-makers. In this case, the “threshold” maturity becomes the notional “acceptable” level (Figure 63). Senior decision makers are required to approve the acceptability score, based on the benchmark expected uncertainty range.

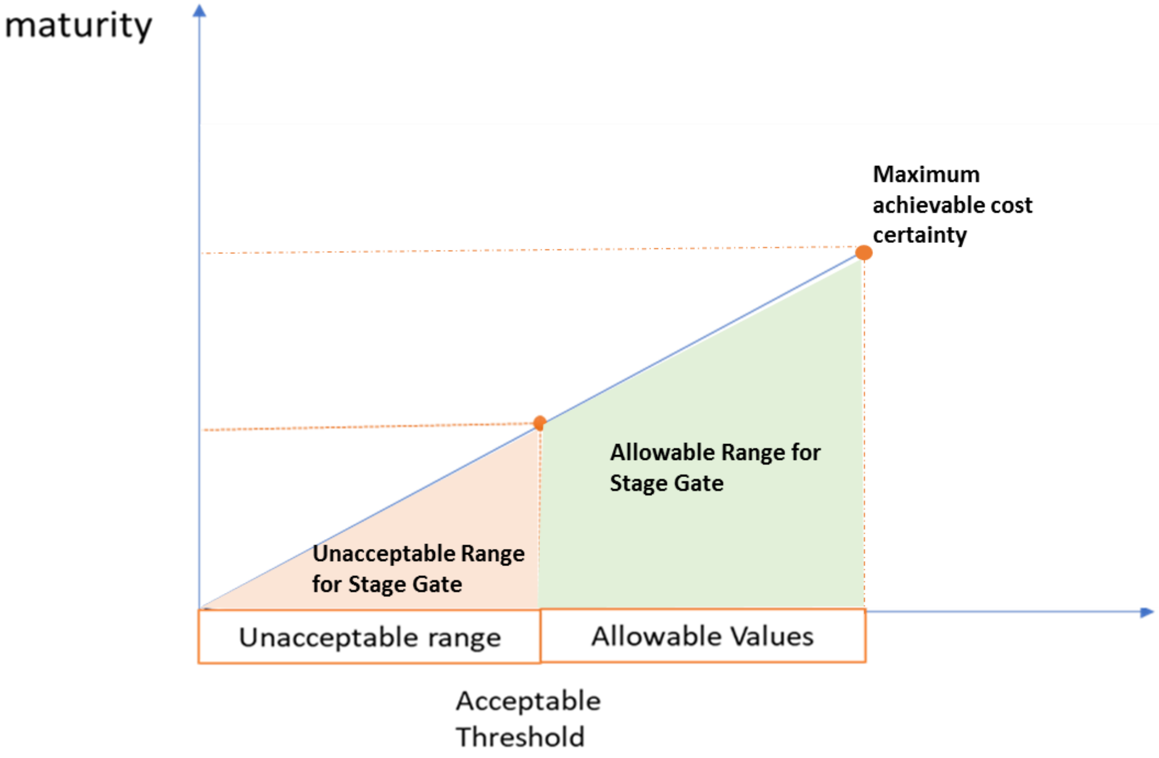


Figure 63: Interpreting the “Acceptable cost maturity” point

6.5 Discussion

To manage the product cost maturity the ACUBA method acts as a performance metric that can be used to assess the progression towards a target. The benefits and limitations of the ACUBA method are discussed in this Section.

6.5.1 Benefits of applying the ACUBA method

The first identified benefit of the ACUBA method is the support it provides to early planning of the development programme activities. The expected cost maturity at the end of the design stage can be used to compare the planned design activities against the benchmark acceptable uncertainty range for the product design. A variety of scenarios can be developed in the ACUBA method to identify a set of design activities that will lead to an acceptable cost maturity. The product cost maturity rating can then be used as a Key Performance Indicator (KPI) to measure progress during the execution of design activities.

The ACUBA method also supports a more critical analysis of the cost estimates used in design decision making. A standardised approach to presenting product cost maturity information could support a general understanding of early cost estimate uncertainty analysis. The component maturity can be broken into each source of uncertainty. The relative influence of each component can be identified by normalising the individual component cost against the overall system product. The highest impact cost maturity components can then be placed in priority order. Highlighting these sources of information uncertainty facilitates clearer communication between different functions within the design team.

By understanding the maturity of the unit cost of the SMR, the output from employing ACUBA method can support the LCOE scenario analysis. The PBS that is generated as a result, with an associated maturity rating can then be used to support the commercial feasibility estimate, by providing a distribution of possible product costs. The change in LCOE as the product design matures can also be measured. The ACUBA method illustrates the confidence in the cost estimate and the sources of uncertainty. Using semantics these can then be used to strategically reduce uncertainty.

6.5.2 Limitations of applying the ACUBA method

Several limitations associated with the ACUBA method have been identified. The limitations relate to the technique used to weight the sources of cost uncertainty, establishing the acceptability criteria for product cost maturity and the ability to propagate uncertainty for individual cost components to an overall product cost maturity.

The weightings for each source of uncertainty are generated using qualitative methods. The ANP is identified as a way of establishing the relative importance of each source of uncertainty on a product cost estimate. For the ACUBA method the weights generated are treated as nominal values which are employed for each cost estimate to derive the maturity rating. The need to rely on expert judgement and subjective analysis for the process is identified as a key limitation. The relative weighting of cost uncertainty sources is likely to vary depending on the expert who is elicited. A statistical based technique such as regression analysis could be used to establish the weightings based on actual data accumulated for previous projects. However, this data (related to the actual final cost of each source of uncertainty versus the estimated cost) is not recorded by the organisation for the early design stage. To record this information a set of attributes would need to be developed for the selection of the most relevant weightings for the specific project and would require the collection of data over the entire development phase.

A benchmark of acceptable uncertainty at the end of a design stage is expected to be industry or project specific. The validity of the semantic relationships associating the quantitative uncertainty ranges have not been validated. The assessment of expected cost maturity at this stage of the design process uses the semantic definitions of cost maturity and is associated with the expected information available for at a particular stage. The notion of acceptability relates to the ability to understand the expected maturity of a cost estimate for a particular stage of the design development process.

For a clear representation of the product cost maturity, the ACUBA method needs to account for propagation of uncertainty by acknowledging dependencies based on the knowledge available at the time. The technique proposed for the ACUBA method is to use DSM, although the ability to elicit a clear set of dependency of information needs to be tested.

6.6 Summary

The cost maturity metric is an assessment of the confidence the estimator has in the estimate that has been generated. The ACUBA method attempts to identify the current maturity of the product cost, to illustrate the acceptability of the estimate maturity, and presents scenarios where the design team can obtain more certainty by carrying out additional design activities. The ACUBA method establishes the importance weightings for sources of uncertainty to the cost maturity. By establishing an acceptable cost uncertainty metric for the end of the concept design phase, a threshold level can be set allowing for the product cost maturity. The benefits and limitations of the ACUBA method have also been outlined. Subjectivity and qualitative assessments are more prevalent at the early concept design stage where little detail is available about the product and sources of cost due the immaturity of the design.

The practicality of each of the steps involved in carrying out the ACUBA method is investigated in the next chapter. The extent to which this approach is valid requires further investigation. At the early concept phase, where estimates are subjective, the maturity metric is also subjective. Determining the estimating effort required is based on the perception of acceptability rather than a quantifiable range. The weighting of sources of cost uncertainty on the product maturity for component estimates will need to be verified. In addition, there is a need for a standardised and agreed set of semantics for the maturity ratings and related questions to derive component maturity scores.

To derive the overall product cost maturity a clear and valid approach is required to propagate the individual component cost maturities that are quantified. The ACUBA method relies on deriving dependencies of information between key components using the design development plan, and the dependencies between design decisions and the expected production of information. The practical application and validity of this approach to establishing dependencies is investigated further in Chapter 7. In addition, the ability to identify the influence of each individual decision on component and product cost maturity will need to be evaluated.

7 Decision Support Using the ACUBA Method

7.1 Chapter Overview

This chapter forms the final part of the solution development for the method (Figure 64) applying the ACUBA method presented in Chapter 6 to the early concept design decisions of the case study project. This chapter aligns with Objective 5:

Validate the developed method.

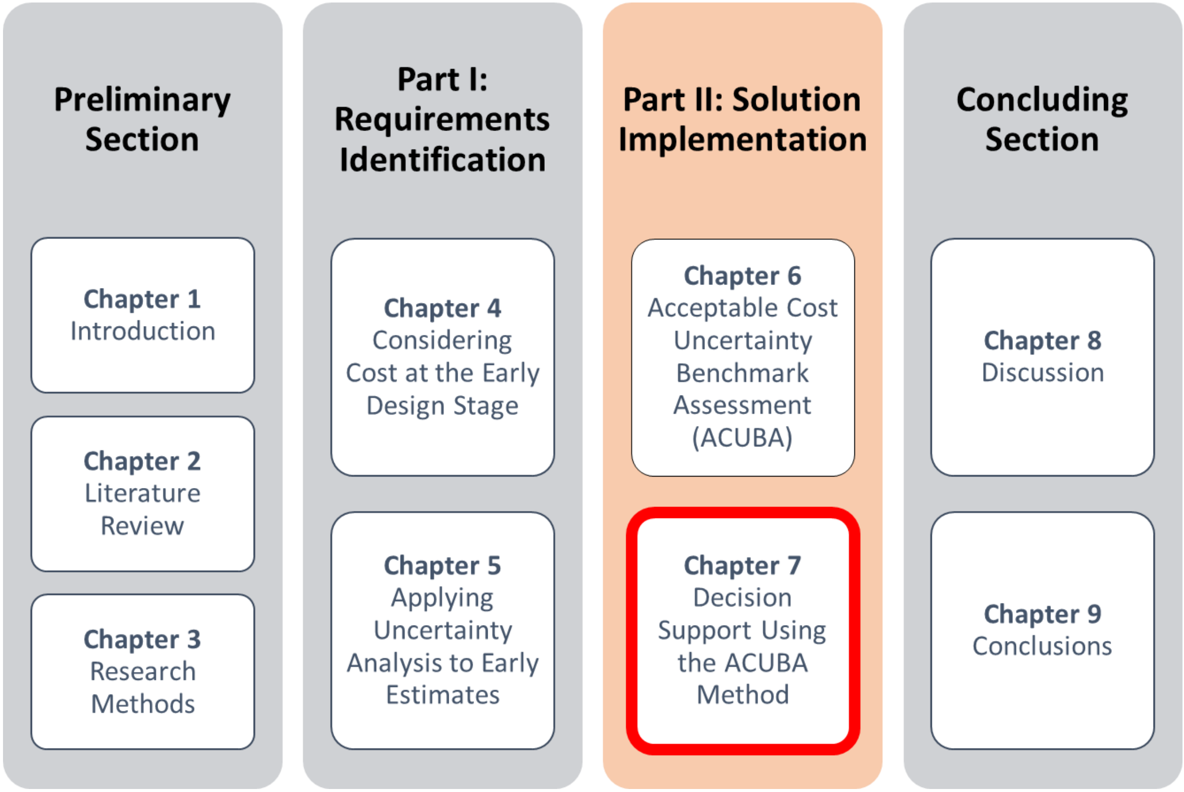


Figure 64: Chapter 7 in the context of the thesis

Section 7.2 presents the preliminary activities associated with setting up the ACUBA process, focusing on two key aspects. Firstly, the selected semantic scales used to qualitatively describe the information maturity used to generate the component cost estimate is justified. The importance of different sources of information maturity on the cost maturity are then quantified. The case study application of the ACUBA method is presented in Section 7.3. A benchmark maturity assessment of the cost estimate is generated for the concept development stage. A decision matrix is then used to map the information dependence between the planned design decisions. Component and product level maturity estimates are then presented based on the information available to the design team and the estimator. The results of the maturity assessment are then analysed. Simple optimisation is used to illustrate the ability of the ACUBA method to identify priority areas to improve the maturity of the cost estimate to a notional acceptable level. Section 7.4 presents a discussion on the implementation of the ACUBA method, limitations and further improvements required. A summary of the findings is presented in Section 7.5.

7.2 Semantics and Weightings for Sources of Uncertainty

Both the semantics developed and the weights associated with each source of uncertainty are static inputs in the ACUBA method as shown in Figure 65. These inputs are required to support the ACUBA method, but are not carried out by the design team itself. The development of a set of semantics describing different levels of maturity and the establishment of weightings for each source of uncertainty are described in this section.

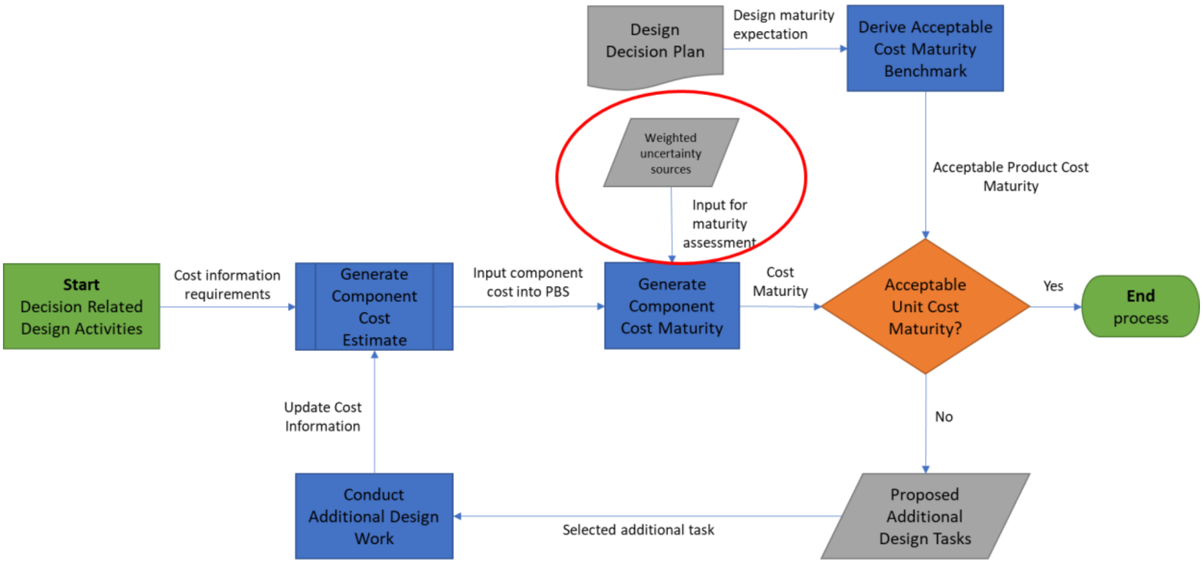


Figure 65: Preliminary activities in the ACUBA method

7.2.1 Semantics for Sources of Cost Uncertainty

The ACUBA method relies on a metric with a consistent set of semantics that are used to relate the qualitative responses of the cost estimator to the quantitative uncertainty range. These semantics are then applied at the component level to assess the cost estimate maturity.

Early in the study it was identified that the semantics for the cost EML derived from the company process were not directly applicable to the case study application (Table 11).

Table 11: Cost maturity level aligned with project stage within organisation documentation

Project Stage	Stage 0 (Feasibility)	Stage 1a (Concept)	Stage 1b (Detail Design)	Stage 2 (Production)
Cost Maturity Level	Minimum 2	Minimum 3	Minimum 4 Maximum 6	Minimum 7 Maximum 9

The original process is applied to multi-generational projects for which previous data within the organisation is available. More information would be expected to be available at an early design stage for such iterative projects compared with the case study under investigation here. Therefore, the minimum maturity for an early estimate, and the associated semantic language, differs from project to project.

The development of semantic language involved a triangulation of document analysis of the existing maturity process within the wider organisation, interviews with the cost estimator (to gather experiential information), and cross-referencing with the ACUBA process. To generate the semantic levels an analysis of company process data was combined with a structured elicitation with the estimator. Firstly, the types of information expected at the end of each stage gate were adapted from existing processes and assigned to each level of the scale used in the original cost EML. This step establishes a standard set of definitions, to structure the elicitation verification with the estimator.

The second step involved a structured analysis of the definitions to allocate relevant definitions for the case application. The estimator was asked “what is the minimum amount of information required to carry out an estimate?” The responses are shown in Table 12.

Table 12: Minimum information required to generate an estimate

Engineering Definition	A rough outline of the major component definition, geometry and material information, quality requirements
Manufacturing Definition	High level definition of a generic process to determine general rate numbers (although, as a minimum given a sufficient amount of engineering definition the cost estimator can provide a general idea of the expected processes to produce the component
Supply Chain Definition	Generic supply chain rates can be determined given a minimum amount of engineering definition, the cost estimator can provide a general cost using either the existing database of supply chain rates or expert judgement

The minimum amount of information formed the value 1 on the ordinal scale generated for the maturity metric. The initial definitions were then modified based on the structured analysis of the expert elicitation and adapted to suit the case study programme. The estimator was presented with the set of definitions and was asked to assess for:

- Relevance – to the case study project
- Reflectiveness – Whether or not the statements reflect the categories they are placed in

The estimator was asked the following questions:

1. For decision X what is the minimum amount of engineering definition required to generate an estimate?
2. For decision X what is the minimum amount of manufacturing process definition required to generate an estimate?
3. For decision X what is the minimum amount of supply chain definition required to generate an estimate?

Finally, the expected information available for each design phase based on standard company process guidelines were aligned with the expected level of maturity. The results of this alignment together with the maturity ratings and definitions are presented in Table 13. These definitions are based on the specific case study and the expected levels of maturity at each gate stage.

Table 13: Revised maturity scale aligned with expected metrics at gate stages for case study project

Aligned Stage Gate	**Level**	**Cost Maturity**		
		Engineering	**Manufacturing**	**Supply Chain**
Stage 2 Production	9	Product is already a proven design in operation	Full definition and proven for specific application	All supply data available with transparency and proven capability
	8	Approved for production drawing	Validated full method of manufacture	Contracted supplier with partial transparency
	7	Drawing released for manufacturing acceptance	Full definition, not proven for specific application	Relevant data available, not fully proven capability
Stage 1b Design Development	6	Dimensioned & tolerance drawings released,	Manufacturing processes defined	Supplier defined not contracted
	5	3D model with all features defined	Mostly defined but some operations need a higher level of detail	Acceptable definition - confidence in competitiveness
	4	Semi-detailed model,	Method of manufacture same or adapted from similar scale part	Supply chain identified
Stage 1a Concept Stage	3	Model scaled from a similar part and material selected	Limited definition	Some definition of the supply chain – non-specific data
Stage 0 Feasibility	2	Concept drawing, scaled from similar part	Some manufacturing definition	Identified some specific suppliers
	1	Basic, un-dimensioned drawing	No manufacturing method specified	No supply chain specified

The definitions associated with cost maturity and cost uncertainty were collected using the model adapted from the organisation guidance documents and the expected performance criteria within the case study design team. For each level of maturity and each category of cost uncertainty the interview was used to verify that the related information was appropriate for the maturity rating and confidence in the estimate.

7.2.2 Uncertainty Weightings Using AHP

This sub-section describes the development of importance weightings for the different sources of cost uncertainty identified in Chapter 6. The AHP was applied to quantify the relative weights of each source of uncertainty and to determine the efficacy of each approach. The change in each type of uncertainty is investigated for different types of decision encountered at the early concept design stage. An initial attempt was made to carry out the ANP analysis. The resource intensiveness of the expert elicitation stage was illustrated by the need for the participant to complete 84 pairwise comparison questions. Despite the concerted efforts of the participant to complete the questionnaire, no consistency could be achieved with the results. Instead, the AHP was carried out, requiring fewer pair wise comparisons. The complete AHP analysis is shown in Appendix D. The key steps and results are presented below.

7.2.2.1 Model Construction

The AHP network consists of a goal, a set of criteria and a set of alternatives. A set of criteria (the sources of uncertainty) and a set of sub-criteria are assessed for their importance on decisions related to the design, selection of a manufacturing process and supply chain. Table 14 shows the allocation of different sub-criteria to each type of knowledge uncertainty using a binary dependency matrix.

Figure 66 shows the structure of the AHP model, where the first level describes the goal of the analysis which is to ***rank the relative importance of each source of uncertainty to the confidence in an estimate for different types of design decision***.

Table 14: Allocation of sub-criteria to sources of knowledge uncertainty

Sub-criteria	Definition (Source of Knowledge Uncertainty)		
	Engineering	Manufacturing	Supply Chain
Raw Material Specification	1	0	0
Raw Material Gross Mass	0	1	0
Raw Material Cost Rate	0	0	1
Manufacturing Process Setup Time	0	1	0
Manufacturing Equipment Run Cost Rate	0	1	0
Manufacturing Labour Cost Rate	0	1	0
Procured Parts List	1	0	0
Quantity of Procured Parts	1	0	0
Quantity of Procurement Services	1	0	0
Procured Services Supplier Description	0	0	1
Procured Services Cost	0	0	1

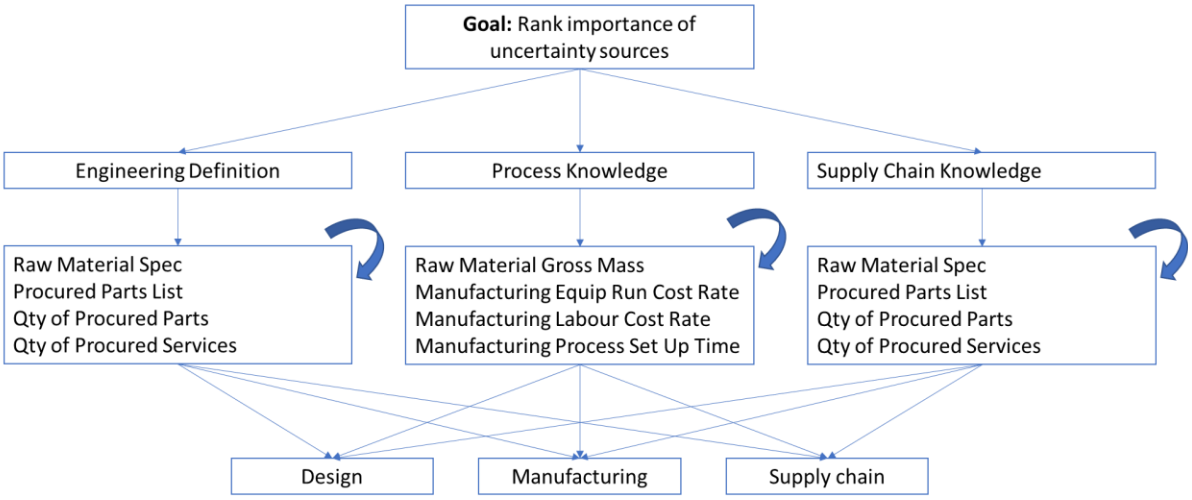


Figure 66: Structure of the AHP model

A criteria cluster is then assigned to the next level of the model which incorporates a node for each source of uncertainty. For each criteria cluster another layer of sub-criteria is assigned. Each node within the sub-criteria are linked in the AHP model (inner-dependence).

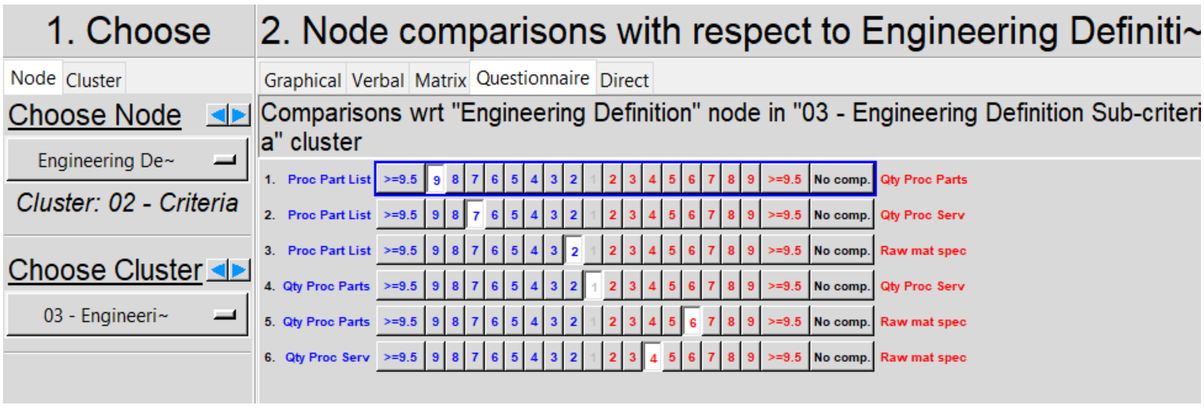
Table 15 describes each of the decision types as defined in separate clusters in the "Outcome" layer. Several types of decision are categorised at the early concept design phase. These related to engineering design, manufacturing process and supply chain decisions. The weighting of importance of each source of uncertainty was expected to change depending on the type of decision.

Table 15: Decision types as alternative options in the AHP

Decision Type	Description
Engineering Design	Related to deciding the design of a component or subsystem specifically
Manufacturing process	Related to deciding on the manufacturing process
Supply Chain	Related to deciding on the supply chain including supply chain strategy

7.2.2.2 Pair-wise Comparison

A pair-wise comparison questionnaire was completed by the estimator for each sub-criteria and criteria in relation to the goal question and the types of decision, an example of which is shown in Figure 67. The pairwise questionnaires were carried out using Super Decisions software (Version 2.8). Several rounds of questioning were required to achieve a consistent set of responses. Achieving consistency with few comparisons requires the absolute importance of one element over another. If a participant does not adequately distinguish between possible choices (e.g. by allocating equal importance to different options), inconsistencies are more likely to occur. The estimator was requested to review several pairwise comparison questions which were most sensitive to the inconsistency.



Cluster: 02 - Criteria

2. Node comparisons with respect to Engineering Definiti~

Comparisons wrt "Engineering Definition" node in "03 - Engineering Definition Sub-criteria" cluster

1.	Proc Part List	>=9.5	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	Qty Proc Parts
2.	Proc Part List	>=9.5	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	Qty Proc Serv
3.	Proc Part List	>=9.5	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	Raw mat spec
4.	Qty Proc Parts	>=9.5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	>=9.5	No comp.	Qty Proc Serv
5.	Qty Proc Parts	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	>=9.5	No comp.	Raw mat spec
6.	Qty Proc Serv	>=9.5	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	>=9.5	No comp.	Raw mat spec

Figure 67: Example pairwise comparison questionnaire used to assess the engineering definition importance weighting

7.2.2.3 Results

Table 16 presents the relative importance weightings for engineering definition, manufacturing definition and supply chain definition without establishing the type of decision. The results show that engineering definition is the most important source of uncertainty influencing the confidence an estimator has in the estimate.

Table 16: Absolute importance weightings for sources of knowledge uncertainty

Uncertainty Source	**Relative Importance**
Engineering Definition	0.76
Manufacturing Definition	0.16
Supply Chain Definition	0.08

Table 17 shows the results of the rankings of different sources of uncertainty when the estimator is presented with different types of decision. There is a significant difference in the importance of different sources of information uncertainty when considering the type of decision for which a cost estimate is used. Engineering definition is still a significant factor considered in each decision scenario. However, intuitively, process knowledge becomes the most important factor in a decision related to manufacturing, and supply chain uncertainty becomes the most important for a decision considering supply chain decisions.

Table 17: Relative importance weightings accounting for type of decision

	Relative Importance Weighting		
Decision Type	Engineering Def	Process Knowledge	Supply Chain Def
Design	**0.81**	0.11	0.07
Manufacturing	0.40	**0.52**	0.08
Supply Chain	0.36	0.07	**0.57**

The type of decision and purpose of the estimate affect the importance weighting of each source of uncertainty. Therefore, the ACUBA method uses the relative importance weightings that account for different types of decision for the assessment of cost maturity.

7.3 ACUBA Assessment of SMR Cost Estimate Maturity

In this section the early design decisions carried out in the case study are analysed with the ACUBA method applied retrospectively to the cost data generated for each decision. The following ACUBA steps are described in this section:

1. Establish the start of design phase maturity rating to produce a benchmark maturity rating.
2. Identify the decisions carried out in the previous design stage.
3. Map design decision dependencies using DSM.
4. Calculate the component and product cost maturity ratings.
5. Influencing the product cost maturity through design decisions (scenario analysis).

7.3.1 Benchmark estimate maturity

The feasibility stage (Stage 0 of the gated process) estimate provides the benchmark used to baseline the maturity of the product cost estimate in the ACUBA method. The cost information available at the end of the previous stage gate is not enough to generate a bottom up cost estimate. Given that there is not enough information, the minimum maturity rating of 1 is assigned to the product cost and each of the identified subsystems.

7.3.2 Early Concept Design Stage Decisions

In this section the design decisions carried out during Stage 1 of the gated process in the case study are analysed using the ACUBA method. The aim of the early design stage defined is to demonstrate the viability of the concept, and the likelihood of meeting the product requirements. Each sequential design decision is assumed to result in an increase in product maturity. The implementation of the ACUBA method focuses on the progress of a single subsystem to illustrate the impact of an increase in the engineering definition on cost maturity. For commercial reasons, the design decisions are represented in Table 18 by number and generically categorised as either a design, manufacturing or supply chain-related decision. Actual cost data representing the commercial case is not used.

The majority of the decisions centre on design, with cost information generated for several key components. The decisions which are related to the development process itself do not directly lead to an increase in product maturity and are not incorporated into the ACUBA method. Two decisions are related specifically to supply chain and one relates to manufacturing. Decisions related to safety are assumed to be associated with increasing engineering definition and are assumed to be a design decision rather than manufacturing process or supply chain knowledge.

Table 18: Types identified for Stage 1 decisions

Decision No.	Decision Type
1	Design
2	Design
3	Safety (assumed to be Design)
4	Supply Chain
5	**Development**
6	Design
7	Design
8	Manufacturing
9	**Development**
10	Design
11	Supply Chain
12	Design

7.3.3 Mapping design decisions dependencies

This section focuses on the use of DSM to connect different sources of cost uncertainty for cost elements identified and used in each previous decision. The DSM provides a graphical way of representing the information flow dependencies between the design decisions. By identifying the information flows, the propagation of each source of uncertainty can be more clearly identified through the PBS, to provide a measure of the overall cost maturity measure.

As stated in Assumption 1 (Section 6.3) the dependencies between decisions forms the basis for understanding the structure of the Product Breakdown Structure (PBS) and, therefore, the propagation of component cost maturity to an overall product maturity rating. Each decision that requires cost information (i.e. an estimate to be generated) is defined in the network. The decision and node approach described in Hansen and Andraesen (2004) is used to structure design decisions into a network, connected by information flows.

The first task is to identify dependencies from the perspective of the design team relating to how each decision provides information to other decisions. This task could be carried out when planning the Stage-Gate© activities. In this study the DSM was carried out retrospectively on previous decisions. The senior design engineer, the supply chain manager and manufacturing engineer were asked to identify the dependency of each decision with respect to each source of information.

Table 19 shows the combined DSM. The relationships are presented as binary, i.e. a 1 for a relationship, and blank where no coupling exists. Each decision is listed as the row and column label for each of the information types of the DSM. There are several types of relationship defined in the DSM. Parallel relationships are those where no interdependence between decisions have been identified. These will not have an influence on each other when the cost components are related. Coupled tasks are those which require an exchange of some information to make a decision.

Table 19: Dependency assessment for design information flow between decisions

Decisions	1	2	3	4	5	6	7	8	9	10	11	12
1	■											
2	1	■										
3	1		■									
4				■								
5		1	1	1	■							
6	1	1	1		1	■						
7	1						■					
8	1							■				
9									■			
10				1						■		
11											■	
12												■

The dependencies are then used to generate the product breakdown structures shown in Figure 68. The associated cost component information is represented in the PBS based on the information flows identified in the dependency chart. This dependency is also used to propagate component maturity to an overall product maturity rating.

The PBS shows the components for which an estimate has been generated. Some of the components have been used in multiple decisions. The component dependencies use the latest decision for which the component information is generated to reduce duplication of linkages. Key subsystems for which estimates were generated have also been incorporated to produce an overall product cost maturity. Given that the baseline cost estimate is produced using a top down approach the total subsystem cost is separated into the identified component costs and a single component representing the undefined elements of the subsystem combined. The minimum maturity is applied for the single component, with no dependencies identified. At the current design stage most of the decisions have focused more on a single subsystem. However, the expected impact on associated sub-systems are also identified at the system level in the dependency structure.

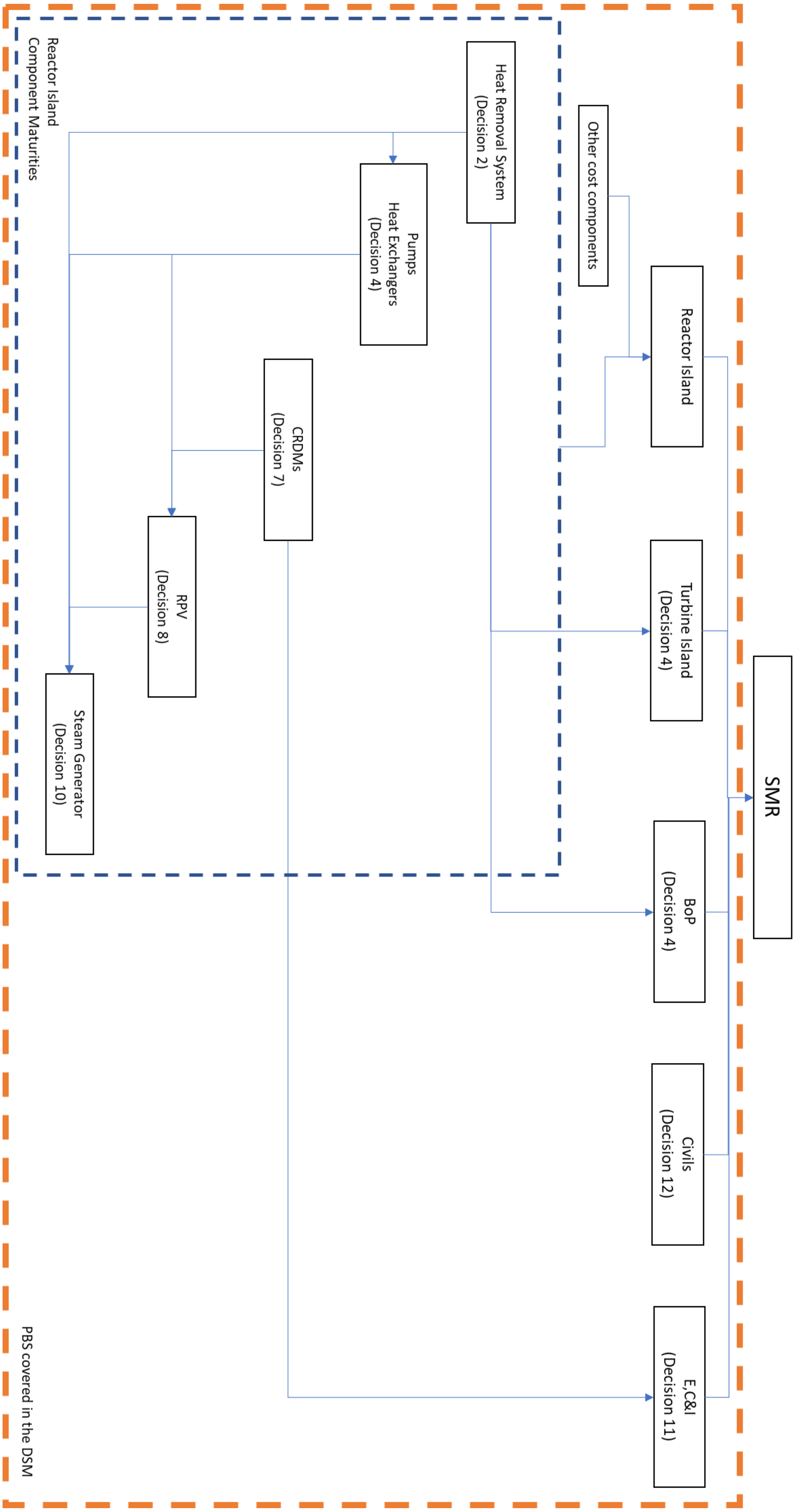


Figure 68: Structure of PBS based on decision dependencies

7.3.4 Component and Product Cost Maturity Assessment

A maturity score is assigned to each of the component cost estimates used for each decision. The maturity score is produced by assessing the quality of the information used to estimate the cost combined with the uncertainty weighting (produced using AHP, see Section 7.2). The uncertainty weighting is dependent on the type of decision for which the estimate is generated. The estimator inputs the most likely value for the cost estimate and then selects the sources of data used to produce the estimate using the Semantic scale. Table 20 presents the results of the component level maturity assessment based on the associated information available and the type of decision for which the estimate was used.

Table 20: Component maturity ratings for each decision

Decision	Component	Decision Type	Component Maturity Rating
2	Steam Generator	Design	3
2	Heat Removal System	Design	1
3	RPV	Design	3
3	CRDMs	Design	1
3	Pumps	Design	3
3	Heat Exchangers	Design	2
4	RPV	Supply Chain	2
4	CRDMs	Supply Chain	4
4	Pressuriser	Supply Chain	2
4	Heat Exchangers	Supply Chain	2
4	Civil Structures	Supply Chain	1
4	Turbine Island	Supply Chain	3
4	EC&I	Supply Chain	3
4	BoP	Supply Chain	3
6	CRDMs	Design	4
7	RPV	Design	4
7	CRDMs	Design	4
8	RPV	Manufacturing	4
10	Steam generator	Design	3
11	EC&I	Supply Chain	4
12	Civil structures	Design	1

For decision 1 the high-level subsystem cost estimates are used, with no additional design information effort to increase the maturity of the cost estimate. Therefore, no component estimates are allocated for decision 1. Several cost components are used for different decisions. For example, the RPV cost information is used to support decisions 3, 4, 7 and 8. With each decision, additional information is available creating a change in maturity for the estimate. Figure 69 shows how the RPV maturity changes with each decision.

For decision 3 the RPV cost estimate is at maturity score 3. However, the maturity reduces slightly for decision 4. Fuzzy numbers are used here illustratively to show the change in maturity compared with the previous design decision for decision 4. This reduction in maturity is because the type of decision is different. Decision 3 is a design decision, and the engineering definition for the RPV is sufficient to produce an overall component level maturity of 3. Decision 4 is a supply chain related decision, which places a greater importance weighting to the information source from supply chain compared with other sources of information. The supply chain information for the RPV at this stage is low enough to cause a slight drop in the maturity rating. This may be a useful effect of the maturity rating, as it could indicate to the design team that the assumed estimate generated for previous decision may not be of sufficient maturity for this type of decision.

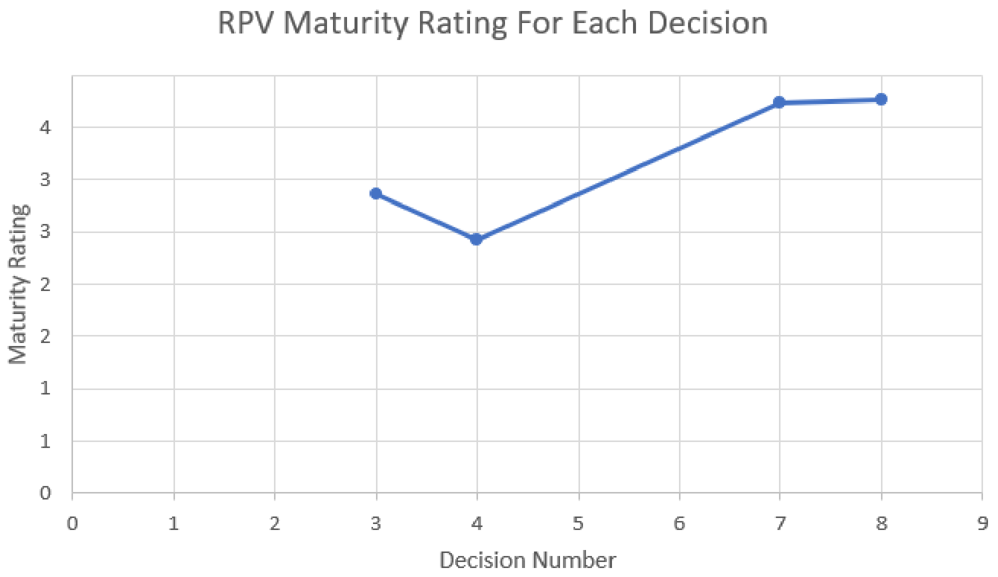


Figure 69: RPV maturity changes with each decision - fuzzy scale for illustrative purposes

7.3.4.1 Product Cost Maturity

The product cost maturity at the end of Stage 1 is obtained using the dependency structure for decisions and the latest cost estimate generated for each component available at the end of the design stage. Using the dependencies to propagate each source of uncertainty between cost elements results in an overall system maturity rating. Where several components feed in to the same cost element the weighted average of each cost component maturity is used to derive the overall maturity for the cost element. Based on the information available at the end of the development stage the DSM for the product cost maturity is shown in Table 21.

Table 21: Product cost maturity using end of stage gate component maturity rating

System	Component	Component Maturity	Subsystem Normalised Maturity	System Normalised Maturity	Total Product Maturity
SMR					2
Reactor Island				0.44	
Other Components		1	0.29		
Reactor Key Components			1.65		
	Heat Removal System	0.49			
	Pumps	0.31			
	Heat Exchangers	0.07			
	CRDMs	0.27			
	Pressuriser	0.075			
	RPV	0.38			
	Steam Generator	0.73			
Turbine Island				0.39	
BoP				0.31	
Civils				0.29	
EC&I				0.80	

Not all the components are defined for the Reactor Island subsystem. Therefore, another component is generated as a dummy which represents information which has not been generated. Based on the benchmark estimate with an assigned component maturity rating of 1, the dummy in the Reactor Island contribute to the normalised maturity for the subsystem. All components for which estimates have been generated contribute to the overall product cost maturity rating. Based on the dependency structure, the propagation of cost maturity and relative magnitude of each cost component the maturity of each subsystem the overall SMR cost maturity is 2.

7.3.5 Influencing the Product Cost Maturity

The aim of this subsection is to illustrate the potential benefit of the DSM approach to identifying and prioritising the drivers of the product cost maturity. DSM is used to identify the cost components which have the highest impact on increasing the product cost maturity. The key activities that will influence the product cost maturity are identified as activities the design team can realistically enact to achieve an improved maturity.

Two assumptions are needed at this stage to proceed with the case example. Firstly, the maximum achievable cost maturity at the end of Stage 1 for the case study is arbitrarily set at 4. The minimum acceptable (threshold) maturity level is set at 3. Given that the overall product cost maturity is 2, there is a need to increase the product maturity to a minimum score of 3. Using these assumptions, the cost components can be presented on the DSM with an associated colour representing the acceptability of the maturity rating (Table 22).

The values presented in the diagonal boxes represent the normalised maturity rating calculated as described in chapter 6. The colour coding of red, yellow and green are assigned based on the component maturity scores and whether the maturity ratings are below the threshold acceptable level, at the threshold or at the maximum achievable maturity rating respectively.

Table 22: Matrix representing cost component information at end of the stage gate

	1	2	3	4	5	6	7	8	9	10	11
(1) HRS	0.41										
(2) Pumps	1	0.11									
(3) HXS	1		0.03								
(4) CRDMs				0.07							
(5) RPV		1	1	1	0.10						
(6) SG	1	1	1		1	0.24					
(7) TI	1						0.14				
(8) BoP	1							0.12			
(9) Civils									0.29		
(10) EC&I				1						0.23	
(11) Other											0.29

7.3.5.1 Optimising the DSM

To identify the priority order of actions to increase the product maturity score, the level of interdependence (i.e. the number of dependencies identified in the matrix), the component maturity rating and the magnitude of the impact on cost maturity can be used as optimising criteria. Simple partitioning is used here to identify the priorities. Firstly, the components are sorted by colour coding, with the components of lowest maturity placed towards the top left of the matrix and components of the maximum achievable maturity (shaded in green) placed at the bottom right (Table 23).

The next stage of partitioning is to arrange the components within each colour code by the magnitude of cost impact. Red shows a cost component below the nominal threshold. These are identified as priority areas for improving the cost maturity. Amber indicates that the component is above the threshold (expected) but that some activities could still be carried out to reach the limit (achievable) in cost maturity at this stage. Green shows a component with the maximum achievable maturity of information available to make a decision and that no additional work should be carried out to improve the estimate at this stage. The highest magnitude impact on the cost maturity are moved towards the top left, while the lowest magnitude cost components are moved down towards the bottom right as illustrated in Table 24.

Table 23: Simple partitioning of DSM based on component maturity

	1	9	11	2	3	7	8	6	4	10	5
1	0.41										
9		0.29									
11			0.29								
2	1			0.11							
3	1				0.03						
7	1					0.14					
8	1						0.12				
6	1			1	1			0.24			1
4									0.07		
10									1	0.23	
5				1	1				1		0.10

Table 24: DSM showing simple partitioning by cost impact of each component

	1	11	9	6	7	8	2	3	10	5	4
1	0.41										
11		0.29									
9			0.29								
6	1			0.24			1	1		1	
7	1				0.14						
8	1					0.12					
2	1						0.11				
3	1							0.03			
10									0.23		1
5							1	1		0.10	1
4											0.07

Where other subsystems have not been matured sufficiently the product cost maturity remains low, and these have a significant influence on the overall maturity. The recommendations for the design team to improve the maturity of the cost estimate can be presented as shown in Table 25. The focus in this assessment should be on improving the cost estimates for the HRS, Other Reactor Island and Civils cost components.

Table 25: Recommendations for additional information to improve product cost maturity

Statement	Recommended Action
Product maturity rating is 2 (below threshold)	Carry out additional design work to achieve the threshold maturity rating (3)
Priority activities	1 – Produce semi-detailed model of the Heat Removal System 2 – Produce a model scaled drawing of the Reactor Island from previous, similar designs 3 – Produce a model scaled drawing of the Civils from previous, similar designs

Additional detail is presented to the design team which identifies specific activities which can be carried out to increase the product cost maturity. These activities would require additional effort to the original stage 1 project plan. For the HRS the priority would be on increasing the maturity of design information i.e. to produce a semi-detailed model. There is also the opportunity to increase maturity of manufacturing information assumed from a similar part and the potential to increase the definition of the supply chain. No work has been done on the Other Reactor Island components. The improvement to concept drawing will increase the maturity. But the recommendation is to produce a model scaled drawing from a similar design.

Although this information would not be produced for any specific type of decision and, therefore, it would not have an impact on the overall product maturity. Similarly, the civils has the lowest maturity of 1. The recommendation is to increase the Civils maturity by producing a model scaled drawing from a similar design.

If the design team increase the HRS as recommended, the component maturity passes the threshold level, but the product maturity remains at 2, below the threshold level. If, in addition, the recommended activities for the Other Reactor Island component is carried out, the component maturity increases to 3. However, the product maturity still stays at 2. By also carrying out the additional activities recommended for the Civils component, the product maturity reaches the threshold level of 3. Table 26 shows the impact of the change in information which can then be used to update the priority of the DSM matrix to show the new set of priorities for achieving increased product maturity.

Table 26: New DSM optimised following recommended actions

	1	11	9	6	7	8	2	3	10	5	4
1	0.41										
11		0.29									
9			0.29								
6	1			0.24			1	1		1	
7	1				0.14						
8	1					0.12					
2	1						0.11				
3	1							0.03			
10									0.23		1
5							1	1		0.10	1
4											0.07

7.4 Discussion

This section critically assesses the ability of the ACUBA method to perform as a decision support tool. The verification stage of the research aims to identify whether the ACUBA method is feasible and applicable at the early concept development phase. No decisions in the case study were carried out during the validation period of the research. The ACUBA method was, therefore, applied retrospectively to existing estimates generated for previous decisions.

7.4.1 Maturity Rating

The semantics developed in this case study are based on the categories of information from the perspective of a single, experienced cost estimator. One advantage of the use of qualitative language from a semantic set is standardisation of data collection methods. In this case, however, there is a limited data set available to produce the semantic scale and it is not possible to validate the ratings assigned to each qualitative statement.

A longitudinal case study, where the actual cost for each component is available would allow the uncertainty ranges associated with each of the nominal semantic scales to be developed. The uncertainty ranges could be applied to different scenarios to calculate the range of LCOE values. Such an approach would necessitate a research project that would include recording the required data over an extended period of time of 10 years or more. Even with the longitudinal study, the results would be case-specific and not generalisable to other product development projects.

7.4.2 AHP

AHP is a simple approach, requiring few resources to obtain a consistent set of weightings for the sources of uncertainty. It is clear from discussions with the design development team that the identified sub-criteria are interrelated. The ANP was identified in Chapter 6 as a method that could be used to establish the relative importance of each source of uncertainty by taking into consideration the interdependencies. However, the effort required to achieve consistency and the number of pairwise comparisons made with the ANP approach is not feasible in practice.

7.4.3 Implementing the ACUBA Steps

The change in importance of each source of uncertainty as the product matures is not accounted for in the ACUBA method. The early design stage, for example, places greater importance on engineering definition. By the end of Stage Gate 1 the main concept that will be taken forward and developed is selected, with many of the cost defining decisions having been made. Expectations on achievable maturity are assumed to differ based on the project type and historical experience available to guide the design team and the cost estimator. The focus of design development incorporate design for manufacture, design for supply chain optimisation, design for safety and design for cost. At a later stage in the development process, for example when contracts are being issued, supply chain may have a higher importance weighting.

Considering that the concept design stage is only partially complete during this study, the full impact of design decisions made at this stage on the overall product cost maturity cannot be assessed. What is achievable should be established internally. By interviewing the stakeholders involved in decision making at the next gate, the achievable cost uncertainty can be determined based on the semantic language used in the ACUBA method.

By understanding how cost uncertainty propagates through the PBS hierarchy cost elements which may have previously been considered as low impact, may be identified as driving cost uncertainty. There is limited information at the early design stage and limited time to compile information to produce an estimate. The design team, cost estimator and the commercial team need to select relevant components to generate more confidence in the estimate. The ACUBA method results can be used as a communication tool to present an idea of what information is and is not available and give a realistic interpretation of the early design stage epistemic uncertainty. The ease with which this uncertainty can be communicated at the early design stage can make a difference to how decisions are made, and the need for further information or rationale to base the decision upon.

There appears to be no reason to apply the hierarchy structure to define items in the PBS at the early design stage, other than to categorise information which will be generated at a later stage. The focus should be on the decisions themselves, the information that will be generated as a result of the decisions made, and the information required to make those decisions and their interdependence. By establishing the components or system level cost estimates that are generated to support these design decisions only the components with information should be included in the PBS.

7.5 Summary

This chapter has applied the ACUBA method to the early design stage of the case study organisation. Early estimating is qualitative and subjective. Applying uncertainty ranges is based on the judgement of the individual estimator. The use of a cost maturity metric is shown to support the prioritisation of activities to achieve a level of confidence in the early estimate. Decision making during design can be presented in terms of a set of metrics, to be utilized as benchmarks at the various decision gate points. Use of the maturity metric as a standardising qualitative tool is most effective at the early design stage. The maturity metric can support the decision rationale and support the planning efforts for different disciplines involved at the early design stage.

The aim of the method is not to provide additional precision or accuracy to an estimate, but to help the design team to be equipped with a way of understanding and contextualising and communicating cost uncertainty data. Cost maturity ratings can be used as a universal language supported by qualitative descriptions as a basis to support the rationale for targeted design effort. The ACUBA method supports a standardised approach to understanding the uncertainty associated with an early cost estimate where traditionally subjective uncertainty ranges are applied.

8 Discussion

8.1 Chapter Overview

This chapter provides a discussion on the implementation of the ACUBA method, its wider applicability outside of the case study, and how it might be integrated into the design process. The discussion forms the first part of the concluding section as shown in Figure 70.

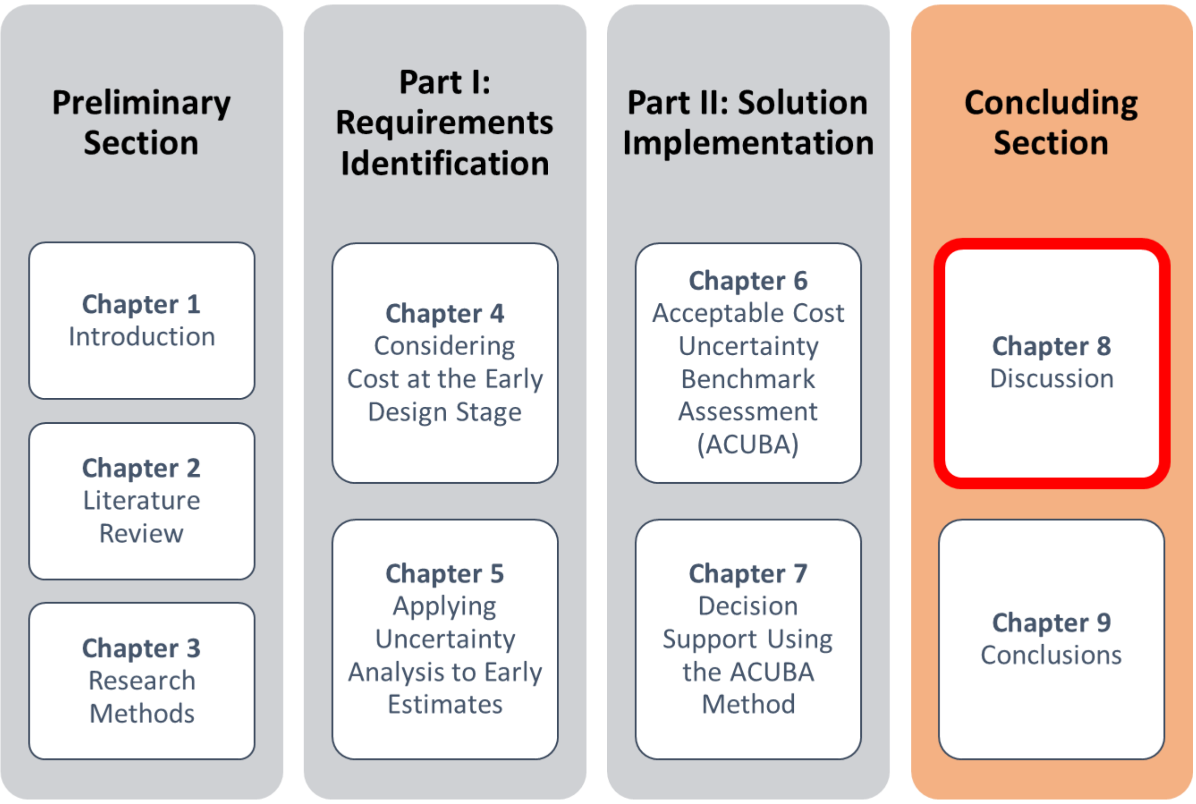


Figure 70: Discussion chapter within the context of the thesis

Section 8.2 discusses the wider applicability of the ACUBA method outside of the case study under investigation in this research. The output from the ACUBA method and the limitations of the method in supporting the decision-making process is presented in Section 8.3. One of the requirements of the ACUBA method is to integrate with existing processes at the early concept development phase. A set of generalised steps to implement the method are proposed in Section 8.4. Finally, in Section 8.5 the methods used in this research are assessed based on their suitability for resolving the stated research aim and objectives.

8.2 Wider Applicability of the ACUBA Method

The ACUBA method has been developed with a focus on supporting design decisions at the early concept development stage of the case study by providing a metric to standardise the interpretation of subjective cost uncertainty. The requirements of a decision support method using cost information are summarised here based on the research carried out in the case study organisation. The case study product being developed is innovative in terms of manufacturing, assembly and construction processes applied. The organisation also develops products that are iterative and multi-generational. That is, the design evolves for each generation of product being produced. For this discussion on wider applicability two types of product are defined. Firstly, the innovative product for which little data is expected at the early design stage. Innovative can also be thought of as First of A Kind (FOAK), where previous experience and knowledge is only applicable through reasoning. The second product type is Nth of A Kind (NOAK), for which previous experience and data could be used to produce new cost estimates. A set of requirements for the ACUBA method were defined in Chapter 6. Each requirement is now compared with the wider relevance to early design decision making for different projects.

8.2.1.1 Requirement 1

The method needs to be able to use minimal cost information to support decision rationale.

For innovative products there will be little design information from which to produce a cost estimate. The estimating techniques available and associated subjective uncertainty ranges would necessitate the use of cost maturity ratings. For NOAK products there should be data available from previous iterations that could be incorporated to reduce the subjectivity of early concept design decisions. However, if there is a fundamental change in technology or design for a system or group of systems the maturity ratings could be employed to represent this increase in uncertainty.

8.2.1.2 Requirement 2

The method must incorporate cost uncertainty as this heavily influences early stage estimates.

Cost uncertainty can drive different decisions depending on its interpretation and presentation (see Chapter 5). However, without a clear sensitivity analysis to identify cost uncertainty drivers, and quality data to base the uncertainty analysis on, the uncertainty ranges will be different for each expert producing the analysis. This could be the case for both FOAK and NOAK products. The ACUBA method attempts to minimise variation in the interpretation of epistemic cost uncertainty based on the subjective input from the estimator.

8.2.1.3 Requirement 3

The method must support the design team to understand how and when decisions should be made in terms of how this influences the cost estimate.

The ACUBA method has been designed to be incorporated into the Stage-Gate© process. The points at which an ACUBA assessment should be carried out in the gated process is illustrated in Figure 71. The generalised method only applies to the gated approach with defined milestone points. Design programmes that do not use stage gates need to adapt the method for use with milestone decision points.

The ACUBA method needs to be calibrated for the expected, achievable and required uncertainty ranges at each decision point. This is dependent on the availability of personnel to establish the benchmark. Although this could be simple to apply, some analysis would be required to understand the level of information that would be available at each design stage, thereby determining a maximum achievable maturity for a cost estimate.

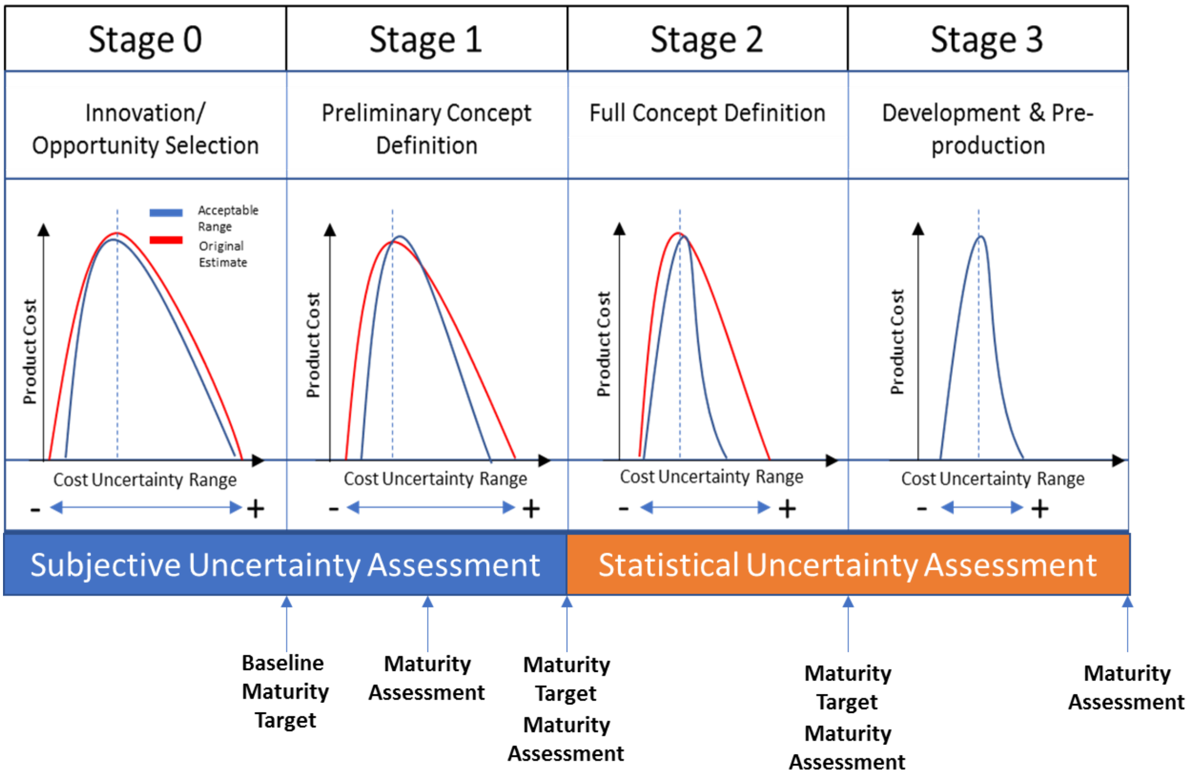


Figure 71: When to carry out the ACUBA maturity assessment

FOAK products are likely to have far more challenging and uncertain R&D as part of the early development stage. Less will be known about the product, and so setting far too high an expectation of cost certainty could negatively impact on innovative thinking. However, the stage at which the ACUBA is supposed to be applied should focus more on the delivery of a single concept, and its implementation to the innovative product development steps should be limited. Equally the designers could use the ACUBA method to set expectations on the cost maturity and use the sensitive areas to provide a business case for further development in specific systems which have a lower maturity rating, but which are the drivers of uncertainty. These drivers may be less identifiable through traditional sensitivity analysis employed to design developments which may focus on the largest cost elements.

8.2.1.4 Requirement 4

The method requires a way of including the interdependent nature of design decisions into the cost analysis.

The availability of dependency data is different for FOAK and NOAK products, which means the way in which dependencies are identified will be different. The approach taken with the case study is to use DSM to present the dependencies as defined by the project plan between different decisions. Another approach would be to identify the dependencies using the subjective assessment of the design team members. However, actual data can be used to produce Cost Estimating Relationships (CERs) for NOAK products, reducing the subjectivity of this activity which is unavoidable with an innovative product. The DSM approach would potentially be less accurate in identifying interdependencies for NOAK products which will have a complete product breakdown structure from previous experience. Dependencies can then be identified from existing data and used to propagate cost uncertainty using dependency relationships rather than the hierarchical structure of the PBS.

8.2.1.5 Requirement 5

The method must provide a clear way of communicating cost information to multiple design stage stakeholders.

Training is required to produce the maturity rating and to interpret the output data. Inputs will need to be standardised, with clear guidelines for cost estimators on how to implement the ACUBA method. Planning prior to the design stage should incorporate the ACUBA method. The outputs of the ACUBA method presents information that links to direct design development activities (see Section 8.3 for further discussion). The integration with the PBS is also critical to show the fluidity of the maturity rating with each change in information in real-time. Once the method is standardised the interpretation of cost uncertainty and source of uncertainty are also standardised. The decisions based on the analysis of cost maturity will provide clearer rationale for the decision-maker.

One way of generalising the method is to use existing frameworks that relate uncertainty and risk in decision-making. The Risk In Decision Making (RIDM) method proposed by NASA (2010) supports “robust decision making”. Based on this best practice the generalised steps for the ACUBA method implementation are shown in Figure 72.

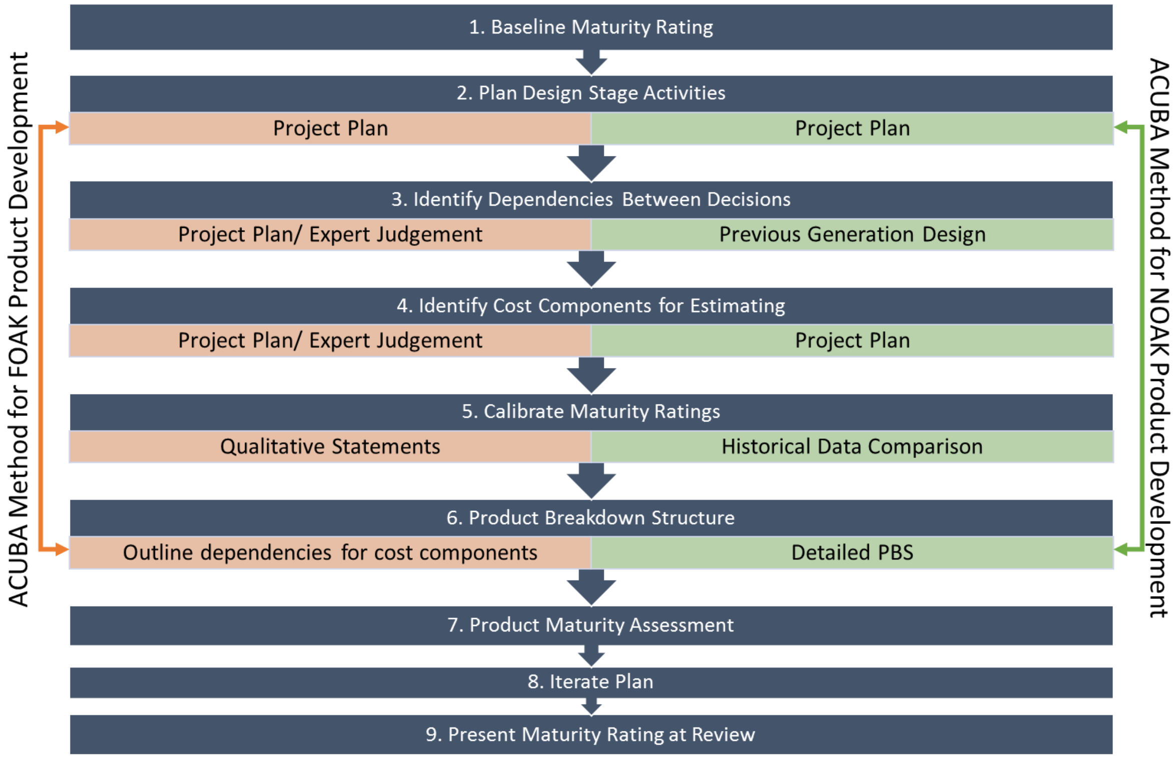


Figure 72: Generalised ACUBA method steps for innovative and multi-generational product development projects

8.3 Interpreting the ACUBA Output

Decision-makers at the early design stage require a standard approach to understanding and interpreting cost data. The application of the ACUBA method allows the cost estimator to standardise the approach for communicating cost information. A cost uncertainty range with an early estimate would not demonstrate effectively where the lack of confidence derives from. There is a need to understand the scope of the analysis and communicate the results appropriately in order to support decisions made on the basis of cost at the early design stage. In the workshop each participant was required to make a decision based on their own interpretation and expertise.

As there are different perspectives from different functions (such as those identified in chapter 5), a clear understanding of the cost requirements is needed. In this case, the SMR product requirements suggest design decisions should lean towards those which will achieve greater product cost certainty and lower cost. This can be used as the basis for presenting information and calibrating the acceptable uncertainty metric to the level of risk appetite. A product which is less constrained by achieving cost certainty at the early stages but is more driven by the need to reduce costs may be calibrated such that a lower acceptable uncertainty rating could be set.

Figure 73 illustrates how different sources of cost might be influenced by implementing the ACUBA method. Primarily, the method is applied at the early design stage by identifying the influencing factors on the product or component cost maturity. One of the key requirements for the SMR is construction cost certainty. The ACUBA metric attempts to represent the magnitude of each source of epistemic uncertainty for the cost estimate generated at the early design stage.

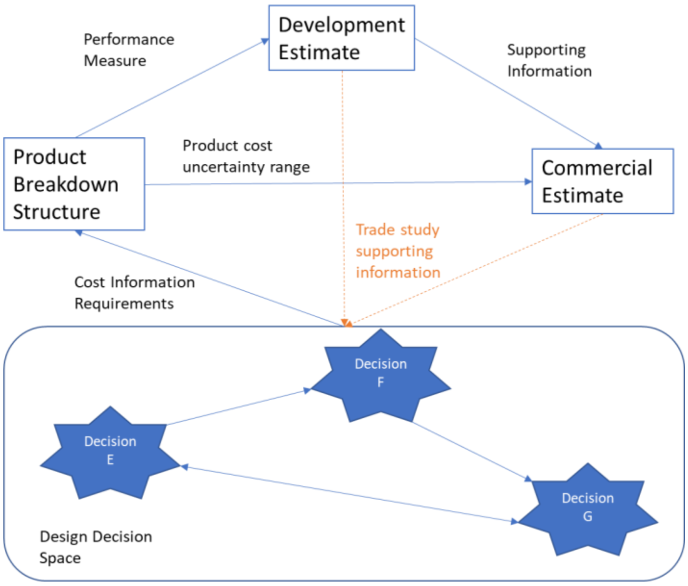


Figure 73: ACUBA method providing maturity ratings to support other non-product related cost activities

The useful application of the ACUBA method would require the decision-makers at the outset of a project to establish the acceptable maturity level (which can be associated with the risk tolerance at the early design stage). From a baseline estimate which provides the current maturity the design team can then assess the resources required to achieve the acceptable uncertainty. In such a way project cost estimating is supported by the effort required to achieve an acceptable product cost. Differing levels of acceptability can be applied at the system, subsystem and component level. The process could be used to understand the rate at which maturity of the cost estimate is increasing, and how each decision influences it. The ACUBA method also provides a design development planning tool and a decision support method. It is dynamic, so it can account for incremental changes to information availability. Although, the ACUBA method requires validating using actual cost data to establish if the uncertainty relationships identified at the early concept stage hold true. The ACUBA process also interfaces with the LCOE estimate. There is an influence on the LCOE, and this is measured using the established uncertainty metrics to provide a sensitivity range for the epistemic uncertainty around the capital cost of the SMR.

The implementation of the ACUBA method allows a design team to come to a clear decision (be that a selected option, or the request for additional information). Further work could be carried out into investigating the impact of different forms of information presentation on the decision-making by different project team members at the early design stage. The maturity rating system could also be linked to each level of an associated quantitative cost confidence (such as the uncertainty distributions described in 5.2.1). An area which has not been explored yet is the ability to link different maturity metrics. Other maturity metrics such as Technology Readiness Level could be linked to the effort required to increase the cost estimate maturity.

8.4 End User Assessment

End user assessment of the ACUBA method is presented here based on a decision experiment carried out in the case study organisation. Based on the ACUBA method identified in Chapter 6, and the design decision-making approach presented in Chapter 4, a decision scenario was presented as a decision meeting. The method applied is briefly described in the following section, followed by an analysis of the results which inform the next steps for fully operationalising the ACUBA method presented in Section 8.5.

8.4.1 Method

The design decision scenario was based on the need to select one of the design options for a single component, selecting the most cost-effective option. Cost information was generated using data available in the Generation IV Code Of Accounts produced by the Economic Modelling Working Group (EWMG, 2004) appendix examples. For the decision scenario, the overall costs of the three possible options were presented with selected information. Each of these design options were at differing levels of cost maturity based on the method used to estimate them.

Chapter 4 identified the key cost criteria relate to the V&V cost, component cost and LCOE. For each decision the component cost with uncertainty, unit cost and LCOE was presented. Several variants of the component were presented. The product unit cost and lifecycle cost are related to the component cost based on the uncertainty range associated with the component cost (all other costs and variables are held as fixed for the experiment). The only variant is the display of the component cost information.

The procedure for the focus group experiment was communicated to the participants at the start. Two groups made up of 4 participants each were elicited in the study (Table 27). Four participants were selected to represent different functions within the project team in each group. Framing is described as “two logically equivalent (but not transparently equivalent) statements of a problem lead decision makers to choose different options” (Rabin, 1998, p. 36). Framing here relates to the different ways of presenting cost uncertainty information for the component and unit cost i.e. using the ACUBA maturity rating with cost uncertainty range and just a cost uncertainty range. The information which each presentation is based on is the same in both cases.

The data used to form each of the uncertainty presentation methods was the same for both focus groups. The main variable, therefore, is the presentation of cost uncertainty information for the component cost and the product maturity cost. The basic level of cost maturity for each option was presented to the design team as the first part of the assessment. The design team were then presented with the option to select one of the options based on the information that they had available. Crucially, the design team were also able to choose to gather more information to develop the design further, thereby increasing the maturity of the cost estimate.

Table 27: Participants for end user assessment study

Represented Function	Group 1	Group 2
Design	Modelling & Analytics	Design Engineer
Project Management	Project Engineer	Project Manager
Commercial	Supply Chain Manager	Supply Chain Manager
Manufacturing	Manufacturing Lead	Manufacturing Engineer

The options were shown to participants with the associated cost information. The options were to select one of the options or to alternatively select more information from a discrete number of choices. The participants were told that they could ask for more information (either more engineering design information, supply chain information or manufacturing process information), but that the additional information requires additional man-hours that will increase the development cost. The participants were then asked to record their initial decision on the questionnaire. For each decision, the component cost with uncertainty, unit cost, LCOE is given, and the option for requesting additional information. The cost estimate was updated in real-time if additional information was requested.

The participants were given 5 minutes to deliberate with each other about the possible decision to take. Separately, the researcher records the group decision, the number of minutes to reach consensus of decision, and the reason why the option was selected. Having completed the decision in one round, the next round of cost information was shown to participants with updated values. The same method was carried out again for 2 subsequent rounds. In the final round, participants were asked to write down their preference for each of the four options assigning ranks from 1 (highest preference) to 4 (lowest preference). The participants were asked to discuss their final option selection. The observer records the time to make a decision, the final decision selected and the group decision as to why it was selected.

8.4.2 Results

In the preliminary question, each participant was asked to rank the importance of each cost requirement individually (Table 28). All participants in group 1 and group 2 selected LCOE as the most important cost requirement for the SMR. The main reason for the LCOE being selected was as a measure of competitiveness for the end user.

When group 1 was presented with the first set of options in round 1 of the experiment the consensus was to select the option with the lowest LCOE. Prior to the group discussion each participant was asked to note down their preferred option. Despite some discussion about the large uncertainty in unit cost, and the need for more information about risk and schedule impact, group consensus led to selecting the lowest LCOE option. The selection of the lowest LCOE option ended the experiment at round 1.

When group 2 was presented with the first set of options in round 1 of the experiment the consensus was to select option D (obtain more information). Each participant also selected the option D in their individual assessment. At round 2 there was less consensus, with 2 participants (commercial and project management) wanting to obtain more detail (selecting option D) while the other 2 participants (design and manufacturing) wanting to selection the lowest LCOE (option C). After 15 minutes of discussion the group agreed to select option C. The main reason presented was that this option provided the lowest LCOE with enough maturity to make a decision.

Table 28: Cost information available to participants after each round

Round 1

Supporting Data	Basic Outline Sketch
Estimating Approach	Cost scaled down from PWR reference Code of Accounts Ref from 2001, cost of a large reactor pressure vessel. (Size scaled down for a nominal size RPV for 1000MW)

						5th of a Kind	
	Description	Median RPV Cost (£)	Reactor Power Capacity	Upper Bound	Lower Bound	NSSS Cost	LCOE (£/MWh)
Option A	Scaled Down Pressure Vessel	16483200	476	32966400	8241600	24882157.35	64
Option B	Smaller Pressure Vessel	14834880	340	29669760	7417440	22393941.61	61
Option C	Compact Pressure Vessel	12461299.2	255	24922598.4	6230649.6	18810910.96	59

Option D	*Obtain Additional Information*	Engineering Definition	Manufacturing Process Information	Supply Chain Information
	Cost of Additional Information	200 man hours	40 man hours	40 man hours

Round 2

Supporting Data	asic dimensioned drawings, large forgings main manufacturing process, no suppliers identified
Estimating Approach	Cost calculated in semi-bottom up from engineering outline. Manufacturing processes assumed, no supplier identified

						5th of a Kind	
	Description	Median RPV Cost (£)	Reactor Power Capacity	Upper Bound	Lower Bound	NSSS Cost	LCOE (£/MWh)
Option A	Pressure Vessel OD 3157mm	19500000	411.4	29250000	13650000	29436157.32	68
Option B	Pressure Vessel OD 3092mm	16400000	370.6	24600000	11480000	24756563.08	60
Option C	Pressure Vessel OD 2740mm	12500000	302.6	18750000	8750000	18869331.61	57

Option D	*Obtain Additional Information*	Engineering Definition	Manufacturing Process Information	Supply Chain Information
	Cost of Additional Information	800 man hours	160 man hours	250 man hours

Round 3

Supporting Data	Basic dimensioned drawings, large forgings main manufacturing process, suppliers identified
Estimating Approach	Bottom up database cost rates for material, estimated weights for upper and lower section, estimated labour rates for forgings, supplier estimated rates

						5th of a Kind	
	Description	Median RPV Cost (£)	Reactor Power Capacity	Upper Bound	Lower Bound	NSSS Cost	LCOE (£/MWh)
Option A	Pressure Vessel OD 3157mm	19250858.18	411.4	25026115.64	15400686.55	29060066.15	68
Option B	Pressure Vessel OD 3092mm	18814233.65	370.6	24458503.75	15051386.92	28400961.11	61
Option C	Pressure Vessel OD 2740mm	16826681.56	302.6	21874686.02	13461345.25	25400658.74	59

8.4.3 Improving the ACUBA Method

Two areas of improvement have been identified from the end user assessment. Firstly, there is a need to understand how each cost characteristic influences the other. Group 1, convinced that the right decision was to select the lowest LCOE option were not influenced to gather more data, despite some discussion on the need to gain more certainty from 2 participants. Secondly, the cost and time required to improve the maturity of an estimate is not presented. The associated impact of development cost on the maturity for each option was also identified by participants as information that could support decisions. The maturity metric does not, at this stage, provide a clear relationship between the unit cost, LCOE cost and development cost.

8.5 Operationalising into the Design Process

The maturity ratings are determined at the planning stage, during the execution of design stages to support specific decisions and to support progression through the stage gate. By understanding the main systems, subsystems and components which will be influenced by all the decisions to be made before a gate review the expected maturity can be estimated. This provides a benchmark of expected uncertainty at the review. A process emerges where the design team will be expected to generate specific information to enable manufacturing engineers, supply chain engineers, and estimator to carry out the necessary activities to generate an acceptable cost estimate.

To an extent what is deemed an achievable level of cost maturity is based on the willingness of the design organisation to commit resources to gain additional knowledge. This is limited by the decisions that are made up to that point, as the likelihood of change affecting the knowledge gained is still high at the early design stage. Early decisions are carried out during design reviews or at gate stages. The decision outcome will be influenced by the certainty with which a design solution will achieve the product requirements. Acceptance of the design at the early stage is then the understanding of the resources required to reduce uncertainty, or a willingness to accept the current level of uncertainty associated with the estimate.

Once the estimate has been generated an understanding of the level of certainty associated with the cost components is required by the design team. The interpretation. These can then be built into the requirements and used as attributes against which the various concepts are measured. The time required to generate the estimate is not explicitly described in any of the methods presented. The time or resources required to carry out the estimating activity could be an important dimension for the acceptability of a cost estimate and could be incorporated into the uncertainty analysis.

The impact of design decisions up to the current point in the gate stage are used to assess the progress towards an acceptable cost maturity and the required activities to achieve acceptable cost maturity. A target maturity rating for the end of the development stage could be set based on the expected information that would be available at the product level.

Design decisions are based on multiple criteria. Profitability in new product introduction requires the developer to balance customer “wants and needs” with cost, quality and time targets that are achieved through execution of a development process. Cost is only one performance measure used to select a particular design option or course of action. The ACUBA method does not incorporate other decision considerations such as safety, or functionality. Integration with other decision support tools could add a significant layer of complexity. The method will need to evidence that it supports decision making, particularly with regards to cost requirements. In addition, how the method interfaces with other multi-criteria decision analysis tools will need confirming. Integration is required to MCDA tools used to support early design decisions.

8.6 Critique of Applied Research Methods

A mixed methods approach was used to first understand the context within which cost is used by the design development team at the early concept stage for the SMR, and then to frame the research problem. The purpose of this two-phase, sequential mixed methods study was to explore participant views with the intent of using the analysis to develop and test the method from a representative sample population (Figure 74). The studies described in this thesis revolved around a single case. The cross-sectional approach describes snapshots from within the development programme of a single project. The early design stage is dynamic, with processes and decision outcomes often remaining fuzzy and uncertain. Some assumptions (particularly in Chapter 4 and

Chapter 6) regarding the expectation of cost uncertainty are based on the perception of the entire product development lifecycle.

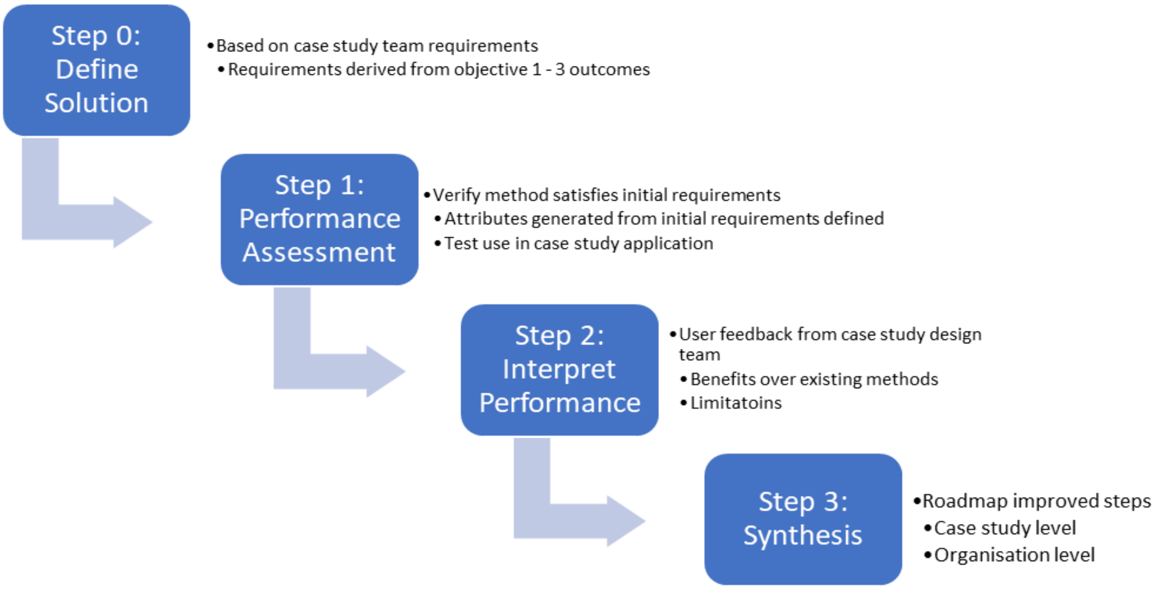


Figure 74: Key steps to design decision making in engineering (Collignian et al, 2012)

A participatory approach was used to provide a more in-depth investigation into how the case study organisation uses cost uncertainty information to make design decisions. Improving the accuracy of a cost model may be perceived to lead to clearer rationale to support design decisions. However, the use of specific cost models based on historical data or expert judgement may lead to decisions which are anchored in an understanding of early estimates. With better or new information, it may come as a surprise to the decision maker that the estimate may deviate significantly from the early estimate. The interview method allowed participants to share information and direct the development of the discussion without being restricted by the limits of a structured questionnaire. It also allowed participants to discuss their own viewpoints free of influence from other participants in the study, as would have been the case in a workshop approach.

The research problem was identified through an extensive analysis of the existing literature and clarified through analysis of semi-structured interviews within the case study organisation. A significant driver for the research aim and objectives, and ultimately the research strategy applied was the context of the development of the SMR. The SMR product development in the organisation bounds the scope of the research presented in this thesis. A review of documents does not provide the as-is process used by the design team, but a generic standard model to be adopted. Although it provided a useful basis to assess the approach used by the case study organisation. The process identified in Chapter 4 provides a snapshot in time of the development process from a select number of senior decision makers. With new information and changing requirements, a follow up investigation could have revealed a change in approach. In addition, the lack of a Cost Estimator at this stage of the product development programme limited the depth to which the model could interpret the use of cost information.

The production of a representative model is dependent on the ability of the researcher to effectively translate the interview data into codes, and to visualise these in a simple, informative and accurate way. The development process is a dynamic activity. The dynamism is not represented adequately in the IDEF0 model. The process is also specific to each project. The design development process is iterative particularly when carrying out design optioneering. The IDEF0 model does not take into account the flow of time, and so does not describe the sometimes circular and iterative nature of the development process. The linear representation does, however, describe the key steps involved in the NPD process.

9 Conclusions and Further Work

This chapter forms the final part of the thesis (Figure 75). The aim of this research was to:

> ***develop a method which uses cost uncertainty information to support decision making at the early development stage for the UK SMR*.**

A method has been developed to quantify the impact of design decisions on cost uncertainty. This method has been applied to the early concept development stage of the SMR project. By identifying the accuracy of the estimate generated, the decision-maker can better understand the impact of decisions, and the timing of decisions on the cost confidence level. By presenting the sources of cost uncertainty to the decision maker a more reasoned assessment of the design options presented is possible.

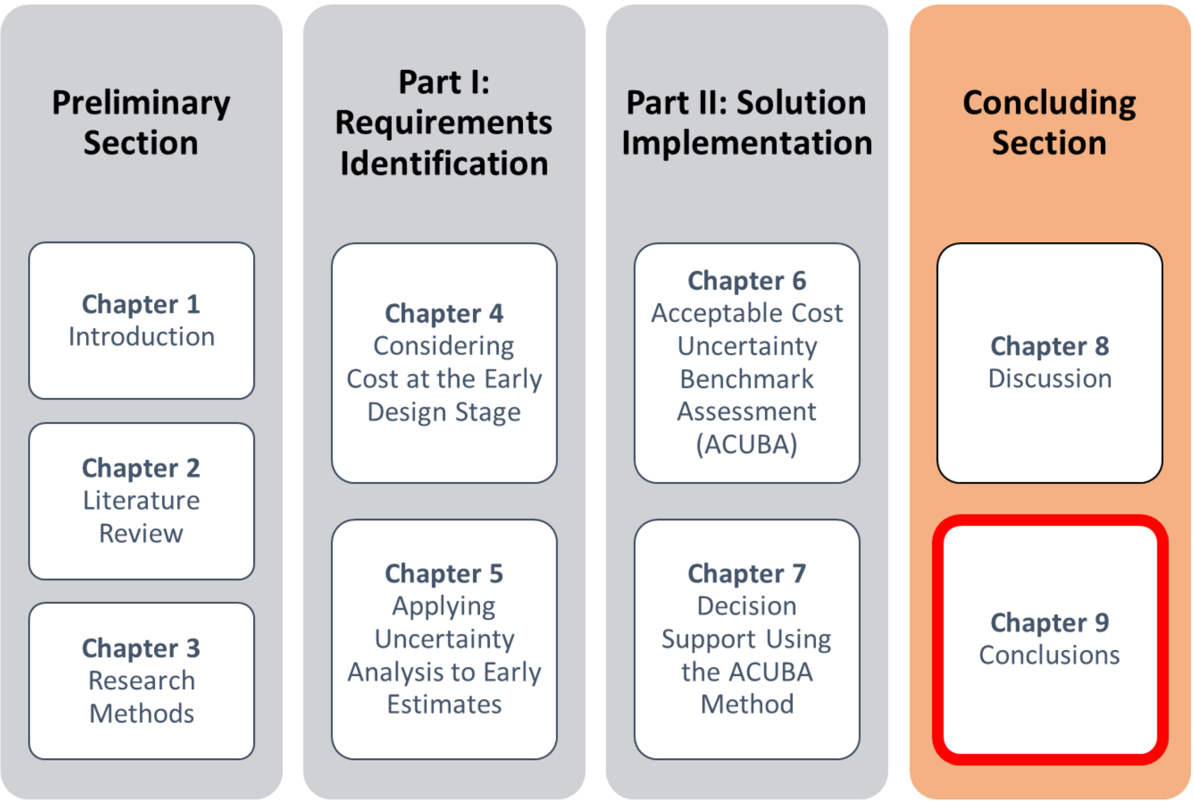


Figure 75: Conclusions chapter within the context of the thesis

The following Section provides a summary of the research objectives stated in Chapter 1. The contribution to research and significance of the research presented in this thesis is presented in Section 9.2. Finally, in Section 9.3, the next steps for the research are proposed.

9.1 Review of Research Objectives

The research objectives presented in Chapter 1, and then restated in Chapter 3, provided the basis of the research methods applied. Each of these objectives are considered in turn in this section.

9.1.1 Research Objective 1

RO1 was “to define the design decision making process and how cost is used to support design decision making.” The research investigated how early concept development stage cost information supports the design team decision rationale to increase confidence in the cost estimate. The elicitation study resulted in a model of the early development process and a gap analysis which supported the next stage of the research. A key finding was that cost was used in trading options, but little was mentioned about cost uncertainty analysis.

9.1.2 Research Objective 2

RO2 was “to ascertain the appropriate uncertainty levels at each stage of the design phase.” At the early design stage cost estimates are subject to inherent epistemic uncertainty. No existing methods applied in the case study could ascertain the appropriate uncertainty levels at the early design stage. A cost estimate may be deemed to be suitable if the expected accuracy meets the specified quality requirements. In traditional uncertainty analysis this may be presented as a required accuracy range for example selecting options with a narrower distribution of possible costs. A key finding of the research is related to the subjectivity of early stage cost uncertainty analysis. A need was identified for a method that can benchmark the suitable accuracy of the cost estimate for each major decision point.

9.1.3 Research Objective 3

RO3 was “to identify the key influences on the cost uncertainty (cost uncertainty drivers).” Cost uncertainty is reducible through the collection and interpretation of new information. The accuracy of a cost estimate is limited by the quality of the information used to produce it. Depending on the decision, different sources of uncertainty influence cost confidence. The need for a standard approach to the interpretation of early stage cost uncertainty has been identified.

9.1.4 Research Objective 4

RO4 was “to create rules to determine acceptable uncertainty range and whether estimate generated at the defined stage is acceptable.” Through carrying out research activities to meet the first three research objectives a set of requirements were identified that supported the development of the ACUBA method. Cost estimate maturity is shown to provide a supporting rationale for design decision making. In the ACUBA method the drivers of epistemic cost uncertainty associated with design decisions are identified. The ability to make a decision is related to knowledge usage and knowledge management. That is, the right **knowledge** available at the right **time** to the right **stakeholders**. A consistent method of measuring and reporting uncertainty could produce a measurable trend as the design matures. The metric, therefore, needs to be dependable, representative and viable at the early concept design phase. The ACUBA method provides this standard approach

9.1.5 Research Objective 5

RO5 was “to validate the method.” The ACUBA method has been verified by identifying its applicability to the case study. To this extent “the usefulness” of the ACUBA method has been discussed through structured focus groups with experts in the organisation. However, the method has not been fully applied to the scenarios for which it has been developed. This research has verified the usefulness of the ACUBA method to the case study design team. The ACUBA method cannot be generally applied more widely until it has been employed to a wider number of case studies. The wider application could lead to a benchmark set of acceptable maturity ranges that are used by individual organisations, or industries.

9.2 Contribution to Research

The main contribution of this research is a method for presenting more detail on the sources of cost uncertainty associated with an estimate at the early design stage using a maturity metric. The entire PBS is not available, nor is a complete set of data related to each component. Not only is there not enough design detail, there is not enough time to compile and make sense of the information. The ease with which this uncertainty can be communicated at the early design stage can make a difference to the decisions that are made. Presenting cost uncertainty data as a metric has been shown to support decision making in the case study organisation. The maturity metric can be used by the case study design team to understand the confidence in the estimate, to support the early design decision making process.

The product cost maturity metric can also be used as a performance indicator by the programme team to identify progress towards a mature cost estimate and cost certainty (a key requirement of the SMR product). The maturity of the estimate changes based on the type of information used to produce the estimate, resulting in an associated change to the cost uncertainty. Carrying out specific design activities can alter the maturity of a cost estimate. The ACUBA method can, therefore, be used to support decision points and the rationale behind design development planning.

A large body of literature exists around understanding the LCOE, a key metric used to identify the cost needs of the utility, investor or owner. LCOE provides the lifecycle cost estimate from this perspective, comparing the investment criteria for different types of power generation technology. Little research has been carried out in the early design stage cost estimating for SMRs. Cost estimating for NPPs focuses predominantly on the requirements and perspective of the investor. In the wider body of literature for cost estimating at the early design stage methods such as target costing, activity-based costing, function cost analysis, value engineering and benchmarking have been described. Interpreting cost uncertainty at the early design stage is less understood in literature. As the research progressed, the needs for cost information evolved. The lack of detail at the early design development stage where a nominal value (e.g. a percentage contingency applied to the estimated product cost) is applied restricts the analysis of cost uncertainty to qualitative techniques. Two questions arose which were used to drive the development of a method to manage design for cost uncertainty:

- What information does the design team have?
- What information is available at each stage of the design process?

For the early design stages there is no clear indication of what would be deemed acceptable level of maturity by the design team. This leads to the risk that a design team will over or under design, not meeting the expectation of gate keepers, and those that control the fate of the project. The maturity metric will need to be able to translate the level of cost uncertainty attributed with each stage gate, to support the acceptability of the decision against what is possible from the available techniques.

9.3 Future Research

The application of the ACUBA method to real-world scenarios will identify the wider usefulness of the method beyond the case study presented in this thesis. The case study relates to a single development programme. To fully validate the method requires a longitudinal case study comparing multiple applications of the ACUBA method. Two longitudinal studies involving different product development processes applying the ACUBA method would go a step further. In the longitudinal approach a detailed investigation could be made into the use of cost information, the types of design decision made, and the impact of the ACUBA method on the product cost development and uncertainty.

9.3.1 Addressing Subjectivity of the ACUBA Method

The main drawbacks of the ACUBA method relate to the need for subjective input from participants and the lack of a validated set of uncertainty ranges for the early design stage. The design team need to be elicited prior to the start of the development stage to identify key decision dependencies influencing different cost components to establish an overall product maturity. Further, there is no validated set of uncertainty ranges for the early design development stage of a NPP, therefore the acceptability of the level of maturity developed in this research is case specific.

Future research should develop a benchmark maturity rating for each stage of the gated development process using data from a variety of programmes. Benchmarking could be carried out internally to an organisation or at a wider industry level scale. The ACUBA method should be integrated as a metric within an established MCDA tool. The ACUBA method can then be used by the development team to optimise the use of limited resources available at the early stage to provide more certainty for the aspect of the design that appears to be driving cost uncertainty.

The ACUBA method follows the stage-gate process as defined within the design team. In this subsection, two other common decision gate processes widely used in industry are described, and the applicability of the ACUBA method to these are critiqued. The opportunity for the ACUBA method to use benchmarked data from multiple industries is then discussed based on the alignment with a newly developed International Construction Measurement Standard (ICMR, 2019).

9.3.1.1 APM P3M Lifecycle Phases

The APM define a decision gate as “an approval event and decision point in the life cycle where the project or programme has to demonstrate continuing viability and the required level of maturity” (PMBoK, 2019). Similar questions are identified as decision-criteria for each stage gate, related to the technical and commercial outputs of the project and their acceptability relative to the objectives of the organisation (Figure 76). The achievability of the expected outcomes and the level of maturity of the project are also assessed. The APM Body of Knowledge also identify that committing resources when the desired outcome of the project is highly uncertainty is unadvisable. Stage-gates provide the governance mechanism to support the design team in maintaining focus on aspects of the development programme that drive uncertainty.

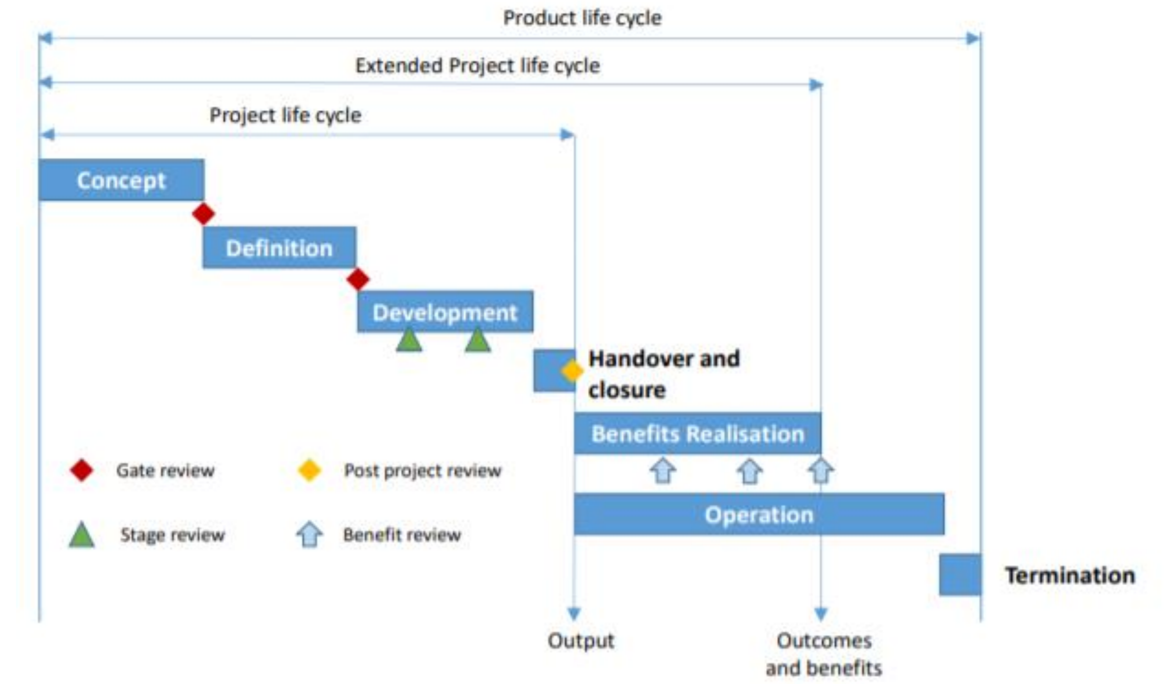


Figure 76: Project lifecycle (PMBoK, 2019)

Pardessus (2004) present an example of the application of stage gates using the APM structure to the development lifecycle of an Airbus aircraft (Figure 77). The ACUBA method could be adapted to fit the APM process, as it follows similar decision gates. The uncertainty categories should follow the organisation or industry-specific semantics, while the importance weighting for each source of uncertainty would need to be assessed for the specific development program.

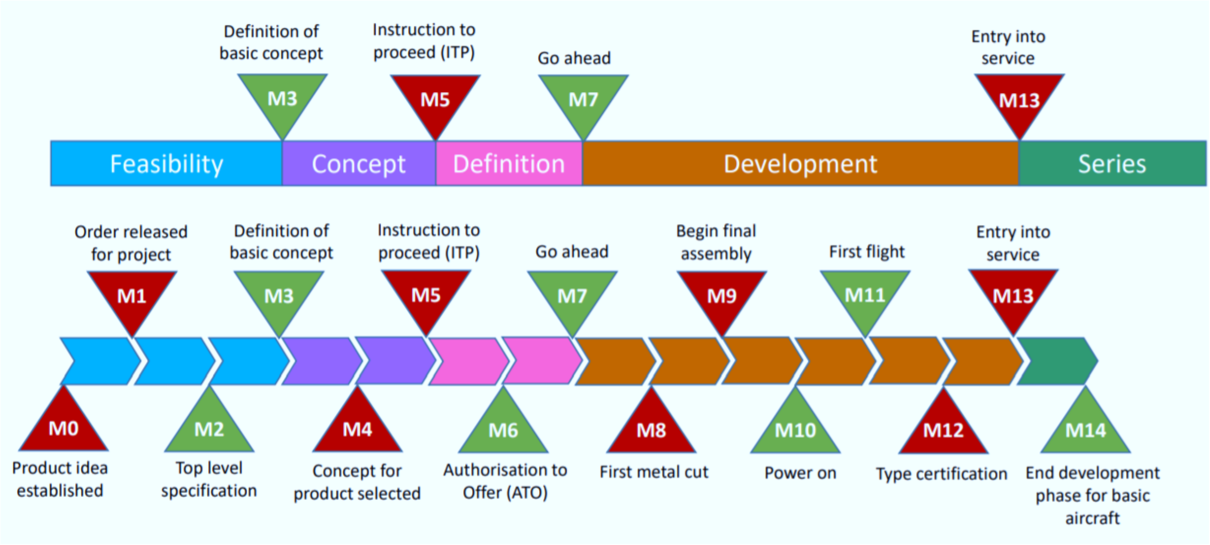
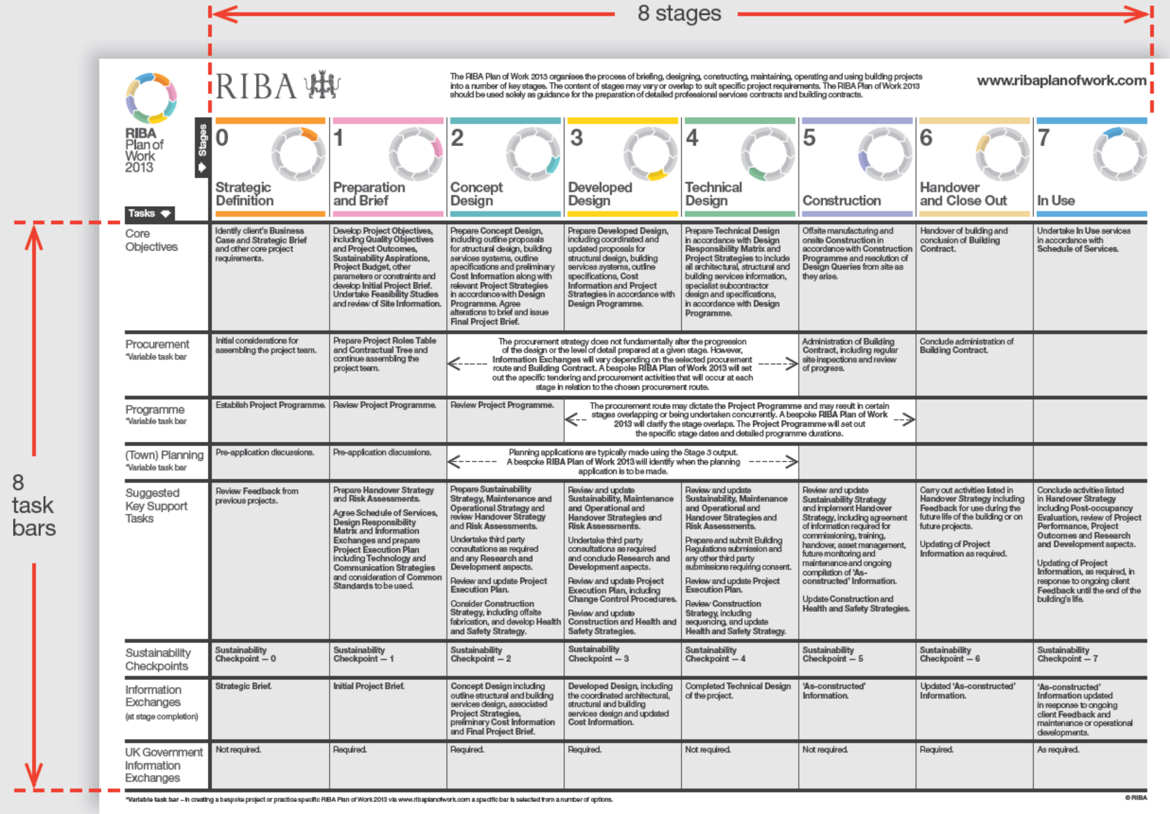


Figure 77: Example APM gate process for aircraft development program (Pardessus, 2004)

9.3.1.2 RIBA Plan of Work (2013)

The Royal Institute of Builders and Architects (RIBA) define a “Plan of Work” consisting of eight distinct stages. Each stage has a set of 8 high level tasks categorised into 4 stages for design, with concept design defined as the third stage of the programme (Figure 78).



RIBA Plan of Work 2013

The RIBA Plan of Work 2013 organises the process of briefing, designing, constructing, maintaining, operating and using building projects into a number of key stages. The content of stages may vary or overlap to suit specific project requirements. The RIBA Plan of Work 2013 should be used solely as guidance for the preparation of detailed professional services contracts and building contracts.

www.ribaplanofwork.com

Stages / Tasks	0 Strategic Definition	1 Preparation and Brief	2 Concept Design	3 Developed Design	4 Technical Design	5 Construction	6 Handover and Close Out	7 In Use
Core Objectives	Identify client's Business Case and Strategic Brief and other core project requirements.	Develop Project Objectives, including Quality Objectives and Project Outcomes, Sustainability Aspirations, Project Budget, other parameters or constraints and develop Initial Project Brief. Undertake Feasibility Studies and review of Site Information.	Prepare Concept Design, including outline proposals for structural design, building services systems, outline specifications and preliminary Cost Information along with relevant Project Strategies in accordance with Design Programme. Agree alterations to brief and issue Final Project Brief.	Prepare Developed Design, including coordinated and updated proposals for structural design, building services systems, outline specifications, Cost Information and Project Strategies in accordance with Design Programme.	Prepare Technical Design in accordance with Design Responsibility Matrix and Project Strategies to include all architectural, structural and building services information, specialist subcontractor design and specifications, in accordance with Design Programme.	Offsite manufacturing and onsite Construction in accordance with Construction Programme and resolution of Design Queries from site as they arise.	Handover of building and conclusion of Building Contract.	Undertake In Use services in accordance with Schedule of Services.
Procurement *Variable task bar	Initial considerations for assembling the project team.	Prepare Project Roles Table and Contractual Tree and continue assembling the project team.	<---- The procurement strategy does not fundamentally alter the progression of the design or the level of detail prepared at a given stage. However, Information Exchanges will vary depending on the selected procurement route and Building Contract. A bespoke RIBA Plan of Work 2013 will set out the specific tendering and procurement activities that will occur at each stage in relation to the chosen procurement route. ---->			Administration of Building Contract, including regular site inspections and review of progress.	Conclude administration of Building Contract.	
Programme *Variable task bar	Establish Project Programme.	Review Project Programme.	Review Project Programme.	<-- The procurement route may dictate the Project Programme and may result in certain stages overlapping or being undertaken concurrently. A bespoke RIBA Plan of Work 2013 will clarify the stage overlaps. The Project Programme will set out the specific stage dates and detailed programme durations. -->				
(Town) Planning *Variable task bar	Pre-application discussions.	Pre-application discussions.	<------ Planning applications are typically made using the Stage 3 output. A bespoke RIBA Plan of Work 2013 will identify when the planning application is to be made. ------>					
Suggested Key Support Tasks	Review Feedback from previous projects.	Prepare Handover Strategy and Risk Assessments. Agree Schedule of Services, Design Responsibility Matrix and Information Exchanges and prepare Project Execution Plan including Technology and Communication Strategies and consideration of Common Standards to be used.	Prepare Sustainability Strategy, Maintenance and Operational Strategy and review Handover Strategy and Risk Assessments. Undertake third party consultations as required and any Research and Development aspects. Review and update Project Execution Plan. Consider Construction Strategy, including offsite fabrication, and develop Health and Safety Strategy.	Review and update Sustainability, Maintenance and Operational and Handover Strategies and Risk Assessments. Undertake third party consultations as required and conclude Research and Development aspects. Review and update Project Execution Plan, including Change Control Procedures. Review and update Construction and Health and Safety Strategies.	Review and update Sustainability, Maintenance and Operational and Handover Strategies and Risk Assessments. Prepare and submit Building Regulations submission and any other third party submissions requiring consent. Review and update Project Execution Plan. Review Construction Strategy, including sequencing, and update Health and Safety Strategy.	Review and update Sustainability Strategy and implement Handover Strategy, including agreement of information required for commissioning, training, handover, asset management, future monitoring and maintenance and ongoing compilation of 'As-constructed' Information. Update Construction and Health and Safety Strategies.	Carry out activities listed in Handover Strategy including Feedback for use during the future life of the building or on future projects. Updating of Project Information as required.	Conclude activities listed in Handover Strategy including Post-occupancy Evaluation, review of Project Performance, Project Outcomes and Research and Development aspects. Updating of Project Information, as required, in response to ongoing client Feedback until the end of the building's life.
Sustainability Checkpoints	Sustainability Checkpoint — 0	Sustainability Checkpoint — 1	Sustainability Checkpoint — 2	Sustainability Checkpoint — 3	Sustainability Checkpoint — 4	Sustainability Checkpoint — 5	Sustainability Checkpoint — 6	Sustainability Checkpoint — 7
Information Exchanges (at stage completion)	Strategic Brief.	Initial Project Brief.	Concept Design including outline structural and building services design, associated Project Strategies, preliminary Cost Information and Final Project Brief.	Developed Design, including the coordinated architectural, structural and building services design and updated Cost Information.	Completed Technical Design of the project.	'As-constructed' Information.	Updated 'As-constructed' Information.	'As-constructed' Information updated in response to ongoing client Feedback and maintenance or operational developments.
UK Government Information Exchanges	Not required.	Required.	Required.	Required.	Not required.	Not required.	Required.	As required.

*Variable task bar – In creating a bespoke project or practice specific RIBA Plan of Work 2013 via www.ribaplanofwork.com a specific bar is selected from a number of options.

© RIBA

Figure 78: Extract of RIBA Plan of Work Process (RIBA, 2013)

The task bars refer to specific information expected to be generated at each stage of the project. These include sustainability checkpoints. The RIBA process follows the expected process for constructing a building, rather than focusing on the build programme as a set of integrated systems. The ACUBA metric could be modified to incorporate a different set of uncertainty sources (i.e. not supply chain, engineering definition or manufacturing route), such as Sustainability Checkpoints, Planning, or Programme as identified in the RIBA Plan of Work (2013). However, this would require a complete study of the sources of uncertainty, impact weighting of each source on the confidence of the estimate, and the assessment of the interdependencies of subsystems and their relative impact on cost maturity.

9.3.1.3 International Construction Measurement Standard (2019)

As well as the stages of the development process, the cost breakdown structure should also be understood to support the development of interdependencies. There are many cost breakdown structures available to codify the various costs associated with a nuclear power plant program. The cost structure should be based on an established and widely applied standard for the ACUBA method to be commonly applied across multiple projects. The IAEA (2000) have a standard code of accounts as does the Economic Modelling Working Group of the Generation IV International Forum (EWMG, 2007). A recent development is the International Construction Measurement Rules (ICMR 2019), which could become a common framework for major construction projects in the future. A standard, common coding system to ensure recording of costs and scope definition across multiple stakeholders is key to ensure consistency of cost estimates across different stages of the project lifecycle. ICMR standardisation of cost categories could support the benchmarking and assessing of maturity requirements across different industries, providing a potential avenue for generalising the method based on quantitative experience.

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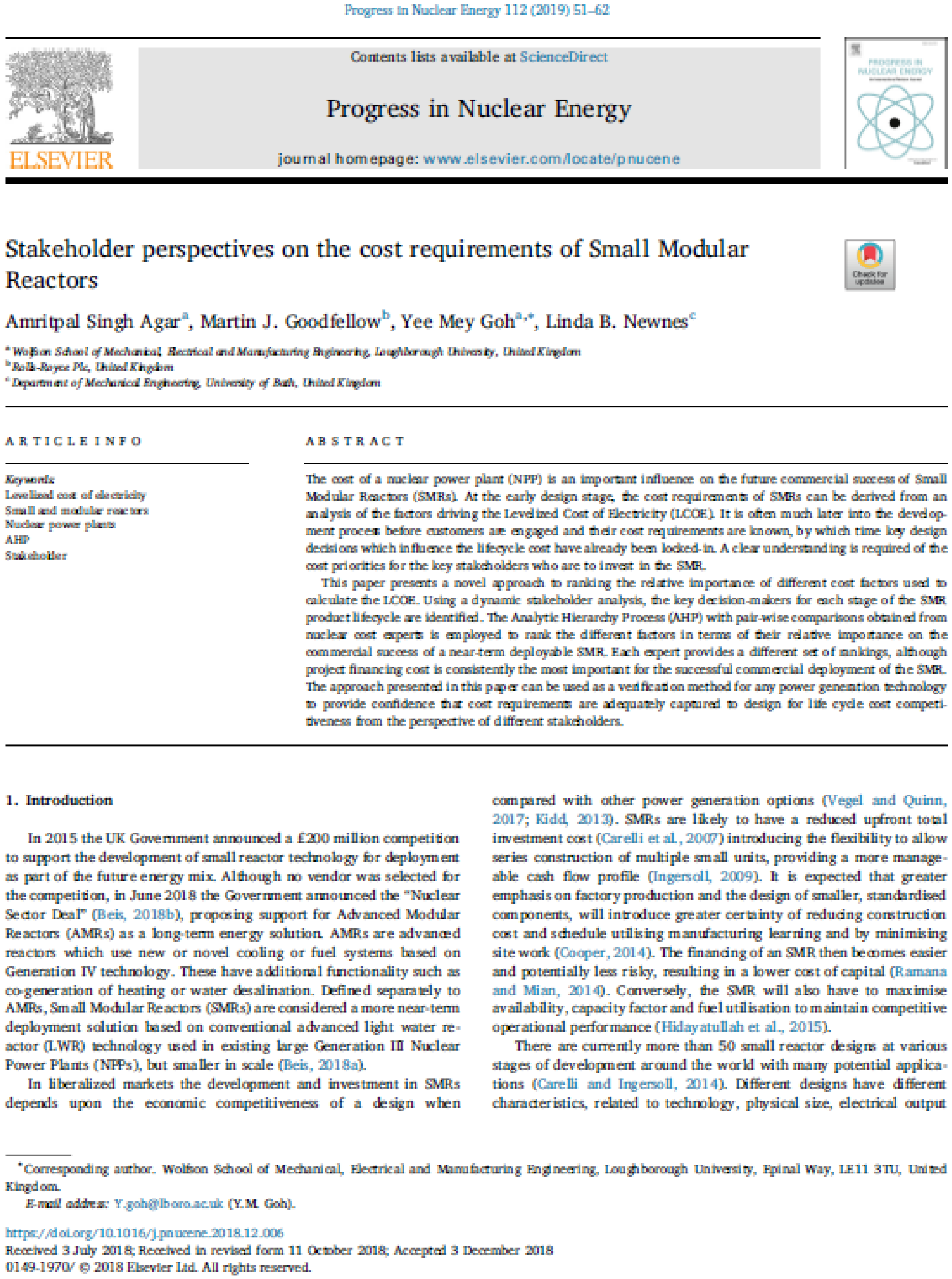
Appendices

Appendix A



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Stakeholder perspectives on the cost requirements of Small Modular Reactors

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ABSTRACT

The cost of a nuclear power plant (NPP) is an important influence on the future commercial success of Small Modular Reactors (SMRs). At the early design stage, the cost requirements of SMRs can be derived from an analysis of the factors driving the Levelized Cost of Electricity (LCOE). It is often much later into the development process before customers are engaged and their cost requirements are known, by which time key design decisions which influence the lifecycle cost have already been locked-in. A clear understanding is required of the cost priorities for the key stakeholders who are to invest in the SMR.

This paper presents a novel approach to ranking the relative importance of different cost factors used to calculate the LCOE. Using a dynamic stakeholder analysis, the key decision-makers for each stage of the SMR product lifecycle are identified. The Analytic Hierarchy Process (AHP) with pair-wise comparisons obtained from nuclear cost experts is employed to rank the different factors in terms of their relative importance on the commercial success of a near-term deployable SMR. Each expert provides a different set of rankings, although project financing cost is consistently the most important for the successful commercial deployment of the SMR. The approach presented in this paper can be used as a verification method for any power generation technology to provide confidence that cost requirements are adequately captured to design for life cycle cost competitiveness from the perspective of different stakeholders.

1. Introduction

In 2015 the UK Government announced a £200 million competition to support the development of small reactor technology for deployment as part of the future energy mix. Although no vendor was selected for the competition, in June 2018 the Government announced the "Nuclear Sector Deal" (Beis, 2018b), proposing support for Advanced Modular Reactors (AMRs) as a long-term energy solution. AMRs are advanced reactors which use new or novel cooling or fuel systems based on Generation IV technology. These have additional functionality such as co-generation of heating or water desalination. Defined separately to AMRs, Small Modular Reactors (SMRs) are considered a more near-term deployment solution based on conventional advanced light water reactor (LWR) technology used in existing large Generation III Nuclear Power Plants (NPPs), but smaller in scale (Beis, 2018a).

In liberalized markets the development and investment in SMRs depends upon the economic competitiveness of a design when compared with other power generation options (Vegel and Quinn, 2017; Kidd, 2013). SMRs are likely to have a reduced upfront total investment cost (Carelli et al., 2007) introducing the flexibility to allow series construction of multiple small units, providing a more manageable cash flow profile (Ingersoll, 2009). It is expected that greater emphasis on factory production and the design of smaller, standardised components, will introduce greater certainty of reducing construction cost and schedule utilising manufacturing learning and by minimising site work (Cooper, 2014). The financing of an SMR then becomes easier and potentially less risky, resulting in a lower cost of capital (Ramana and Mian, 2014). Conversely, the SMR will also have to maximise availability, capacity factor and fuel utilisation to maintain competitive operational performance (Hidayatullah et al., 2015).

There are currently more than 50 small reactor designs at various stages of development around the world with many potential applications (Carelli and Ingersoll, 2014). Different designs have different characteristics, related to technology, physical size, electrical output

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Appendix B

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EXPECTED ACCURACY RANGE OF COST ESTIMATES FOR SMALL MODULAR REACTORS AT THE EARLY CONCEPT DESIGN STAGE

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NOMENCLATURE

EPC - Engineering, Procurement, and Construction
CER – Cost Estimating Relationship
LCC - Life Cycle Cost
LCOE – Levelized Cost of Electricity
LWR – Light Water Reactor
NPP – Nuclear Power Plant
OCC – Overnight Cost of Construction
PBS – Product-cost Breakdown Structure
SMR – Small Modular Reactor
TCIC - Total Capital Investment Cost

ABSTRACT

Life cycle cost is an important consideration for the development and selection of new power generation technology. Large nuclear power plants (NPPs) have been subject to capital cost escalation, stemming from delays related to late design changes, procurement issues for major components, and regulatory enforced changes. These factors have contributed to the significant risk premium associated with gigawatt scale "Gen III+" designs, which have incurred significant financing costs. Large NPPs have become prohibitively expensive for many utility investors in liberalized markets and smaller economies.

The challenge of reducing upfront capital costs is one of the requirements that have driven the development of innovative Small Modular Reactors (SMRs). These designs are said to offer reduced unit cost and reduced risk due to certainty of delivery, which could lead to a lower cost of capital for a utility customer. By offering a product with more cost certainty the SMR could restore investor confidence in nuclear power. The life cycle cost estimates associated with the different SMR designs are uncertain at the early stage of development. However, designers need to understand, with some confidence, the impact of technical decisions at the early development phase on the life cycle cost.

This study presents an overview of cost uncertainty associated with the early design stage of the SMR. The types of cost estimating approaches available at the concept design phase are identified and categorized in terms of their expected accuracy ranges. The Overnight Cost of Construction (OCC) is an important driver of the life cycle cost of a power generation project. The expected accuracy ranges from each estimating method are used to illustrate the sensitivity of cost uncertainty to the level of design maturity. By understanding the sources and impact of cost uncertainty decision making during product development can be optimized to meet both technical and commercial requirements.

Appendix C

A question guide was used to maintain a general structure for each interview and to support the coding of responses at the analysis stage of the study. The preliminary questions were used to understand:

- The role of the participant in the team
- The direct areas of involvement or influence
- Any indirect areas of involvement or influence
- An understanding of the stage of product development for the SMR

The main questions related to the design development process, with each of the questions representing an aspect which could then be used to model:

1. Overall key product requirements
2. Key requirements of their area
3. Information sources to understand product requirements and to
4. How product requirements are prioritised in their area
5. Justifying and recording the rationale for a design decision
6. The key constraints to a decision being made by the participant
7. People involved in providing advice prior to the decision
8. The participants understanding of how cost impacts or is impacted by the design decision
9. Asked if they had any other comments based on design decision making, the process, and the requirements.

Generic Participant number:

Part 1: The Scope

Some questions relating to your current position and related experience

No.	Question	Summary answer
1	Current role/ position in the team	
2	How much relevant experience do you have in relation to you current role?	
3	What aspects of the product design are you directly involved with?	
4	What aspects of the product design do you have an influence over (if not directly involved with)?	
5	What is the current stage of development for the product?	

Part 2: The Process

No.	Question	Summary answer
1	What are the key requirements for the overall product	
2	What are the key requirements for your area of the product design	
3	What are the sources of information used to understand the product requirements	

4	In your decision making process how do you identify and prioritise requirements?	
5	Can you start to outline the design decision making process that you undertake?	
6	How do you record and explain the rationale for design adjustments you make?	
7	Could you please explain the process steps you go through when developing a design?	
8	What are the sources of data do you use to make a design decision?	
9	What constraints do you face that you believe affect your ability to make a decision?	
10	Before making a design decision do you get advice from others? How often do you consult others prior to a decision?	
11	At the present state of development how much does cost influence your design decision making? If possible please give an example from your area of work	
12	To what extent do you understand the cost impact of a design change that you have implemented?	

Appendix D

Interview conducted with WPO.5 in office at [redacted]. The interview was conducted at 1pm on Tuesday afternoon (04/04/2017).

(start of interview)

WP05

INTERVIEWER: Thanks for participating. We'll go through a few questions related to your position and relevant experience. So if you could just briefly state what your current role and position in the team is.

WPO.5: Right, so I'm head of programme for the SMR project, post basis of design. I am working from post, end of April. So looking at the structure of the program [and performance measurement].

INTERVIEWER: Ok, so loosely related to that role, what level of experience do you have, in the past. What relevant experience do you have?

WPO.5: Right, I've been in project management since 1990. So that goes right back to the submarine fleet contract. I then got moved to [redacted] [redacted] as the head of projects, moved through various roles up to managing director. And I've also been [[redacted]] director for both [redacted] and for [[redacted]], both bluechip companies, running the whole of their decommissioning businesses [inaudible].

INTERVIEWER: And, related to product design, what aspects have you been involved with in your experiences?

WPO.5: Very much bespoke products for nuclear decommissioning, in most of the areas I've worked in. So these weren't production projects these were, to an extent, one off products solving different problems.

INTERVIEWER: So, in your role now, what aspects of product design do you have an influence over?

1-Influence

WPO.5: The role that I have, the ultimate objective is to establish a Small Modular Reactor power station that generates power by a given date. Then using the structure of that [Level 1 Programme] to provide activities earlier and [quantify resources required for delivery] and that will therefore lead to a decision being made.

INTERVIEWER: Right, and just to provide context to our discussion, what is the current stage of development for the SMR?

2-Product Development

WPO.5: Towards the Basis of Design. So there are a number of design options still open which we are trying to bottom out. I would say, I am looking at the estimate now and it is quite immature, both from a design and an estimate point of view. We are trying to put some structure behind that and pin down some key milestones, but yeah, very early stages. Lots of design decisions to be made.

INTERVIEWER: Right, so now we are going to move on to what your understanding is of the design decision making process. So this is all from your perspective, but if you want to make references to procedures that you understand, or if you've got general opinions and comments as well feel free to make those as well. So if you just start off by discussing from your point of view what are the key requirements for the SMR. What are the product requirements?

3-Requirements

WPO.5: Is it licensable through GDA, and is it commercially selectable i.e. is it competitive in terms of the Levelised Cost of Energy. And also can we deliver it first to market and deliver power to the grid in early 2030. So those are the key requirements, how do you then go about achieving that, that's what all the various, obviously conflicting requirements that drive decision analysis.

INTERVIEWER: Right, ok. So in terms of your role as programme manager, what do you see as the key requirements for the area that you are looking at. So in terms of the programme manager point of view, what are the key requirements.

3-Requirements

WPO.5: The key requirement for me is that we have a credible program, we have resources in place, we've got the funding to support those resources, we have sufficiently analysed the opportunities, and we selectively fund those, and that will actually help us to [realise the end game. It's all about having that breadth, the overview that we're doing the right thing at the right time, and always looking ahead. From a risk perspective, I tend to think of it at three different levels. I'm trying to see where we are in the development program, with a number of design decisions to be made. You then have the risk associated with delivering that development program. And then you have at the enterprise level, i.e. you're trying to generate a business, multiple units of the SMR [and establish a stable and profitable business].

INTERVIEWER: So, in understanding the product requirements, there are various sources of information that might be used in order to obtain what those product requirements are. So from the perspective of the programme manager, what sort of information would you use, or have you used, to understand those requirements?

4-Information

WPO.5: I've read the basis of requirements. What I think is lacking is a common vision for the project. And I see some of the decisions being made at the moment because there is a lack of that common vision owned by everyone. I'm not directly involved currently, looking to post-BoD, some of the decisions to date, and I don't see any rationale, or any [evidence] in terms of the variables considered in making that decision. There doesn't seem to be an audible trail with a "I see how they came to that decision."

INTERVIEWER: How does that then influence the way you would take the project forward?

1-Influence

WPO.5: Well, from my mind, I would be very keen to understand the impact of decisions, in terms of schedule and cost. [I understand] if we're gonna go down a very bespoke route to give us some differentiation. But if it's the case that it's gonna take longer or [require significant investment] in supply chain and manufacture, that would put the programme in danger, so I will come back to [the importance of] only accept the program [supported change]. [Not forgetting we] must manage the risks.

INTERVIEWER: Right, so we've discussed about programme risk, about schedule risk, and about cost. In your decision making process, how do you identify and then prioritise those requirements? Or how would you go about doing that once the project has passed the BoD phase?

5-Prioritise Requirements

WPO.5: Right, well you can't have everything you want all the time. So normally the decisions in the programme space are very much driven by the programme you are trying to deliver. And so there are flexibilities that a programme, on this lifecycle, we look at the early dates, the critical path. There will be float, but with a flexible programme, you have to consider what are the right variables and criteria you need to consider, to come to a conclusion on a particular issue. Where we are trying to deliver a commercial power station. So, for me, it's important that it is licensable, it is commercially selectable, i.e. the cost of acquiring is competitive, else you won't have a competitive cost of electricity, and that we get to market on time, that we are not

INTERVIEWER: Ok, so this question is more about you formalising the process that you go through. How would you go about recording and then explaining that rationale?

6-Rationale

WPO.5: Right, this is early stages, but I'm trying to introduce a process I've used in the past called GOST, Goals, Objectives, Strategy, and Tactics. And basically you have a vision, and then from the vision, you would normally have two or three goals. And then from those goals you should be able to define objectives. And then from those objectives you define the strategy to realise those. And then you put in place that strategy [through tactics]. By structuring that line you can flow down to your management team. So I had a list of ideas just to try to say to the rest of the team, "this is what I think we're doing". And what I think the key goals are, and therefore, from that I've developed the following objectives, strategy and tactics to realise that [vision and goals].

INTERVIEWER: Right, and how does that compare to what is currently being used?

WPO.5: I've not seen anything that is being used. What I mean is, I see that decisions are being made, and with the people that are making them I think there is a rationale going on, inside their heads, but it's not clear..

4-Information

INTERVIEWER: Ok, so, even more to do with actually more the technical decisions, but if we look at technical from the point of cost and schedule, what sort of data would you use to make decisions that then go towards supporting your goal, towards cost and schedule?

WPO.5: Right, well where we are at the moment, as I said, we are very much in a [immature Level 1 territory]. We're trying to deploy a number of estimating processes, and try and come at it from at least three different methods [using a combination of top down and bottom up estimating techniques to define cost ranges that represent current uncertainty, both risks and opportunities. The output will be compared with the business case and acceptability of the results of our work]. That depends on what level of agreement they are homing in on, what we think the [inaudible] realistic cost of this organisation is [and how this develops over time]. What we should be doing, it's a package still to do post basis of design, is a properly structured planning estimate. Where we hold workshops with the design team to identify all the areas of the product, all the design activities necessary to define and verify the product [creating a level 4 logic linked resource loaded programme]. And we've got the logic built-in, the resources of the estimates in. We have a basis to say "that's the plan we are going to deliver". And then you monitor that using Earned Value Analysis, and interrogate the causes of schedule delay and cost overrun.

7-Decision Constraints

INTERVIEWER: So, again like we've discussed, there is uncertainty at this stage of the design. There's also uncertainty about the rationale behind the decisions that have been made so far. Going forward into this next phase, what are the constraints, that you think you'll face, in your ability to make certain decisions?

WPO.5: [All decisions should be addressed against the 3 primary objectives of delivering a licensable product, that meets cost of electricity affordability targets and achieves first to the market position in order to secure a market size to underpin the investment required].

7-Decision Constraints

INTERVIEWER: So, what sort of constraints do you envisage to meet that, or..

WPO.5: Currently, I think it's funding. Whether we can have the amount of resource necessary. Because there are a number of parallel problems. So we need to make progress on the design, we need to develop our processes and procedures, such that we can sit in front of the Office of Nuclear Regulation (ONR). We can demonstrate quite simply that we are fit for purpose. The current assessment is that, you know, some of our processes and procedures are not fit for purpose at the moment. So we've got to progress the design, we've got to progress our capability, we've got to recruit the right people for the right role, and we've also got to start engaging with the supply chain, to make sure that they're going to be fit. And then for the design we've got the small task of trying to verify that design through test work so that it will get through GDA (Generic Design Assessment). So there's a number of [challenges] critical to the program, so if we don't have appropriate resources and funding in place to do that then somethings can only be moved ~~some~~ one way, because you can't really take the [design] through GDA [until you are confident you are ready].

INTERVIEWER: Right, ok. So, when it comes to your decision making, the process that you go through with your decision making, as the programme manager, do you get advice from others, and how often do you consult with others prior to making your decision?

WPO.5: Yes, so I've not had to make key fundamental decisions. I mean some of the design decisions have been made. (Programme related decisions around the work to be done), you have to get buy-in. You need to get visibility of a) the decision is current, and the reasons for it. Visibility of it, hasn't been made in isolation, you've taken on board peoples' views and contributions. [If you are going to get buy in and closure on a decision, otherwise the risk is individuals have not accepted or acknowledge the decision, which can lead to nugatory work, frustration and inefficiencies].

INTERVIEWER: You've alluded to the point that there were decisions being made, that some of the decisions might have been…

WPO.5: Yeah, I've not been involved in them, but I've been in meetings where I think to myself "this is how we are building up the programme" and trying to engage with them, and [sense not everyone has bought into decisions made today].

INTERVIEWER: Is that with different levels of the team?

WPO.5: Yeah, it can be. It comes back to that vision. If we have that vision, and we're clear about the key goals of that vision, and the objectives, then a decision may be attached to the strategy. But if it's not communicated then people struggle to [understand and accept the decision].

INTERVIEWER: I think that's quite interesting. Do you see a disconnect between the visualisation of what the target actually is or what the scope is of what we are doing? Or what the end goal is? Or is it the disconnect in the communication of what that goal is to the rest of the team?

WPO.5: I think it's the disconnection of the day to day decisions, ~~of~~ from what people perceive the vision is. I don't know the vision, I've read a lot of documents, I can see a sort of ~~the~~ vision, therefore what the key goals are under it, [can be deduced], and I've written down [to convey] this is what I think we're about. As I've gone through ~~that~~ this one of the tactics was we'll use some sort of multi criteria decision analysis tool that captures and looks at how many decisions you're making [can be justified and communicated].

7-Decision Constraints

INTERVIEWER: And this isn't just purely technical decisions, so they include business decisions, so both sorts of decisions that support the PILM gate?

WPO.5: Yeah, well I I've come in and I've inherited a figure for the development at peak resource load in 2023, which is unrealistic]. [inaudible]. What I've done, once I fixed the [level 1 programme and defined the organisation structure to base a cost estimate] on that, I've gone back into that and tried to restructure an equivalent. So I've got a level of detail, so if anyone wants to go back they can see how we got to that figure.

8-Understanding Cost

INTERVIEWER: Right, ok. So this is taking it back a step, and focussing more on cost. At the present stage of the design development, how much does cost influence your decision making? If it's possible, could you give an example in the work that you've done and how cost has influenced the decisions you've made?

WPO.5: Ok, well I can think of a number of ways, but specifically on this role, I'm trying to get my head around cost. I don't understand it at the moment. I've got a figure, it looks high to me. So if I can establish that that figure may be by some other method by statistical correlation or validation of it. So I'm trying to understand the cost. Cost is important, schedule also, because schedule tends to drive cost anyway. Others important factors are safety and quality, and environment aswell, as they are business drivers as well. You have a major issue on one of those and your market disappears over night.

9-Cost Impact

INTERVIEWER: So to what extent do you understand the cost impact of a design decision that might be made, and how does that go back to what you are saying, fundamentally, what the cost might be?

WPO.5: Yeah, so when we are making a decision, if it's likely to come in time and cost on the programme, fine. (example given of unique product design that will take longer than scheduled duration in the programme), you need to capture all that and bring it back to that decision board. To say is this our decision, does it make the system design better or does it add more cost? [inaudible]. [Decisions need to be justified via their impact on the three principal objectives of licensable, cost of electricity and first to market].

8-Cost Understanding

INTERVIEWER: Right, so that was probably all the questions that I wanted to ask. What is interesting is that, in a number of the interviews I've carried out the Levelised Cost of Electricity has been mentioned. So I want to ask, generally, what is your understanding of what that is? And what that represents, and how that influences design?

WPO.5: It's a way to compare power station with power station, because it's a measure of electrical output for a given cost. And it's a way of rationalising so that you can compare technologies, because that's the levelised cost of electricity. What are the capital costs, operating costs, and the output of the station. And while that's useful, for comparing technologies, and attractiveness to power operators, it can be a bit of a distraction in project delivery. Because you are actually spending man-hours and spending pound notes trying to hit a schedule. And you can't really focus on that because if you get that wrong it impacts on the levelised cost of electricity anyway. So I think we've got to start dealing in physical currency and not some comparative currency that drives technology choice.

8-Cost Understanding

INTERVIEWER: Right, so what would that be? What would that physical currency be instead of the Levelised Cost of Electricity?

WPO.5: In terms of delivering the design I think the currency we need to set is we need to start setting budget constraints within the teams, which controls the design activity. So the deliverables have assigned a budget and duration, and need to keep to that constraint. The other thing we must give them is the cost that we've provisioned to buy that plant and equipment for. So in doing that design there must be a process by which we can regularly update or inform you. This can help with standardisation and economies of scale. So yesterday we were looking at commodities strategies, and some of the comments that were passed there were that how do you use the understanding of the supply chain to drive the design solution?

INTERVIEWER: To what extent, then, is that a move away from how things have been done ?

WPO.5: I think we are so early on, taking it back to the vision, to have a licensable SMR that is commercially attractive, and is first to market. If that's the high level vision, and you break those goals down: Commercially attractive, that means we have to get our Levelised Cost of Electricity down to comparative to other power stations. Well how do we reduce our program, how do we get our design costs down, how do we get our product cost down.

8-Understanding Cost

INTERVIEWER: Ok, so that's been really useful for me. As a final question, is there anything around cost, is there anything that you have an idea on or an opinion on, regarding the project?

WPO.5: It's how we handle a level of uncertainty relative to the [maturity of the design, this requires a standardised way of handling uncertainty around design options when the decisions are yet to be undertaken as well the uncertainty around management of risks and realisation of opportunities. It is important that a consistent measure of uncertainty is used and reported so that confidence can be deduced from the trend of this variable as the design matures]. [Inaudible]. It's not easy, we are treading new ground here. I'm sure other projects have done it. But not anyone in the team here.

INTERVIEWER: Great, well, thank you very much. I'll close the interview there.

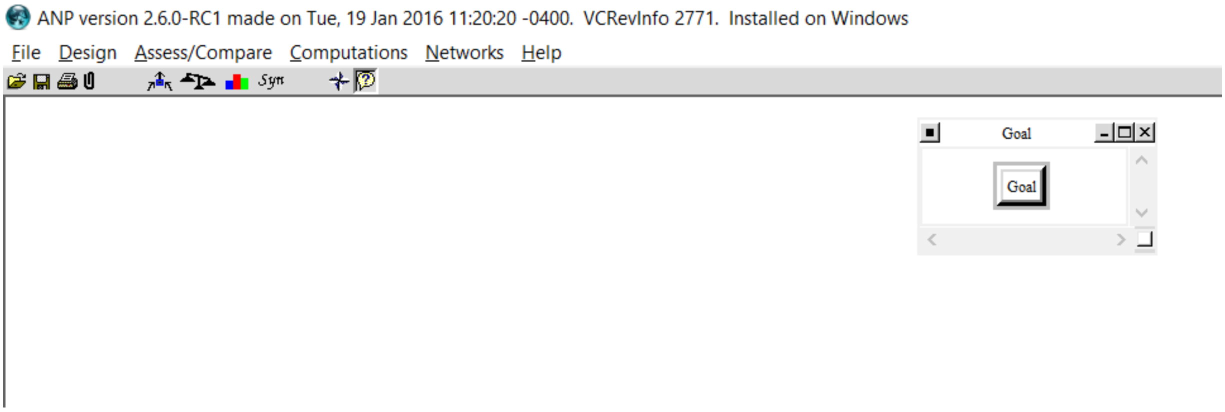
(End of the interview)

Appendix E

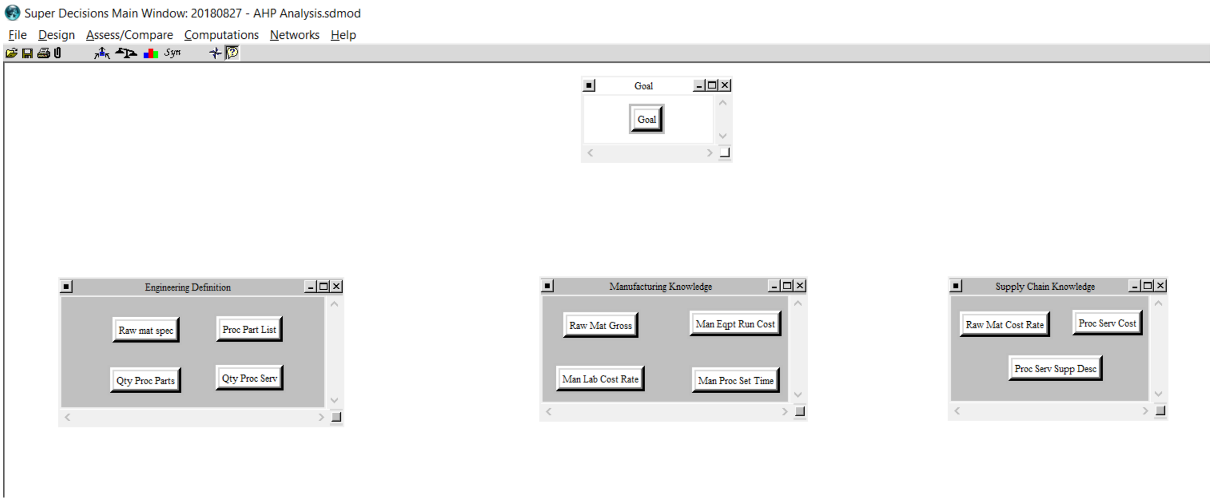
This appendix describes the process of building the AHP Model in Superdecisions software.

Building the Model

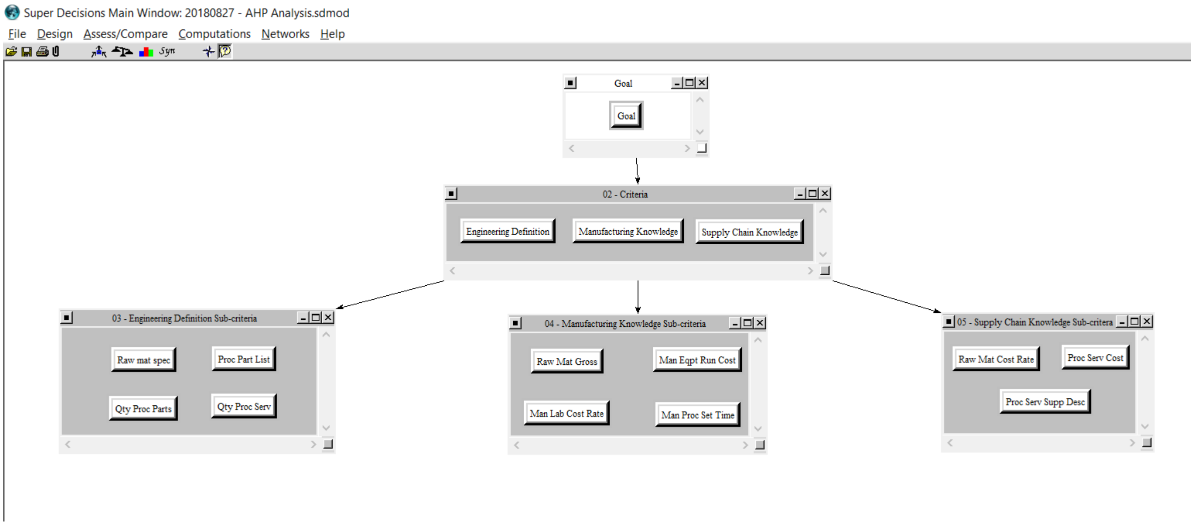
- Assign the goal node to the goal cluster



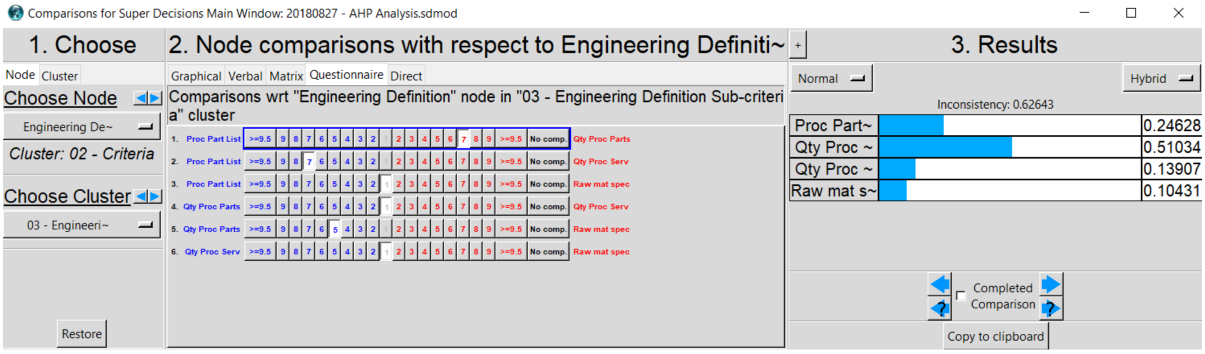
- Create clusters for each of the criteria and add nodes to each cluster



- Connect the node goal to each cluster and connect each of the nodes within each cluster to each other node within each cluster to create the innerdependencies.



- Input pairwise comparison questionnaire data for each cluster:



Comparisons wrt "Engineering Definition" node in "03 - Engineering Definition Sub-criteria" cluster

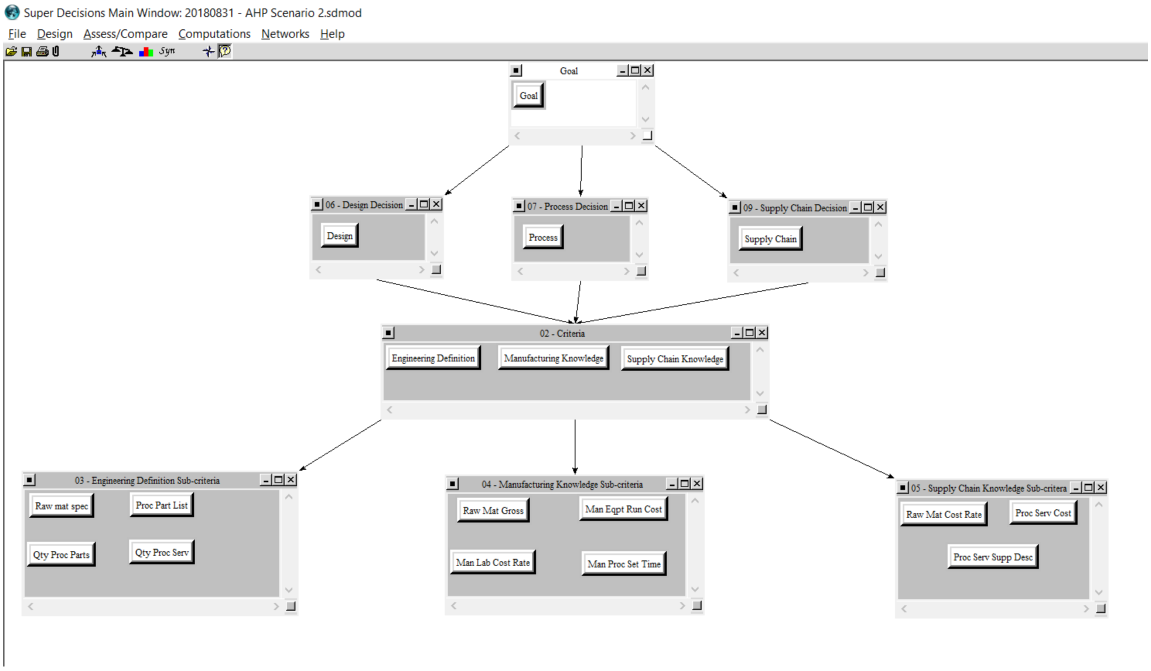
1. Proc Part List >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. Qty Proc Parts
2. Proc Part List >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. Qty Proc Serv
3. Proc Part List >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. Raw mat spec
4. Qty Proc Parts >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. Qty Proc Serv
5. Qty Proc Parts >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. Raw mat spec
6. Qty Proc Serv >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. Raw mat spec

Inconsistency: 0.62643

Proc Part~	0.24628
Qty Proc ~	0.51034
Qty Proc ~	0.13907
Raw mat s~	0.10431

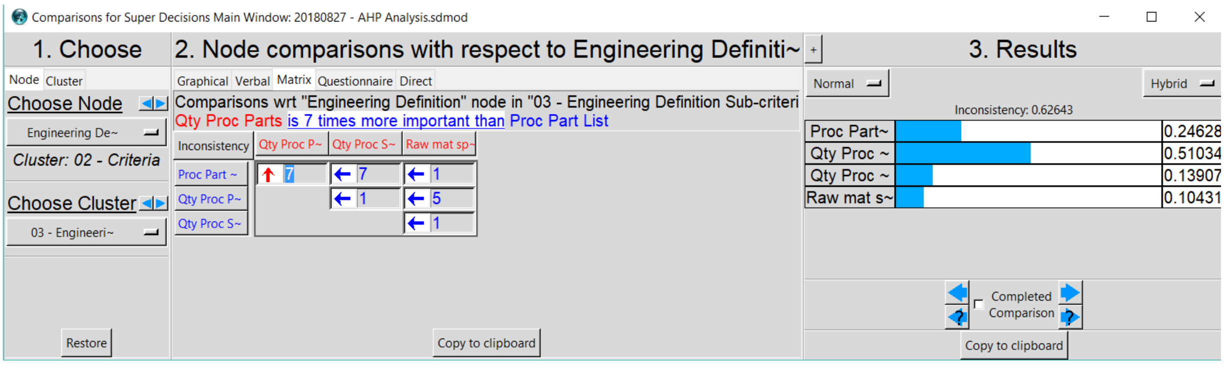
- For each type of decision create clusters for each of the outcomes related to the goal (i.e. the sets of alternative outcomes). Connect the goal to each of these outcomes. Connect these outcomes to each of the nodes for each source of uncertainty.

- Carry out pairwise comparisons for each type of decision relative to each type of definition.



Initial Results

Initial results from pairwise comparison showed large inconsistencies. The participant was asked to revise their previous pairwise responses.



Cluster: 02 - Criteria

Comparisons wrt "Engineering Definition" node in "03 - Engineering Definition Sub-criteri

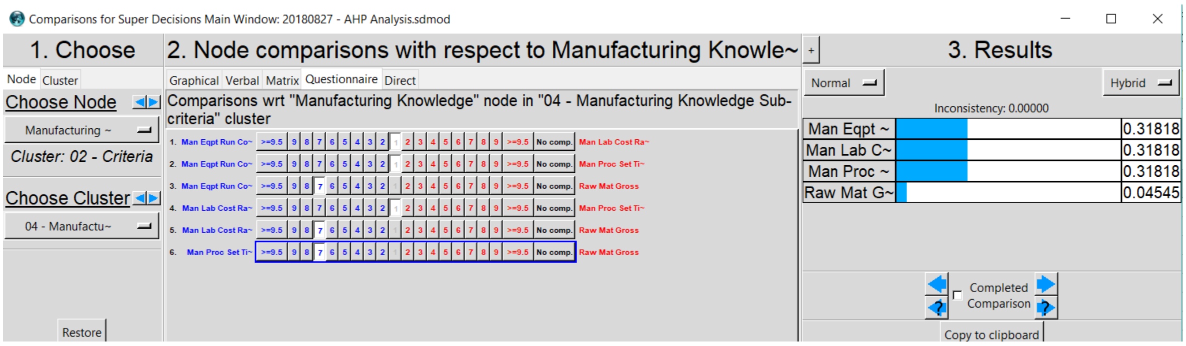
Qty Proc Parts is 7 times more important than Proc Part List

Inconsistency	Qty Proc P~	Qty Proc S~	Raw mat sp~
Proc Part ~	↑ 7	← 7	← 1
Qty Proc P~		← 1	← 5
Qty Proc S~			← 1

Inconsistency: 0.62643

Proc Part~	0.24628
Qty Proc ~	0.51034
Qty Proc ~	0.13907
Raw mat s~	0.10431

Uncertainty Source	Inconsistency in Response
Engineering Definition	0.62643
Manufacturing Knowledge	0.00000
Supply Chain Knowledge	0.41893



2. Node comparisons with respect to Manufacturing Knowle~

Cluster: 02 - Criteria

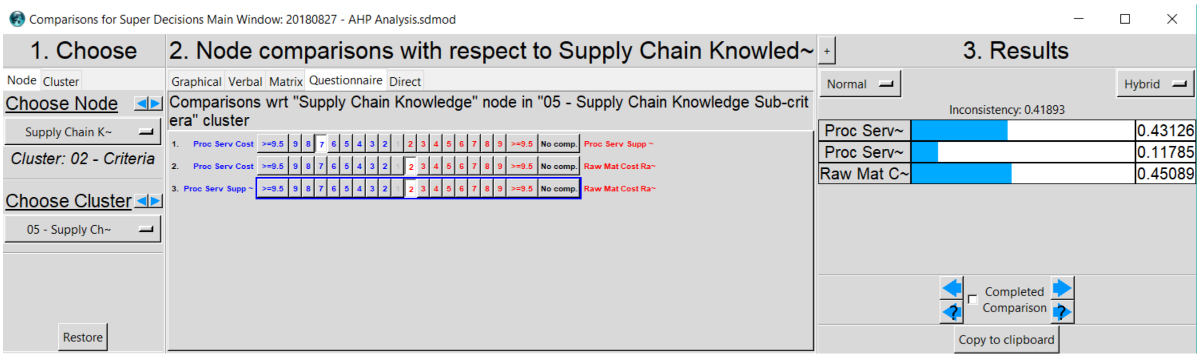
Comparisons wrt "Manufacturing Knowledge" node in "04 - Manufacturing Knowledge Sub-criteria" cluster

1. Man Eqpt Run Co~ 1 Man Lab Cost Ra~
2. Man Eqpt Run Co~ 1 Man Proc Set Ti~
3. Man Eqpt Run Co~ 7 Raw Mat Gross
4. Man Lab Cost Ra~ 1 Man Proc Set Ti~
5. Man Lab Cost Ra~ 7 Raw Mat Gross
6. Man Proc Set Ti~ 7 Raw Mat Gross

Inconsistency: 0.00000

Man Eqpt ~	0.31818
Man Lab C~	0.31818
Man Proc ~	0.31818
Raw Mat G~	0.04545

These initial values were taken for the importance of each type of uncertainty to the manufacturing knowledge source of uncertainty.



2. Node comparisons with respect to Supply Chain Knowled~

Cluster: 02 - Criteria

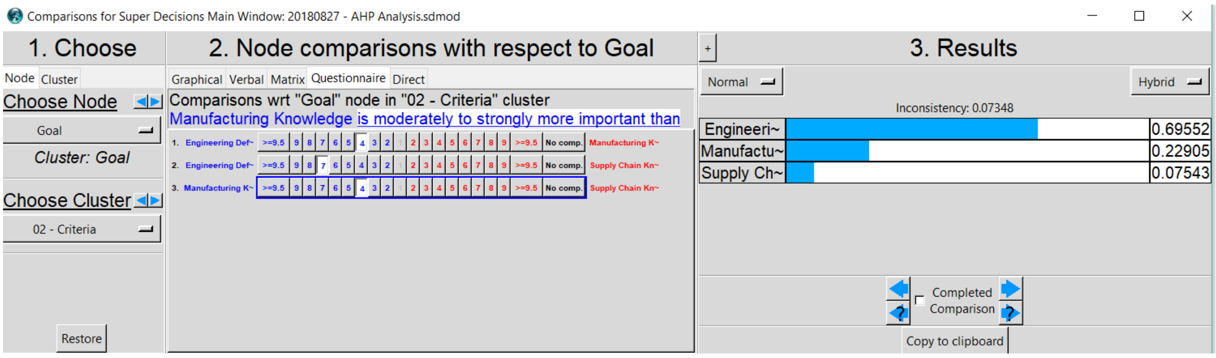
Comparisons wrt "Supply Chain Knowledge" node in "05 - Supply Chain Knowledge Sub-critera" cluster

1. Proc Serv Cost 7 Proc Serv Supp ~
2. Proc Serv Cost 2 Raw Mat Cost Ra~
3. Proc Serv Supp ~ 2 Raw Mat Cost Ra~

Inconsistency: 0.41893

Proc Serv~	0.43126
Proc Serv~	0.11785
Raw Mat C~	0.45089

For the pairwise comparison at the higher level definition nodes inconsistency was also realised.



2. Node comparisons with respect to Goal

Cluster: Goal

Comparisons wrt "Goal" node in "02 - Criteria" cluster

Manufacturing Knowledge is moderately to strongly more important than

1. Engineering Def~ 4 Manufacturing K~
2. Engineering Def~ 7 Supply Chain Kn~
3. Manufacturing K~ 4 Supply Chain Kn~

Inconsistency: 0.07348

Engineeri~	0.69552
Manufactu~	0.22905
Supply Ch~	0.07543

Revised Pairwise Comparisons

*Engineering Def*inition

Several changes in response were obtained from the participant for the engineering definition cluster. The participant placed greater importance on having a parts list from which to base an estimate, resulting in several changes to the pairwise comparison results. For quality requirement purposes (surface finish, tolerance needs, additional machining operations) the raw material specification was then revised to reflect its importance relative to several other nodes.

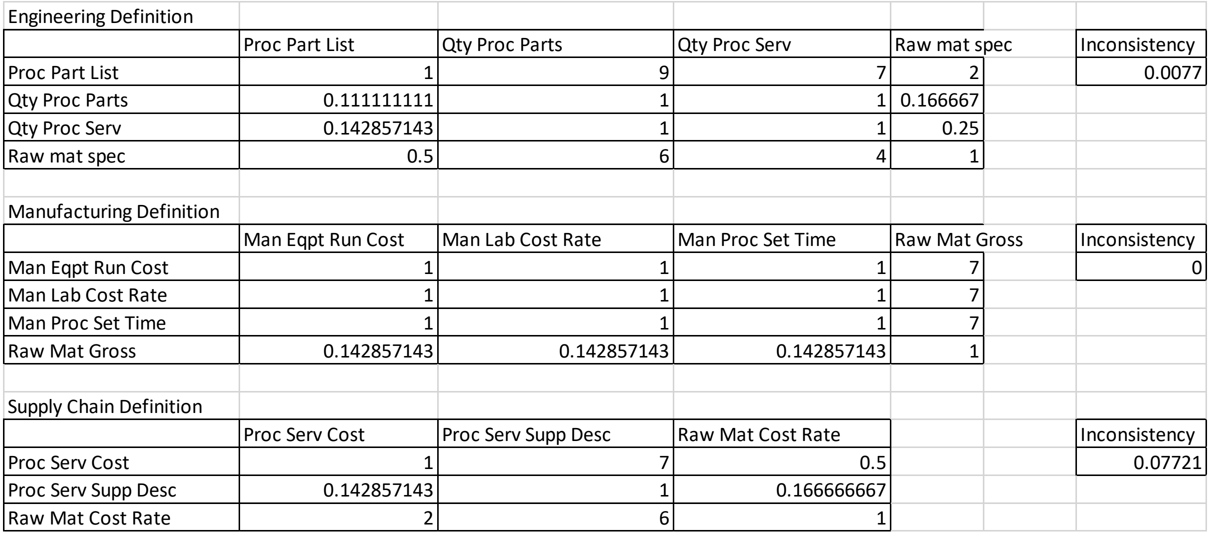
Supply Chain Definition

When asked each pairwise comparison question for supply chain definition, the participant did not change initial responses for the first two questions. When asked to make a relative importance decision on the procured service supplier or raw material cost rate, more importance was placed on the raw material cost rate. The primary reason for adding more importance on raw material cost rate was due to the lack of knowledge about a particular supplier at this time. A general cost rate for the component or material would therefore be more important.

Revising the comparisons each of the sources of uncertainty

The revision of the pairwise comparisons for the sources of uncertainty required the participant to make absolute choices about the relative importance of each source of uncertainty. Primarily this was due to the small number of comparisons. The interviewer emphasised the need for decisive responses from the participant for this section of the survey. Engineering definition was given greater importance by the participant, justifying this by identifying that without any product definition he could not infer the cost from assumptions about the manufacturing or supply chain definition. Whereas, vice versa, it would be impossible to generate an estimate. After 3 rounds of optimising the pairwise comparison responses to remove inconsistencies manufacturing definition was slightly more important than supply chain definition.

Pairwise comparison results



Engineering Definition

	Proc Part List	Qty Proc Parts	Qty Proc Serv	Raw mat spec		Inconsistency
Proc Part List	1	9	7	2		0.0077
Qty Proc Parts	0.111111111	1	1	0.166667		
Qty Proc Serv	0.142857143	1	1	0.25		
Raw mat spec	0.5	6	4	1		

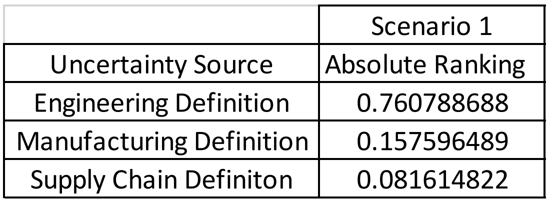
Manufacturing Definition

	Man Eqpt Run Cost	Man Lab Cost Rate	Man Proc Set Time	Raw Mat Gross		Inconsistency
Man Eqpt Run Cost	1	1	1	7		0
Man Lab Cost Rate	1	1	1	7		
Man Proc Set Time	1	1	1	7		
Raw Mat Gross	0.142857143	0.142857143	0.142857143	1		

Supply Chain Definition

	Proc Serv Cost	Proc Serv Supp Desc	Raw Mat Cost Rate			Inconsistency
Proc Serv Cost	1	7	0.5			0.07721
Proc Serv Supp Desc	0.142857143	1	0.166666667			
Raw Mat Cost Rate	2	6	1			

Normalised results



	Scenario 1
Uncertainty Source	Absolute Ranking
Engineering Definition	0.760788688
Manufacturing Definition	0.157596489
Supply Chain Definiton	0.081614822

Scenario 2

During the pairwise comparison the Value Engineer discussed the need to understand the type of decision to determine the importance of different sources of uncertainty on the confidence in an estimate. Several types of decision were presented as the goal criteria using the following process:

“For decision X (where X was a design, process or supply chain decision) what is the relative importance of criteria 1 versus criteria 2?”

The pairwise comparisons were carried out at the highest level in order to understand the relative importance of the key criteria. Having already established the importance of key sub-criteria on the criteria, there was no need to include the detailed pariwise comparison.

The overall results are presented here for the different decision types. The average values for each type of definition are also included.

Pairwise comparison results

Design Decision

	Engineering Definition	Manufacturing Knowledge	Supply Chain Knowledge		Inconsistency
Engineering Definition	1	9	9		0.05156
Manufacturing Knowledge	0.111111111	1	2		
Supply Chain Knowledge	0.111111111	0.5	1		

Process Decision

	Engineering Definition	Manufacturing Knowledge	Supply Chain Knowledge		Inconsistency
Engineering Definition	1	1	4		0.07069
Manufacturing Knowledge	1	1	9		
Supply Chain Knowledge	0.25	0.111111111	1		

Supply Chain Decision

	Engineering Definition	Manufacturing Knowledge	Supply Chain Knowledge		Inconsistency
Engineering Definition	1	7	0.5		0.05156
Manufacturing Knowledge	0.142857143	1	0.142857143		
Supply Chain Knowledge	2	7	1		

Normalised Results

	Scenario 2			
Uncertainty Source	Design Decision	Process Decision	Supply Chain Decision	Scenario 2 Average
Engineering Definition	0.814212784	0.399815061	0.361351339	0.525126395
Manufacturing Definition	0.113982647	0.52390594	0.065039165	0.234309251
Supply Chain Definiton	0.071804568	0.076278999	0.573609496	0.240564354

For a design decision engineering definition is shown to be far more important than any other type of information for the confidence in a cost estimate. Manufacturing is slightly more important than supply chain, but both are vastly less important than engineering definition.

For a process related definition, as would be expected, the manufacturing definition is shown to be the most important source of uncertainty influencing the confidence in the estimate. Engineering definition still appears to make up a significant proportion of the importance in the estimate confidence, where supply chain definition is minimal (approximately similar importance to the design-related decision.

In the case of a supply chain decision the supply chain definition becomes the most important source of knowledge influencing cost uncertainty. Again, engineering definition is of significant importance, although not as influential as for a design decision or a process decision.

Comparison of Scenario 1 and Scenario 2

Uncertainty Source	Scenario 1	Scenario 2 Average
Engineering Definition	0.760788688	0.525126395
Manufacturing Definition	0.157596489	0.234309251
Supply Chain Definiton	0.081614822	0.240564354

The average of each of the importance for scenario 2 and the absolute values produced for scenario 1 are compared. There is a significant difference in the importance of each source of uncertainty within different scenarios presented to the value engineer. The most similar result in scenario 2 to scenario 1 was obtained when identifying the importance for design related decisions. This may suggest that the design decision was considered as the decision in scenario 1 from the perspective of the value engineer. This question was not asked in this research. What is clear, is that using an absolute value for different types of decision may not be appropriate for the ACUBA method and could have significant influence on the resulting maturity assessment. For the implementation of the ACUBA method each decision type is defined related to the component for which an estimate is generated. The scenario 2 results are used.

Appendix F

Questionnaire: Cost Workshop

Thank you for agreeing to participate in the focus group. There are several rounds of questioning to be completed. Please fill them in when requested to by the focus group facilitator. The questions are based on your opinions and your perspective on the information presented during the focus group.

Section A: Preliminary Questions

1. Current Role: ___________________

2. Please rank the importance of the following cost requirements **in your opinion:**

Cost Requirement	Description	Rank (1=most important, 4=least)
Unit Cost	The need to have a competitive unit cost (also known as construction cost or product cost)	
Competitive LCOE	The need to have a competitive lifecycle cost including construction, operations and maintenance and power generation	
Product Development Cost	The need to have a competitive product development cost (cost to design the SMR)	
Lower Verification & Validation Cost	The need to have a competitive V&V cost.	

3. Briefly state why you have selected your first ranked item.
   ____
   ____
   ____

End of Section A

Please Turn Over

Section B: Decision-related Questions

Please fill this section of the questionnaire in when requested to do so by the focus group facilitator.

First Round:

- Based on the available information please rank your preference for selecting each option:

Option	**Rank (1=most important, 4=least)**
Option A	
Option B	
Option C	
Option D	

- Why did you choose your first-ranked option?

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____

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- Following the group discussion, you are now given an option to change your preferences:

Option	**Rank (1=most important, 4=least)**
Option A	
Option B	
Option C	
Option D	

- Why have you/ have you not changed your first-ranked option?

____

____

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Please Turn Over

<u>Second Round:</u>

Before you commence the next discussion please complete the following questions.

1. Based on the available information please rank your preference for selecting each option:

Option	Rank (1=most important, 4=least)
Option A	
Option B	
Option C	
Option D	

2. Why did you choose your first-ranked option?

____

____

____

3. Following the group discussion, you are now given an option to change your preferences:

Option	Rank (1=most important, 4=least)
Option A	
Option B	
Option C	
Option D	

4. Why have you/ have you not changed your first-ranked option?

____

____

____

Please Turn Over

Final Round:

Before you commence the next discussion please complete the following questions.

1. Based on the available information please rank your preference for selecting each option:

Option	**Rank (1=most important, 3=least)**
Option A	
Option B	
Option C	

2. Why did you choose your first-ranked option?

____

____

____

3. Following the group discussion, you are now given an option to change your preferences:

Option	**Rank (1=most important, 3=least)**
Option A	
Option B	
Option C	

4. Why have you/ have you not changed your first-ranked option?

____

____

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End of Section B

Please Turn Over

Section C: Supplementary Questions

- To what extent does the final group decision match the priority order of cost requirements that you chose in Section A Question 1 (Please tick one option)?

Not at all	Small degree	Moderate degree	High degree	Very high degree

- What additional information do you need to be more certain in your decision?

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End of Section C

Thank you for your participation in this study. Please return this questionnaire to the focus group facilitator.

Administration

Survey Reference: