Cranfield University

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Railway Renewal and Maintenance Cost Estimating

School of Applied Sciences

PhD Thesis

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Supervisor : Professor Rajkumar Roy & Dr Esam Shehab

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ABSTRACT

The aim of this thesis is to present a structured methodology which estimates Railway Infrastructure renewal and maintenance costs when there is a lack of quantitative cost data at the early stages of the project life cycle. Furthermore, this thesis presents renewal and maintenance infrastructure cost estimating issues and investigates current Railway renewal and maintenance cost estimating practice using an industrial case study approach.

A flexible design using a case study strategy is described as the most appropriate approach to the successful completion of this study. Industrial case studies using workshops and interview techniques are the primary sources of data whereas literature is used as the secondary sources of data. Following the identification of Railway renewal and maintenance cost estimating issues, a further review of literature leads to the development of a hypothesis.

In order to investigate the hypothesis a structured cost estimating methodology is developed which comprises four main stages: creating a project structure that composes the goal, project criteria and alternatives; collecting the necessary data in the form of pairwise comparisons made by a domain expert; producing alternative weights using a geometric mean; and finally employing an algorithmic method using the produced alternative weights and the known cost of one alternative per criteria. The model was implemented within a prototype software tool. This provided a means to validate the proposed model using three industrial case studies.

These results provide evidence that the application of a pairwise comparisons based methodology to Railway renewal and maintenance cost estimating problems can provide beneficial. The results indicated that twelve of the fifteen estimates produced by the model were within the expected accuracy and therefore on most occasions prove the hypothesis to be true.

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LIST OF THE AUTHORS PUBLICATIONS

D. Ling, R. Roy., E. Shehab., J Jaiswal. J. Stretch., Modelling the Cost of Railway Asset Renewal Projects Using Pairwise Comparisons, *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*.

D. Ling, R. Roy, E. Shehab, J. Jaiswal., Railway Asset Maintenance and Renewal Cost Estimation Challenges and the Future. *5th Joint ISPA/SCEA International Conference*, Denvor Colorado, USA, June 14-17th 2005.

D. Ling, R. Roy, V. Taratoukhine, Cost Engineering for Track Maintenance & Renewal within the Railway Industry, *4th World Congress on Cost Engineering, Project Management and Quantity Surveying*, Cape Town, South Africa, April 17 – 21st 2004.

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CHAPTER 1. INTRODUCTION

1.1 Overview

This chapter introduces the research background and context. Furthermore it begins by discussing the Railway Renewal and Maintenance Business Environment. A research map that illustrates an overview of the research area follows this. The research context and collaborating organisations are then introduced, as well as a discussion on the restructuring of the Railway Industry that occurred during this project. The research problem and research aim are highlighted before the chapter concludes by presenting the overall structure of the thesis.

1.2 Background

Demand for both passenger travel and freight usage is set to increase (Key Note Publications Ltd (2004). Effective Asset Management is required for the Railways to meet this demand. The assets of an organisation must perform throughout their life cycle if the organisation is to receive maximum benefits. In order to maximise benefits, minimisation of down time and maximisation of usage must be managed correctly. An understanding of the asset in terms of configuration is required in order to manage the asset correctly. Thereby insuring the configuration of the asset is maintained when a part is replaced. Maintenance management is also essential and involves developing applicable corrective, preventative, and predictive maintenance strategies. Corrective maintenance is carried out after the fault has occurred whereas preventative and predictive maintenance look to predict the fault before it occurs. Cost is a key component in the development of any effective maintenance strategy. The aim is to develop a strategy that meets required safety constraints but is the lowest in terms of cost.

The Railway industry has undergone major change over the past few years including a major restructuring. Previous underinvestment has resulted in many of the assets now requiring renewal and maintenance work. Railway infrastructure is suggested by Stalder (2002) to be past its suggested age of replacement and therefore of low quality. Following the 2004 Spending Review the Department of Transport has provided £15bn to the Railways, some of which will directly go into improving the condition of many of the assets. The government, in particular the Office of the Rail Regulation (ORR), which is the economic regulator of the rail industry, requires the industry to understand the costs of the renewal and maintenance work in order to justify the spending and to allow reduction of these costs. Stalder (2002) argues that cost reduction opportunities are apparent throughout the whole life cycle of the infrastructure. Methodologies and tool are urgently needed to provide asset renewal and maintenance cost estimates, which actors within the industry can use to help develop beneficial maintenance strategies. The research has also investigated and contributed to Railway renewal and maintenance cost estimation domain knowledge by addressing some of the cost estimation issues observed.

1.3 Research Overview Map

An 'Overview Map' has been produced, as shown in Figure 1.1, to understand the scope and to help define direction to the research. The overview map is a collection of the key ideas and initial findings mapped together in order to generate and visually represent the research project. This map was generated at the early stages of the research project and provided valuable insight into possible interactions and relationships between the key ideas. Data from published literature and an initial Industry attended focus group are used for the development of this map. Rail Maintenance Managers, Asset Managers and Engineers, a Rail Regulator and University academics were invited to the focus group. A short presentation introduced the attendees to the aims of the focus group and the aims of the

Table 1-1 Focus Group Sample

Attendee	Organisation/ Position
Attendee A	DTI
Attendee B	ORR
Attendee C	SRA
Attendee D	WRISA (ARRC)
Attendee E	NR Midlands
Attendee F	Amey Rail Ltd
Attendee G	Serco Rail Maintenance Ltd
Attendee H	Corus Rail Technologies
Attendee I	Corus Rail Technologies
Attendee J	Cranfield University
Attendee K	Cranfield University

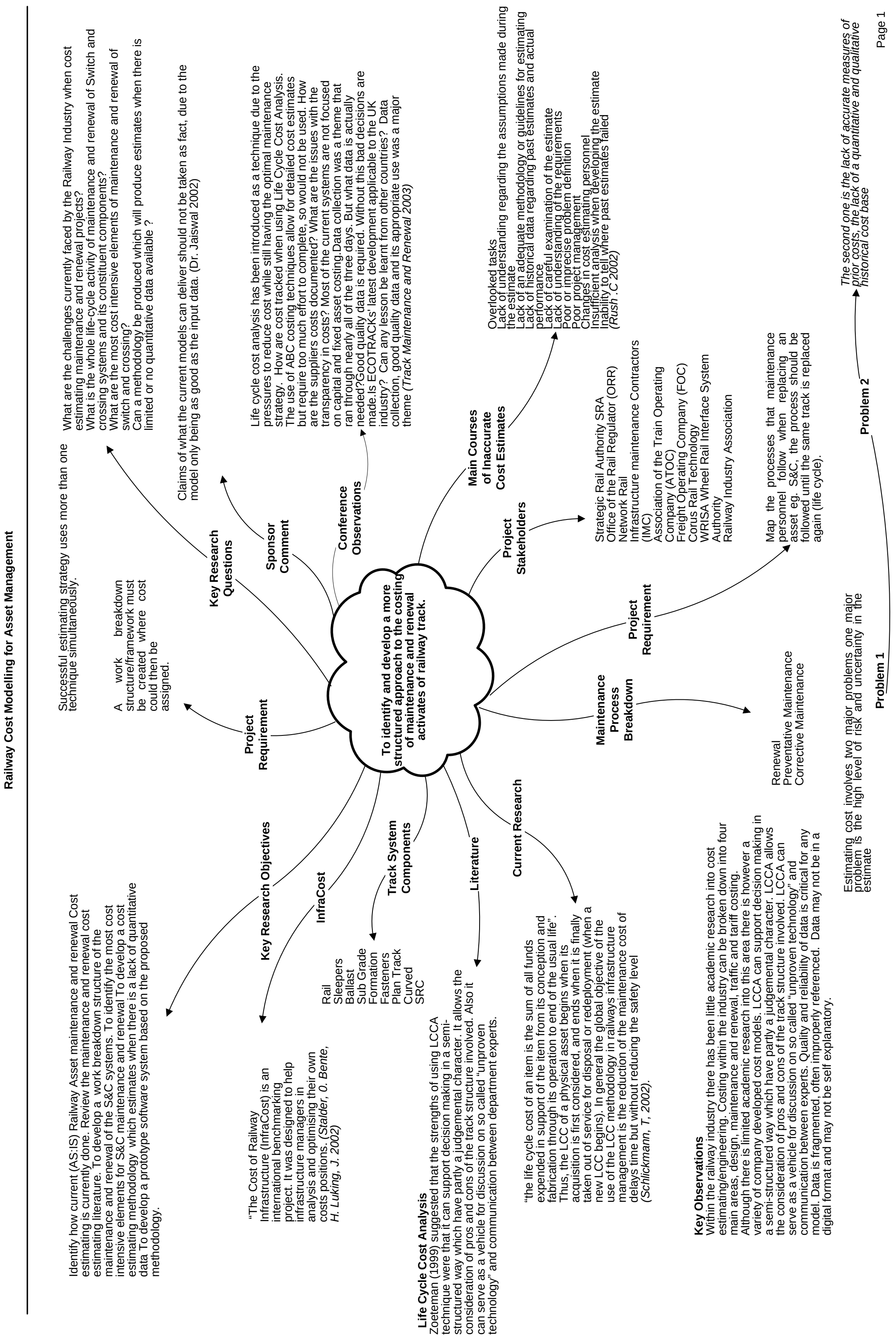


Figure 1-1 Research Overview Map

research project. The discussion was then opened up to the audience who discussed their needs and wants and if the projects aim would achieve these needs and wants. Table 1.1 presents the focus group attendance sample. The overview map as shown in Figure 1.1 presents the key ideas and initial findings grouped around the following ten areas including research questions, research project requirements, key research objectives, main courses of inaccurate cost estimates, sponsor comments, conference observations, key observations to date, track system components, current research/literature, the renewal and maintenance process and the project stakeholders.

1.4 Research Context

Network Rail has two main processes contributing to overall management decisions. The two processes include the Business Planning Process and the Investment Project Lifecycle. The Business Planning Process is a strategic process applied to identify, evaluate, filter and prioritise investment needs (enhancements or renewal of the infrastructure) or applied to develop the initial outline business case for a project before its launch. The Investment Project Lifecycle is a process which manages and controls projects. This involves project inception through to post implementation and realisation of benefits. The Investment Project Lifecycle consists of eight stages, including: Output definition (1), this ascertains the scope of the investment required. Pre-feasibility (2), this stage makes certain that asset condition, safety or standards requirements are identified and included in the scope of the investment. It also ensures that the investment is aligned with the organisational strategy and contributes to targets. As well as identifies the constraints on the network that prevent the delivery of the outputs, defines the increasing capability that must be delivered by the investment and provides confirmation that the outputs can be economically delivered by addressing the identified constraints. Option selection (3), this involves the development of options for addressing the identified constraints and delivering the required increasing network capability. The stage also assesses the options and selects the most appropriate one, together with confirmation that the outputs can be economically delivered. Furthermore, this stage develops options for addressing the identified constraints and delivering the required incremental network capability. It also assesses the options and selects the most appropriate one, together with confirmation that the outputs can be economically delivered. Single Option Development (4) is concerned with the development of the selected single option and is in sufficient detail to allow finalisation of the business case and scheduling of implementation resources. The Detailed Design (5) stages, produces a complete and robust engineering design that allows risks, costs, timescales, resources and benefits to be fully understood prior to commitment to implement. The Construction, Test and Commissioning (6) stage, delivers the asset change / renewal to the appropriate specification and provides confirmation that the asset and system work in accordance with their design and that they deliver the incremental network capability. The Scheme Hand back (7), introduces the asset into operational use and obtains acceptance of the works. Finally the Project Close Out (8) stage ensures that the project is closed out in an orderly manner with updated asset management information, capitalised assets, settled contractual accounts and any contingencies and warranties are put in place. Logging up and other funding arrangements finalised and assumed business benefits are captured in the Business Plan.

To effectively manage projects throughout the Investment Project Lifecycle Network Rail apply a Project Management Framework. The Project Management Framework provides guidance and outlines the ‘products’ required at various stages in the lifecycle. Part of the Project Management Framework is a Cost Engineering Process which explains how the cost plan should be developed throughout the investment lifecycle. The five stages in the Cost Estimating Process consist of stage 1, Order of Magnitude estimate, stage 2 a Budget Estimate, stage 3/4 Feasibility estimate and stage 5 a Definitive estimate.

This research relates to Network Rail management decisions by contributing to the process which manages and controls projects; in particular it relates to the output definition and pre-feasibility stages of the investment lifecycle and relates to stages 1, Order of magnitude estimate and the Stage 2 Budget estimate of the Cost Engineering process as shown in figure below.

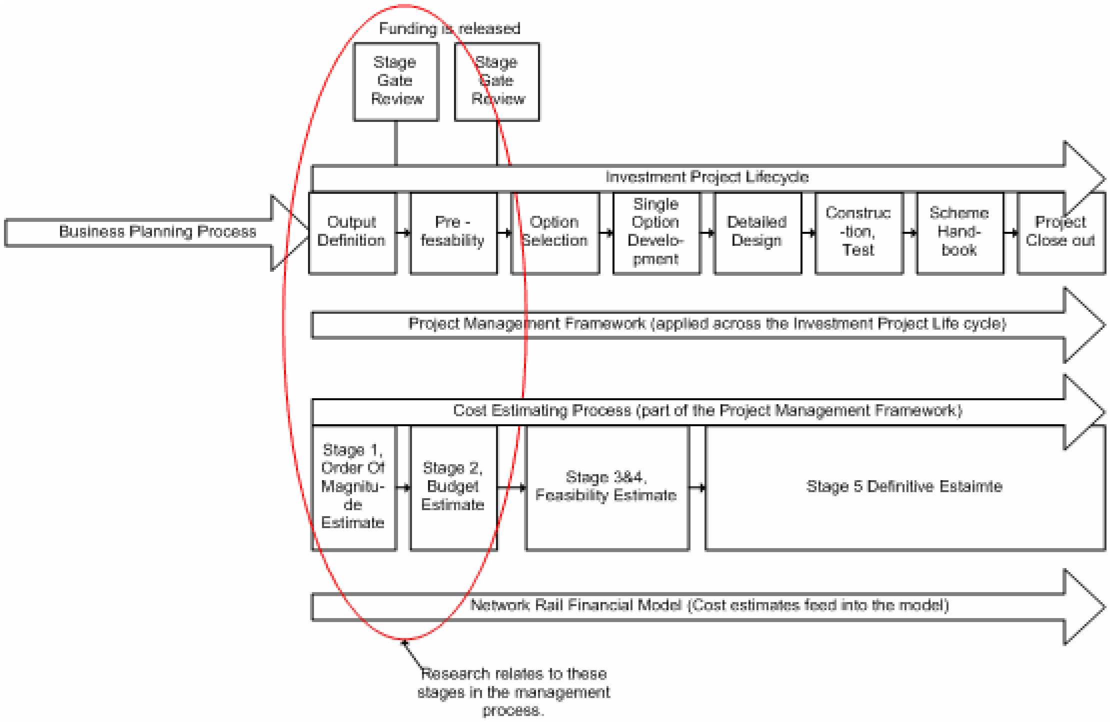


Figure 1.2. Research's Relationship to the Process which Manages and Controls Projects

The order of magnitude estimate is produced at the output definition stage of the investment life cycle. This estimate is an approximate estimate made without detailed data and therefore has the least cost certainty.

The budget estimate is produced at the pre feasibility stage of the investment life cycle. This estimate is created to establish the funds required for the investment and is based on more data then the order of magnitude estimate and therefore has an increase in the cost certainty.

The key decisions concerning Network rail managers at the output definition and pre-feasibility stages of the Investment Project Lifecycle are assessment of whether to proceed with the proposed investment. An investment project appraisal is performed during stage gate reviews which are engaged at the end of each stage of the investment lifecycle. Also investment funding is released from the funded body following successful stage gate reviews. To satisfy the funding authority an assessment of the investment projects is established using a Network Rail developed financial model. The financial model was developed to assist in obtaining investment authority. The aim of the model is to measure investment by assessing: Income earned, Value creation, Profit and Loss effects, Debt profile.

The key objectives of the model are to:

1. Calculate the remuneration on investments using three different methods,
2. Calculate the net present value and internal rate of return under these three methods,
3. Produce accounting financial statements for each method.

The main inputs to the model include

- Control
- Rate of return
    - discount rates
    - depreciation lives
    - costs
    - remuneration
    - sensitivity analysis
- Costs
- Inflation
- Asset Life

This research proposes a model which produces estimated costs which are used as inputs to the Network Rail developed financial model.

This research contributes to both renewal and maintenance programmes. The proposed research is primarily validated and contributes to renewal programmes. However a maintenance case study is also discussed in order to generalise the contribution across both programme areas.

Network Rail business priorities and aspirations include the minimisation and mitigation of risks associated with delivering projects on an operational railway. They aspire to provide a safe and cost effective network and are required to prioritise investment needs. This research provide network rail with an understanding of costs early on in the project life cycle allowing them to develop strategies to reduce these costs and to control the costs therefore reducing the inherent risks of escalating costs.

1.5 Research Collaboration

Corus Rail Technologies are the main sponsor of the research although industrial case studies have been provided by Network Rail, Grant Rail and Stagecoach Supertram Maintenance Limited.

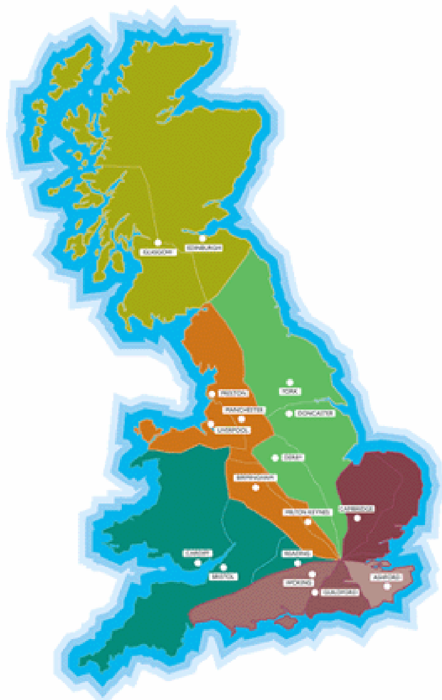
1.5.1 Corus Rail Infrastructure Services

Corus Rail Infrastructure Services is a new organisation within Corus Rail. It utilises the skills from Corus Rail Consultancy, Corus Rail Technologies, and Corus' 50% holding in Grant Rail and specialises in applying technical expertise to improve the rail industry. Consultancy, Design, Renewals and maintenance and Modular Systems are their main areas of expertise.

1.5.2 Network Rail

Providing a reliable and safe rail network represent the main objective of Network Rail. Network Rail maintain 21,000 miles of track across Britain with the freight and train operating companies being their main customers. Network Rail are responsible for the track, level crossings, bridges and tunnels, and signalling systems.

Network Rail are responsible for a total of eight regions, including Scotland Route, London North East Route, London North West Route, Great Western Route, East Anglia Route and Kent, Sussex and Wessex Routes as shown in Figure 1.2.



ROUTES	TOWNS / CITIES
SCOTLAND	GLASGOW EDINBURGH
LONDON NORTH EASTERN	YORK DONCASTER DERBY
LONDON NORTH WESTERN	PRESTON MANCHESTER LIVERPOOL BIRMINGHAM MILTON KEYNES
WESTERN	CARDIFF BRISTOL READING
ANGLIA	CAMBRIDGE WOKING GUILDFORD ASHFORD
WESSEX	
SUSSEX	
KENT	

Figure 1-2 Network Rail Routes (Network Rail (2005)

The business is subdivided into these regions and is designed to help deliver operation and engineering effectively. Regulation (2005; The Office of Rail Regulation (2005) suggests that Network Rail have for the period of 2004/05 track a renewal budget of 574 million.

1.5.3 Grant Rail

Grant Rail, formed in 1996, it is a consortium of companies which formed through a join venture between Volker Wessels and Corus. They provide many renewal contract services to the rail industry including track renewals, specialist plant, signalling, welding, coated rail systems and over head power supply projects. Grant Rail provides renewal projects in the East Midlands, on the West Coast Route Modernisation - Rugby to Watford and some selected areas in the Southern area. Contacts are expected to run for a minimum of five years.

1.5.3.1 Volker Wessels

Volker Wessels is a Dutch based construction company whose activities include design, development and realisation and management of construction projects. They employ a total of 17000 people over 125 offices. The company was founded in 1990 from a merger between IBB Kondor and the Wessels family business. They focus into areas including: development of concepts, urban development a spatial planning, integrated design and construction, initiatives with public and private areas and developing concepts fro developing areas and infrastructure.

1.5.3.2 Corus

Corus specialise in manufacture, processing and distribution of metal products. Also they provide design, technology and consulting services. They specialise in the following market section including, aerospace, automotive, construction, consumer products, energy and power generation, engineering, packaging and rail. Corus have an annul turnover of nine billion and comprises 4 divisions; strip products, long products, distribution and building services and aluminium.

1.5.4 Stagecoach Supertram Maintenance Limited

Stagecoach Supertram maintenance limited are responsible for the maintenance of all aspects relating to the tram network including trams, track overhead power lines, and points (switch and crossings).

Stagecoach Supertram operates three light rail routes around the city of Sheffield and have provided the tram network to the city since 1995. The trams are powered by overhead lines and operate on 160km of track, which enable the trams to cover the 29km route.

1.6 Restructuring of the Railway Industry

The Railway Industry has undergone dramatic change during the course of this research project. The national rail network was privatised in 1996 as part of the restructuring of British Rail. Railtrack became the new owner of this network. However, on 7th October 2001, Railtrack was placed in railway administration. The Department of Transport (2004) suggest that a lack of attention to its core business leading to underinvestment in the infrastructure, poor asset knowledge, and a loss of engineering skills led to the failure of

Railtrack. During March 2002 Network Rail was established as the new owner of the network. Network Rail was limited by Guarantee, which meant it has no shareholders;

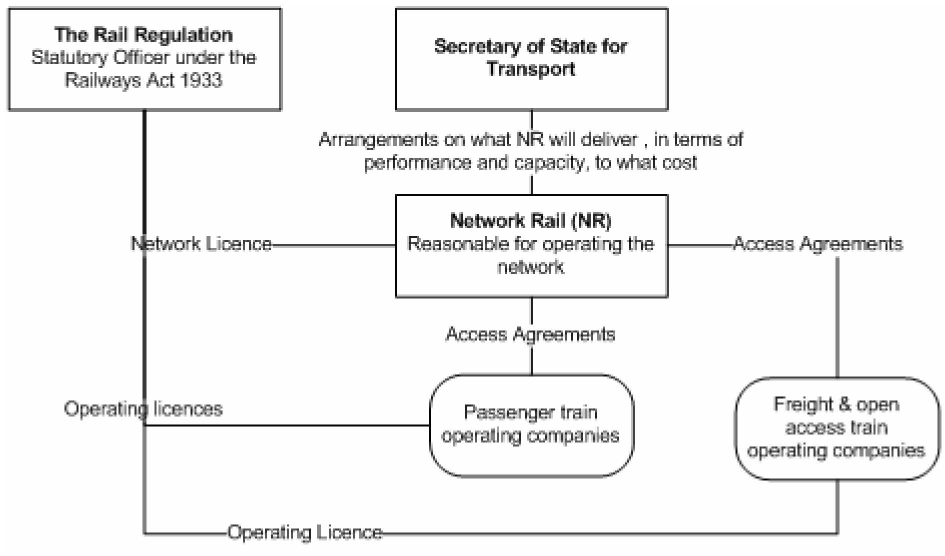


Figure 1-3 New Rail Industry Structure (Comptroller and Auditor General (2004)

rather it has 114 members representing different interest groups. A review was conducted during 2004 since it was felt that the industry and Network Rail were still failing to satisfying performance criteria. In January 2004, the Secretary for Transport announced that the Rail industry was to improve its performance and get to grip with its costs while maintaining a high standard of safety. The structure and organisation of the industry were changed with Network Rail being accountable for the performance of the network. Figure 1.3 illustrates the new structure of the Rail Industry.

The Department of Transport (2004) suggest in the Railway whitepaper ,'The Future of the Railways', that the new structure was based on the following changes.

1. The government will take charge of setting the strategy for the railways.
2. Network Rail will be given clear responsibility for operating the network and for its performance.
3. Track and train companies will work more closely together.

4. There will be an increased role for the Scottish Executive, the Welsh Assembly Government and the London Mayor, and more local decision making in England.
5. The ORR will cover safety, performance, and cost.
6. A better deal for freight will enable the industry and its customers to invest for the long-term.

The Strategic Rail Authority was abolished in 2004, they were previously responsible for the strategic planning of the rail industry and were a government body looking after passenger and freight interests.

1.7 Railway Infrastructure

Rail infrastructure mainly comprises of Permanent Way, Signal Systems, Electrification, Rolling Stock, Level Crossings and Stations. Esveld (2001) suggests Permanent Way comprises track (ballast and slab), switches & crossings and ballast beds. He suggests that Permanent Way is used to transport rolling stock (trains) which includes passengers and freight. He further argues that there are five main requirements of Permanent Way including:

1. The rails and switches must be safe for vehicles run on.
2. Track and switches must provide a level of comfort to the movement of the passengers.
3. Track must be electrically insulated.
4. Track must be constructed in a way which does not cause rolling stock to produce to much environmental pollution.
5. Cost of service life must be as low as possible.
6. Maintenance activities and cost should be as low as possible.

The electrification infrastructure comprises power supply including catenary wires (consists of cables and contact wires) and suspension systems and are used to power the rolling stock. This type of infrastructure is found most often in cities and build-up areas. Benefits of using this type of infrastructure include less noise and air pollution.

Esveld (2001) suggest that level crossings are used when a road crosses the Permanent Way. For safety purposes level crossings may be fitted with lifting gates, semi barrier in combination with flashing lights, flashing lights, or gates which do not swing to the side of the railway.

The signal systems are employed to guide the traffic (rolling stock) effectively and safely around the rail network of permanent way. The main aim of the signal is to give the rolling stock enough warning to stop should there be an obstacle or additional train on the line. Finally the stations are the infrastructure were mainly the rolling stock load and unload goods and were passenger's board.

1.8 Renewal and Maintenance

The maintenance process is concerned with the effective use of materials and a maintenance technique to enable an asset to extend its operational life. It is concerned with replacement of the items such as the components that make up an asset rather than the whole replacement of the asset which is the aim renewal. Decisions whether to renew or keep the asset maintained are based on economics with the cheapest option over the life of the asset being the optimal.

1.9 Cost Estimating

Cost estimating is concerned with predicting the total cost of a project by estimating, in advance, the actual costs of all elements in the project, including plant, labour, materials etc . Cost estimating is required in the current rail environment because Asset mangers are now required to optimise their asset management strategies and reduce there costs. The main approaches involved in cost estimating are bottom up, feature based, design to cost, analogy, parametric (Roy 2003).

1.10 Research Problem

As discussed in the previous sections, the Railway industry had undergone a major restructuring. The Department of Transport (2004) suggests that there had been a failure to control costs. Renewal and maintenance projects are major expenditures for the Railways. Therefore this thesis has addressed the problem of estimating renewal and maintenance costs and has also helped the industry control its costs, by allowing them to better understand its costs early on in the project life cycle. Additionally, following observation from industry, there is a lack of historical cost data to use for cost estimating at the early stages of the project life cycle. Roy (2003) suggests this lack of data creates issues because most cost estimating techniques require large amounts of cost data to produce accurate cost estimates.

1.11 Research Aim

Considering the research problem and context, the main aim of this research is to:

'Develop a structured framework that estimates Railway Infrastructure renewal and maintenance costs when there is a lack of quantitative cost data at the early stages of the project life cycle.'

1.12 Overall Structure of the Thesis

The remainder of this thesis comprises six chapters. Figure 1.4 illustrates the thesis structure. Chapter 2 starts by critically reviewing renewal and maintenance cost estimating literature. The focus of the literature then moves to railway renewal and maintenance cost estimating before issues and the research gap that requires further investigation are identified. The author examines the literature to develop ideas that might address the identified issues. A structured review of cost estimating techniques is then presented with analogy based estimating being the primary focus. The chapter concludes with the discussion of the literature and generation of a hypothesis that the subsequent chapters investigate.

Chapter 3 presents the research objectives and methodology. It discusses available research designs and strategies and justifies the strategy chosen to successfully answer the research questions posed. The chapter concludes with a discussion of the issues and limitations of the chosen strategy.

Railway asset renewal and maintenance cost estimating: current practice is explored in Chapter 4. The chapter presents analysis of the cost estimating processes identified from the use of a structured data collection methodology. Process models and the current cost estimating issues within an industrial case study are the outputs of this chapter. The Chapter also compares the findings with those from literature.

Chapters 5 and 6 are concerned with a discussion on the construct of a cost estimating model in order to explore the hypothesis generated in Chapter 2. Three case studies are presented: (1) a switch and crossing renewal model, (2) a switch and crossing maintenance model, and (3) additional assets including Track, Sidings and Insulated Rail Joint. Each case study concludes with a discussion on the validation of the developed model. Chapter 6 also describes the development of the prototype system.

Chapter 7 presents the discussion, limitations, future work, and conclusions observed from this research project. This chapter has introduced the research area. The following chapter will present a structured review of the research literature related to this study.

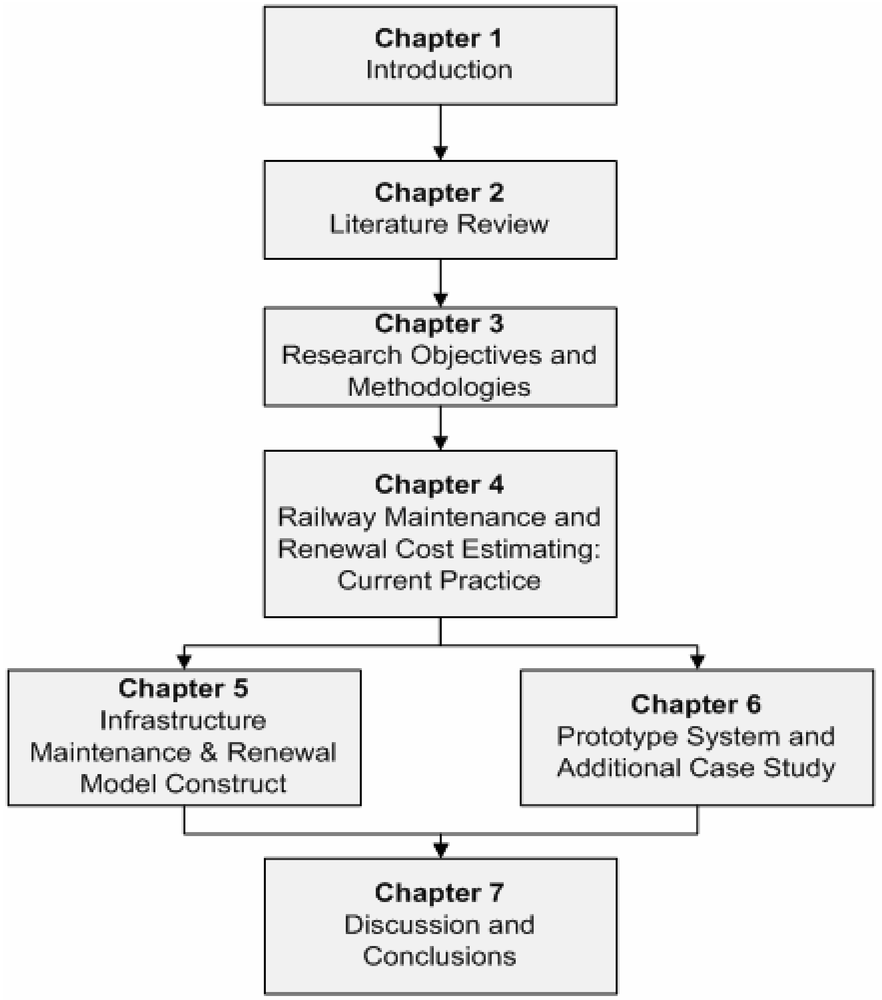


Figure 1-4 Overall Structure of this Thesis

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

The previous chapter discussed the research area, the need for this research and the stakeholders of the research, also presented were the main aim of the thesis. This chapter discusses a structured review of renewal and maintenance cost estimating literature. The chapter has two primary aims. First, to identify renewal and maintenance cost estimating issues, to provide background to the research and to support the argument of the thesis. Second to review the literature with a view to developing ideas that address the renewal and maintenance cost-estimating issues identified from aim one. A research gap that requires further investigation and the generation of a hypothesis are the main outputs of this chapter.

This section of the thesis will summarise the scope of literature the author has reviewed, including: a wide review of renewal and maintenance cost estimating literature, a more focused review of the Railway renewal and maintenance cost estimating literature. Cost estimating approaches and techniques are also reviewed, and finally a specific review of the analogy-based cost estimating approach is discussed. Furthermore, a review of Knowledge Management literature is conducted because the methodology proposed in this thesis captures tacit knowledge from an expert and therefore this review may provide insight into the sharing and reuse of this knowledge.

As previously mentioned the methodology proposed captures and expert judgement from an expert to produce renewal and maintenance cost estimates. Using expert judgement to estimate costs is prone to bias and therefore a review of bias in cost estimating is also presented in this chapter.

The aim of this chapter is to critically review the related research literature, identify renewal and maintenance cost estimating issues and areas that require further investigation.

Section 2.3, discusses renewal and maintenance cost estimating. Section 2.4 reviews the Railway infrastructure cost estimating literature. Section 2.5 summaries and discusses some of the key observations from the review of the renewal and maintenance literature and the research gap is presented. Section 2.6 then discuss the Knowledge Management literature (Knowledge capture and reuse). Section 2.7 then discusses cost-estimating definitions. Section 2.8 reviews cost estimating approaches, followed by a more focused review of the Analogy based estimation approach and bias when using expert judgement. The chapter concludes with identification of a research gap and generation of a hypothesis. The subsequent chapters of this thesis, then explore the research gap and hypothesis

2.2 Renewal and Maintenance Cost Estimating

In the first part of this structured account of literature, the author examines what approaches have been used to estimate renewal and maintenance costs and discusses some of the key issues. To make clear what is meant by renewal and maintenance the following definition has been adopted. *'The maintenance process is concerned with the effective use of materials and a maintenance technique to enable an asset to extend its operational life. It is concerned with replacement of the items such as the components that make up an asset rather than the whole replacement of the asset which is the aim of renewal'.* Decisions whether to renew or keep the asset maintained are manly based on economics with the safest and cheapest option over the life of the asset being the optimal. In the available literature, many authors suggest structured statistical approaches, which use quantitative data to address the problem of producing realist cost estimates. The literature further suggests that when there is a lack of historical data to use within statistical based estimating models cost estimates are produced by unstructured qualitative data (best guess). However, the literature shows that there is no formal scientific research, which addresses the development of renewal and maintenance cost estimates using qualitative data in a formal structured approach. The second part of the review then discusses approaches that address this gap in the literature. Most of the literature with respect to estimating when there is a lack of historical data has it foundation within the software domain. These principles should be applicable across domains and an application of these principles to the Railway renewal and maintenance cost estimating is investigated in this thesis.

To understand what models and approaches have been used to estimate maintenance and renewal costs and to identify the key issues, the author has considered this review, like a ‘funnel’. The review will start wide with a discussion of renewal and maintenance cost estimating across all domains and then quickly narrows into discussing Railway renewal and maintenance cost estimating. The review will then take a wide review of cost estimating approaches, and narrow into a discussion concerning an approach that the author proposes will addresses the research gap.

2.2.1 Historical Developments of Renewal and Maintenance Cost Estimating

For many years, Maintenance Managers and Infrastructure Managers have had difficulties in understanding and developing optimal renewal and maintenance strategies for their assets (Owusa-Ababio and Collura (1989), (Zoeteman and Esveld (1999). The aims of these strategies are to produce an optimal combination of asset performance, risk and cost (The Institute of Asset Management (2004).

Excluding the Railway cost estimating literature, the first published paper concerned with renewal and maintenance cost estimating was published by Myers *et al* (1978). The aim of the study was to produce guidelines for estimating non-fuel operational and maintenance costs for a power plant and to compare energy strategies. Their research proposed the development of a cost breakdown structure, which contained power plant drivers and cost components for each strategy. To create the estimates a ‘bottom up’ technique, a sum of the drivers and cost components costs, is applied. The use of a ‘bottom up’ approach will produce estimates with a high level of accuracy and this approach is still used within organisations today (Network Rail (2003). However, this approach requires quantitative cost data for each cost component and cost driver and the creation of the estimate can be very time consuming (Scott (1998), (Chandler (1984), (NASA (2002). Furthermore, Myers *et al* comment on the lack of understanding the industry has in defining what cost drivers and cost components should be included in the estimate hence the need for their proposed guidelines. Roy, R (2003) also support this claim that within industry there is a lack of understanding of what cost drivers and cost components should be included in the estimate. Tables X,X,X below presents a taxonomy of reviewed literature classified by cost estimating technique/approach, domain and published year.

Table 2-1 Taxonomy of Renewal and Maintenance Cost Estimating Technique Approach

Reference	Technique /Approach
Myers et al (1978), Chandler et al (1984), Adams and Kim (1998), (Scott (1998), NASA (2002)	Bottom up
(Muiga and Reid (1979), , Purdy, J. and Wiegmann, J. (1987), (Al-Suhaibani and Wahby (1999), (Chengalur-Smith *et al.* (1997), Brown and Hockley (2001), Wahby and Al-Suhaibani (2001), Raghavan *et al.* (2001), (Clark *et al.* (2002), NASA (1983),	Parametric
Brideman *et al.* (1979), Owusa-Ababio and Collura (1989), (Lofsten (1999), Shishko (1990), Zoeteman et al (1999),(2001), Edwards *et al.* (2000), Larsson, D and Gunnarsson (2001), (Vatn (2002), Schlickman (2002), Dipl.-Ing (2002), Stalder, (2002).	Life Cycle Cost Analysis
Gogis *et al.* (1990), (Martin (1992), (Bradford and Eck (1994), Sneed (1995), Granja-Alvarez and Barranco-Garcia (1997), Otrtiz-Garcia and Snaith (1999)	Equations / Expressions

Table 2-2 Taxonomy of Renewal and Maintenance Cost Estimating Domains

Reference	Domain
Brown and Hockley (2001)	Aerospace
(Al-Suhaibani and Wahby (1999), Edwards *et al.* (2000), Wahby and Al-Suhaibani (2001),	Agriculture/plant
Adams and Kim (1998), (Chengalur-Smith *et al.* (1997), Thompson and Kerr (2002).	Bridges
Gogis *et al.* (1990), (Ottoman *et al* (1999),	Building/facilities
(Myers *et al.* (1978), NASA (1983)	Electric Power plants
Purdy, J. and Wiegmann, J. (1987), Nutter and Cassady (2002)	Fleet vehicles
(Scott (1998)	Mining
(Lofsten (1999)	Production
(Chandler (1984), Owusa-Ababio and Collura (1989), (Martin (1992), Otrtiz-Garcia and Snaith (1999)	Roads & Highways
Brideman *et al.* (1979), Sneed (1995), Granja-Alvarez and Barranco-Garcia (1997).	Software
Shishko (1990)	Space
(Bradford and Eck (1994)	Transportation systems
(Muiga and Reid (1979), Raghavan *et al.* (2001), (Clark *et al.* (2002),	Water Sciences

Table 2-3 Taxonomy of Year Paper was Published

Reference	Year
(Myers *et al.* (1978), Muiga and Reid (1979), Brideman *et al.* (1979).	1978-80
Nasa (1983), (Chandler (1984),	1981-1985
Purdy and Wiegmann (1987), Owusa-Ababio and Collura (1989), Gogis *et al.* (1990).	1986-1990
(Martin (1992), (Bradford and Eck (1994), Sneed (1995).	1991-1995
Granja-Alvarez and Barranco-Garcia (1997), UNIFE LLC Group, Steinmetz and Ashmore (1997), Adams and Kim (1998), (Lofsten (1999), (Al-Suhaibani and Wahby (1999), Otrtiz-Garcia and Snaith (1999), Shishko (1990), Zoeteman et al (1999), (2001) (Ottoman *et al* (1999),, Edwards *et al.* (2000), (Scott (1998)	1996-2000
Brown and Hockley (2001), Wahby and Al-Suhaibani (2001), Raghavan *et al.* (2001), Larsson, D and Gunnarsson (2001), (Clark *et al.* (2002), Nutter and Cassady (2002), (Vatn (2002), Schlickman (2002), Dipl.-Ing (2002), Stalder, (2002), Thompson and Kerr (2002).	2001-

There has been a generally equal number of renewal and maintenance cost estimating research papers published in each of the domains. However, there has been lightly more published in the 'Highways and Roads' domain. There have been Highways and Roads' renewal and maintenance cost estimating papers published approximately every five years during 1980 – 2000.

Since the first published, paper in 1978 there has been research published approx every two years with no particular trend in estimating approach or domain until 1999, were there was a substantial increase in published research. There are no trends observed in cost estimating approaches or techniques used or applications of these approaches or techniques to domains.

Within the literature, terminology can vary, depending on which domain the literature focuses. The terminology includes 'repair and maintenance' (Al-Suhaibani and Wahby

(1999), 'renewal and maintenance' (Zoeteman and Esveld (1999), rehabilitation (Chengalur-Smith *et al.* (1997) and operations and maintenance (Rast, J. C. (2001), HcCormick (1983)). Maintenance has the same meaning through out the domains. Repair and rehabilitation and renew have a similar meaning: restore something damaged back to its good conditions. The Construction domain often refer to the term 'rehabilitation' whereas the Agricultural domain refer to the term 'repair' and the term 'renewal' is observed to be mainly used in the Railway domain. In addition, the term Operations and Maintenance (O&M) is often used in Production based literature. Similarly, maintenance has the same meaning however, Operations means the controlling of something or the managing of the way it works.

2.2.2 Renewal and Maintenance Management Principles

2.2.2.1 Maintenance Strategies / Policies / Budgets

The major debate within the renewal and maintenance cost estimating literature is one of how best to develop maintenance and renewal strategies/polices and budgeting. The goal of maintenance management is to reduce the adverse effects of failure and to maximise the availability at minimum cost (Lofsten (1999). Managers develop polices and strategies which are programme of actions adopted by an individual, group, or organisation which outline a devised plan of action to reach the goal. Maintenance and Infrastructure Managers have a need to plan strategies or to analysis alternative renewal and maintenance strategies/polices with the aim of choosing the most optimal solution. In order to develop these strategies and polices Maintenance and Infrastructure Managers need to determine future funding requirements, budgets, for the option under consideration. The literature therefore manly discusses the development of models that the authors argue help maintenance managers understand the budget requirements and allow then to make better decisions concerning the development of their renewal and maintenance strategies/polices and plans.

2.2.3 Renewal and Maintenance Techniques

Two main maintenance strategies are emphasised within the literature these include Preventative maintenance and Corrective Maintenance (Cavalier, M and Knapp, G. (1996), (Lofsten (1999), Zoeteman, A. and Esveld, C. (1999), Stalder, (2002). The terms planned or scheduled maintenance are sometimes used to mean preventative maintenance (Shore, B, (1996), Wurzbach R. (2001). And the term unplanned maintenance is also used in the literature and implies Corrective maintenance (Lofsten (1999), Kumar, and Westberg (1997).

2.2.3.1 Preventive Maintenance (PM)

Preventive maintenance (planned or scheduled maintenance) is maintenance that is carried out at predetermined intervals or according to prescribed criteria. It is intended to reduce the probability of failure or the degradation of the functioning of an item (Kawauchi and Rausand (1999) Preventive maintenance can include preplanned and scheduled adjustments, major overhauls, inspections and lubrications, or maintain equipment and facilities to a condition that breakdowns and the need for emergency repair are minimized (Lofsten (1999). The objective of preventative maintenance is to reduce the probability of failure in the period after maintenance is applied. Preventive maintenance (PM) has been applied extensively in industry as a strategic tool for reducing maintenance costs (Wurzbach (2001), (Kawauchi, and Rausand (1999). Unfortunately, management decisions regarding Preventative Maintenance are offer made with insufficient historical data (Cavalier and Knapp (1996). When to implement preventive maintenance is based on time cycles e.g weekly or yearly and intervene before the age when the asset is likely to fail as used in age replacement policies (Kumar and Westberg (1997). In addition, implementation can be based on the condition of the asset. This is called 'Condition based Maintenance' and involves the use of monitoring systems to measure the condition of the asset. When the condition reaches defined levels preventative maintenance will be applied (Stato (1999).

2.2.3.2 Corrective Maintenance (CM)

Corrective maintenance (unplanned maintenance) is maintenance which is carried out after fault recognition and intended to put an item back into the state in which it can perform the required function (Kawauchi and Rausand (1999), (Lofsten (1999). Corrective maintenance activities are unplanned, and are implemented when a failure occurs. Understanding the assets total operating time, operating time since the last repair, failure history, operating conditions or on the values of monitored variables can help recognize what the likely occurrences of corrective maintenance are to be (Kumar and Westberg (1997).

2.2.3.3 Reliability

Reliability is discussed within the literature and is suggested is be a main concern to Infrastructure Managers. The term 'reliability' means the probability that an item can perform a required function under given conditions for a given time interval (Kawauchi, and Rausand (1999), (Sheikh, *et al*, (1990). The goal of a maintenance strategy is to make the asset reliable for as long as possible and therefore available to function. This then will reduce the need for corrective maintenance and therefore reduce costs. A study investigated the use of a 'reliability' approach to estimate the optimal renewal and maintenance time's intervals. A maintenance cost equation was developed based on the predicted renewal and maintenance activities, which were derived from an understanding of the reliability of the system. (Kumar and Westberg (1997). The authors also emphasise that many maintenance schedules was based on expert experience due to a lack of historical data.

The benefits of introducing 'Reliability Centred Maintenance' (RCM) as a strategy are investigated by Svee *et al* (1998). Reliability centred maintenance involves four main processes these include: Functional breakdown that involves braking down the main systems into functions until one reaches a level where it is applicable to assign maintenance. Evaluation of risk, where functional failure, failure modes, failure causes, lifetime characteristic for each failure mode, Mean time to failure (MTTF) without preventive maintenance for each failure mode for each function are identified. Selection of type of maintenance, which involves choosing either, periodic functional test, condition monitoring, scheduled replacement, or scheduled replacement, and finally estimation of potential benefits (Svee *et al* (1998). The RCM methodology provides systematic considerations of system functions and the way functions can fail. It identifies applicable and effective Preventative Maintenance tasks, based on considerations on safety and cost. (European Commission (2000)

2.2.3.4 Availability

Availability is the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided (Kawauchi, and Rausand (1999). In order to analyse the availability of a system an understanding of the following is required: failure frequencies - MTBF: Mean Time between Failures (Zoeteman and Braaksma (2001) and MTTR; Mean time to restore/repair (Kawauchi, and Rausand (1999) Nutter and Cassady (2002). An aim of a renewal and maintenance strategies/polices is to allow the asset to be available for the longest possible time. Gogis *et al.* (1990) produce renewal and maintenance costs by identify life expectancies of roof and air conditioning systems by averaging company published Mean Time between Failures for these components. By understanding when the items would fail, and the required renewal or maintenance action to return the component to its available state, and by applying unit costs they were able to build an estimate. However, the major limitation to this study was the validation process was not complete and therefore the building descriptions and life expectancies may not be valid.

2.2.3.5 Age Replacement Polices and Condition based Maintenance

An interesting study discusses modelling road deterioration against traffic and time to understand failure frequencies (Martin (1992). The model used road roughness as an indication of the point at which the road was in its life and therefore could predict when it was likely to fail and become unavailable based on the projected traffic. Maintenance costs usually increase over time because degradation over the life increases and therefore increase the chance of failure. (Bradford and Eck (1994). This study is interesting because the authors have focused on understanding the current condition of the asset in an attempt to predict when it will fail. Most studies from the literature use the assets age as an indictor of when it is likely to become unavailable, this is called an age replacement policy (Gogis *et al.* (1990), (Marir and Watson (1995), Cavalier and Knapp, (1996), (Kumar and Westberg (1997), (Ottoman *et al* (1999), (Reineke, *et al* (1999). However, the age replacement approach can be cost inefficient because assets could still have life within them and could still perform for a number of years and would still replaced. The condition-based approach there can help reduce costs by optimising the asset replacement time i.e. just before it is to fail. Garcia and Snaith (2002) also stress the importance of understanding the condition as a basis to estimate renewal and maintenance costs. They argue that many visual sampling processes used to understand the condition are prone to errors and that to accuracy predict the condition of an asset a huge amount of visually collected condition data would need to be collected, which is timely and therefore costly, hence there argument that the sampling should be an automated process. Ottoman et al (1999) make a case that condition assessments can be performed in two approaches the first concerns completing condition assessments followed by cost estimates to perform maintenance and repair for deficiencies noted. The second offers condition assessments as a basis for determining the remaining useful life of a system and components, and therefore the related future renewal and maintenance requirements as proposed by Martin (1992).

2.2.4 Renewal and Maintenance Cost Estimating Techniques and Keys Issues

Most of the literature concerning renewal and maintenance cost estimating discusses the development of statistical based cost estimating expressions / models which aim to provide the most accurate estimate and therefore allow infrastructure and maintenance managers make better decisions concerning budgeting and optioneering/optimisation of maintenance and renewal strategies/polices. This section will therefore discuss three main themes of research which are debated most often within the literature these include development of mathematical expressions, a more focused discussion into cost estimating relationship development, using regression analysis as researcher have tended to focus a lot of attention into this area and Life Cycle Cost Analysis.

2.2.4.1 Techniques Used

The development of mathematical equations are commonly discussed in the literature as a valid approach to produce realistic renewal and maintenance cost estimates (Muiga and Reid (1979), (Raghavan *et al.* (2001). Such equations /expressions vary from simple, single-variable formulas to complex algorithms, comprising ‘‘sets of statements that detail a procedure for using predetermined cost drivers/parameters (Ottoman *et al* (1999). Many different cost drivers/parameters are suggested as equations/expression inputs and these are specific to the domain or item being studied. However many of the models observed in the literature aim to estimate the following common high level cost drivers Availability, Reliability and Corrective and Preventative maintenance requirements of the system which then feed into the mathematical equations.

Issues concerning the identification of relationships between renewal and maintenance costs and parameters relating to the asset are emphasised in the literature. Examples of the relationships include: hazardous waste incineration facilities and the various waste specific, design specific and operational factors (McCormick, R. (1984), bridge parameters (Chengalur-Smith *et al* (1997) and repair and maintenance costs and tractor parameters (Al-Suhaibani and Wahby (1999). Al-Suhaibani and Wahby (1999) investigated tractor repair and maintenance in Saudi Arabia. Analysis of approx 1670 work job orders provided classification of types of repair and maintenance events and the study of correlations between tractor age and power with repair and maintenance costs. Not all the job orders had been completed correctly with data descriptions of what work had been done. Wahby and Al-Suhaibani (2001) then extended this study by using the results to developing a repair and maintenance cost model. They propose using regression analysis to develop exponential and multi linear equations. Cost Estimating Relationships (CER) can then be derived. The relationships included accumulative working hours and machine age against repair and maintenance costs. Other researchers have supported the use of regression analysis to develop Cost Estimating Relationships (Chengalur-Smith *et al* (1997), (McCormick (1984), Kumar and Westberg (1997) (NASA (1983). Brown and Hockley (2001) argue that validation of the relationships against the actual costs can be difficult if the item under study does not go into service for many years e.g an aircraft. They also suggest that if new processes or technologies are used, there is limited historical data and so the model could be based on expert judgment and opinion. (Rush (2003) argues that expert judgment can outperform quantitative cost models for accuracy. However, within the renewal and maintenance literature no studies have investigated the use of structured expert judgement to estimate costs. To develop the relationships using regressions analysis large amounts of quantitative data is required (Roy. R (2003). Rast (2001) suggest that these models can be applied at either the order of magnitude stages or the definitive estimate stages in project estimates beause of the high level of accuracy that they produce.

2.2.4.2 Life Cycle Cost Analysis

The life-cycle approach attempts to estimate future renewal and maintenance requirements by breaking down each item into its systems and components and independently applying lifecycle concepts to each system and component. Life-cycle analysis provides an estimation of required frequencies for preventive maintenance, repair, or replacement (Ottoman, *et al* (1999). Owusa-Ababio and Collura (1989), Shishko (1990), Lofsten (1999), Edwards *et al.* (2000) applied lifecycle analysis to developed models which help select the most cost effective maintenance strategy. The life cycle concept derived costs over the whole life span of the asset under study. Costs for each year in the life were identified and a discount rate is applied to each year. The costs are then aggregated to give a total Net Present Value (Lofsten (1999). Many different cost estimating approaches and models could be used to develop the yearly costs, which then feed into the life cycle cost analysis. A Life Cycle Cost (LCC) model is suggested by Shishko (1990) which aims to understand, manage and control Space station "Freedom" costs. The model 'MESSOC' is a component of the overall LCC model and investigates the operation and maintenance costs. A set of algorithms were developed for each identified cost category. "What if" analysis can be conducted and associated costs can be identified. A maintenance equation was developed based on preventative and corrective maintenance requirements. The main limitation to the study was that some of the cost component to the LLC model lacked the necessary data. Life Cycle cost analysis had also been an area of focus by Brideman *et al.* (1979). A model was developed to predict the life cycle costs of software alternatives in order to analyses a specific retrofit/modernisation programme of digital systems. The model included software development and maintenance costs. Sneed (1995), Boehm (1983), Granja-Alvarez and Barranco-Garcia (1997) all argue that software maintenance tasks are the stages that consume most of the resources of a software project. Granja-Alvarez and Barranco-Garcia (1997) propose a model that looked at introducing impact analysis, proportional sizing, quality assessment, and productivity adjustments as ways of improving the current estimating process.

2.2.4.3 Estimating at the Early Project life Cycle Stages

Many of the research studies discussed in the literature emphasise techniques that require large amounts of data to model costs. These models are proposed for use at the later stages in the project life cycle were more detail about the renewal and maintenance requirements are known, therefore more data is available and the accuracy requirements are greater. However, the literature shows that there is little research addressing estimating at the early stages in the project life cycle when there is limited data. At the early project stage, it is important to choose the right construction of systems for a project in order to reduce costs. Adams and Kim (1998) suggest a database that produces cost estimates for renewal and maintenance of bridges based on historical data rather then currently employed expert judgement. An algorithm that included the following steps was developed: Allocate the district activity costs to applicable elements, Average the activity costs for each element, and sum the district activity costs for each renewal and maintenance action. They posed that this approach could be used at the early stages of the project life cycle similar to a top down cost estimating approach. The study lacked relevant data from historical records. The data was at a high level and so did not provide detailed breakdowns of maintenance items/activities required by the database.

Work conducted at the State University of New York by Chengalur-Smith *et al.* (1997) suggest models to predict costs for bridge rehabilitation. Producing realistic estimates at the early stages of the planning process was the aim. Models were developed to predict the components of the bridge deck, superstructure, and substructure. Various techniques were explored to identify which combination would perform best including, estimating components for the whole bridge, unit cost, and low bid-high bid as the independent variable.

2.2.4.4 Renewal and Maintenance Cost Data Collection

Thompson and Kerr (2002) conducted a nationwide questionnaire survey intended to identify the practice of cost data collection and analysis for bridge maintenance and repair. There observations included instances were historical data was missing or incomplete. They argue that the lack of historical data can cause problems in the accuracy of the estimate produced. They suggest that to overcome this limitation expert option can be drawn on or other similar product data could have been used (Bradford and Eck (1994) also back this claim. However, no formal structured process was suggested to capture the expert opinions. There study looked at understanding the cost for a magnetically levitated transportation system. Issues identified were that the transportation system was a new technology and so no data to produce realistic costs was available. However, the authors discuss conventional transit systems and the applicability of this data to the required environment. Cost data collection can be one of the most difficult, time consuming and costly activities within the cost estimating discipline (NASA (2004). This is especially apparent when costs are produced using bottom up approaches were cost data must be identified and collected at a low level of detail. Although most researchers identify historic renewal and maintenance cost data collection as a major bottleneck for the domains there is little efforts observed in improving the data collection process. Researchers have discussed databases as an approach to collect and store the historical cost data and that a benefit of such system is the speed at which the estimate can be produced (Scott (1998). However, they do not discuss or propose a methodology describing how to identify what renewal and maintenance cost data should be collected and how to collect this data.

2.2.5 Key Observations

- The review has highlighted the key aim of all the studies has been to develop and optimise renewal and maintenance strategies, policies and budgets and the relevance of producing cost estimates to meet this aim.
- Mathematical expressions are commonly used to estimate renewal and maintenance costs. The mathematical expressions input cost drivers, which relate to the system under analysis. However, across all domains, Availability, Reliability, Corrective and Preventative maintenance requirements are common high-level cost drivers. This therefore suggests that they are relevant drivers to all renewal and maintenance projects and should be considered in this research project.
- Cost Estimating Relationships are commonly discussed in the literature. Some of the techniques proposed can require substantial data to identify the relationships. However, the review also highlighted that if no data was present then expert judgement could be used and is argued to be more accurate then quantitative cost models (Rush 2003). Considering the aim of this research project is concerned with producing cost estimates when data is unavailable, the use of expert judgement could be a relevant approach. However, the renewal and maintenance literature does suggest any relevant expert judgement based approaches.
- The review has highlighted the relevance of increasing the predictive accuracy of the Availability, Reliability, Corrective and Preventative maintenance requirements in order to produce more accurate renewal and maintenance cost estimates. The literature has shown that most studies discuss the application of a different approach to improve the predictive accuracy of one or more of these four areas.
- Many of the studies focus on producing cost estimates at the later stages in the project life cycle when there is more data available. Very few of the studies reviewed have any relevance to estimating costs at the early project life cycle stages when data is limited.

- Life cycle cost analysis is suggested as a 'good practice' approach to estimate renewal and maintenance costs. This approach is relevant to this research project because it produces cost estimates over the life of the asset. However to produce a life cycle model is out of the scope of this research but would never the less be an important area of future work.
- Expert systems are the most modern approach to reducing renewal and maintenance costs.
- Definitions of renewal and maintenance have not changed historically.
- There have been a range of approaches and techniques used to estimate renewal and maintenance costs. The main approach observed is equations/expression, cost estimating relationship development (Muiga *et al.* (1979) and (Clark *et al.* (2002), Life Cycle Cost Analysis (Zoeteman *et al.* (1999).

The above discussion has highlighted historical developments and the main areas of debate within the renewal and maintenance literature across domains. It has highlighted the key concerns of renewal and maintenance cost estimating and has reviewed many applications and models developed to address these key concerns. The next section will discuss a more focused review of Railway renewal and maintenance cost estimating.

2.3 Railway Infrastructure Cost Estimating

This section will focus on discussing Railway Infrastructure Renewal and Maintenance Cost Estimating.

2.3.1 Railway Renewal and Maintenance Planning Process

In order to produce budgets and therefore develop renewal and maintenance plans/strategies, cost estimates are required. A view on the Railway renewal and maintenance literature suggests that cost estimates are generally produced by aggregating unit costs of the required maintenance and renewal activities which in turn are identified by models which predict future renewal and maintenance requirements based on data of track condition. This is a simplistic view of the planning process however accurately describes the overall process used. Figure XX illustrates a more detailed view of the renewal and maintenance planning process as discussed by Zarembski (1989). The diagram is a very good means of describing the scope of the observed railway renewal and maintenance literature and illustrates the individual areas or groups of areas, which researchers have focused on. An initial observation of the literature is that the main bulk of published work is concerned with discussing models which fit into the 'analysis, future requirement' area of the diagram which are concerned with predicting the future renewal and maintenance requirements. And models which discuss cost benefit analysis investigating different options (Zarembski (1989), (Zoeteman, and Van der Heijden, (2000).

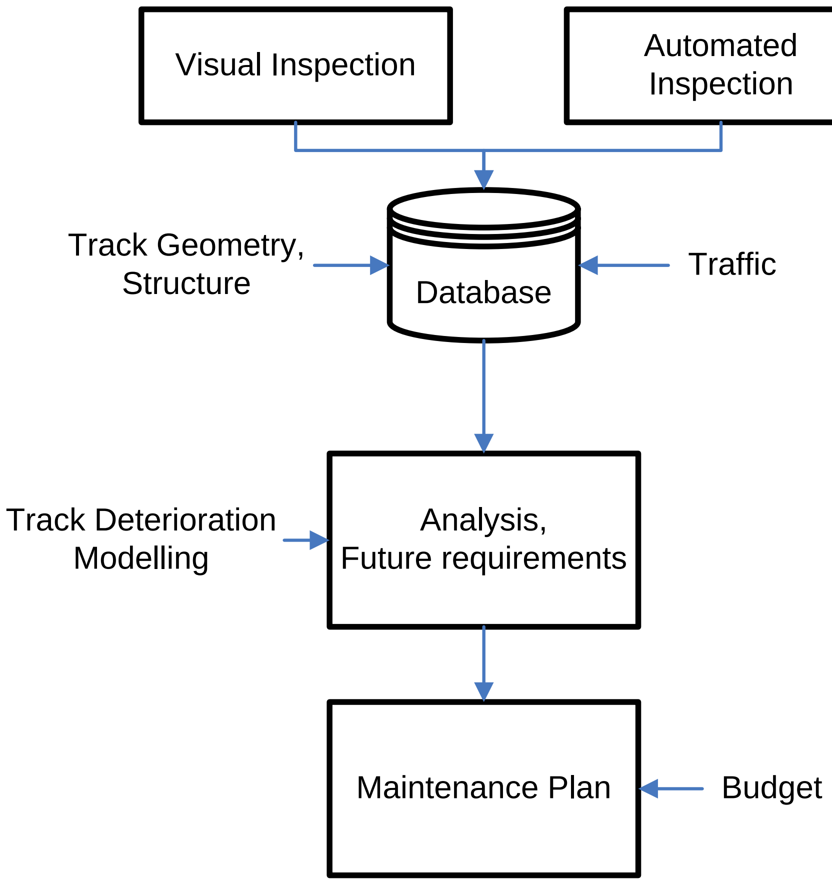


Figure 5 Renewal and Maintenance Planning Process (Zarembski (1989).

2.3.2 Railway Renewal and Maintenance Process

Esveld (2001) defines Railway infrastructure renewal and maintenance as the process necessary to make sure that the track remains at safety and quality requirements at minimum cost. This definition has changed little since Geyer (1935). Esveld (2001) argues that renewal and maintenance is planned considering location conditions, and is based on control data from the measuring systems, visual inspections, and economic data. Esveld (2001) also suggests that track maintenance can be divided into six main categories including:

1. rail geometry,
2. track geometry,
3. track structures,
4. ballast bed,
5. level crossings,
6. miscellaneous.

Maintenance of the track geometry can be subdivided into incidental maintenance (the repair of local irregularities) and systematic maintenance, which is done using heavy track maintenance machines (Esveld (2001) and would involve a major overhaul (Zoeteman, A. (2003). Esveld (2001) suggests that systematic maintenance is often referred to as mechanised maintenance and can be carried out using the following:

1. Tamping machines – to correct level, cant and alignment (Zoeteman, A. (2003)
2. Ballasts regulators – to establish correct ballast profile
3. Stabilisers – to compact ballast
4. Rail-grinding machines – to remove corrugations and grind welds (Zoeteman, A. (2003)
5. Ballast cleaner – to clean ballast bed

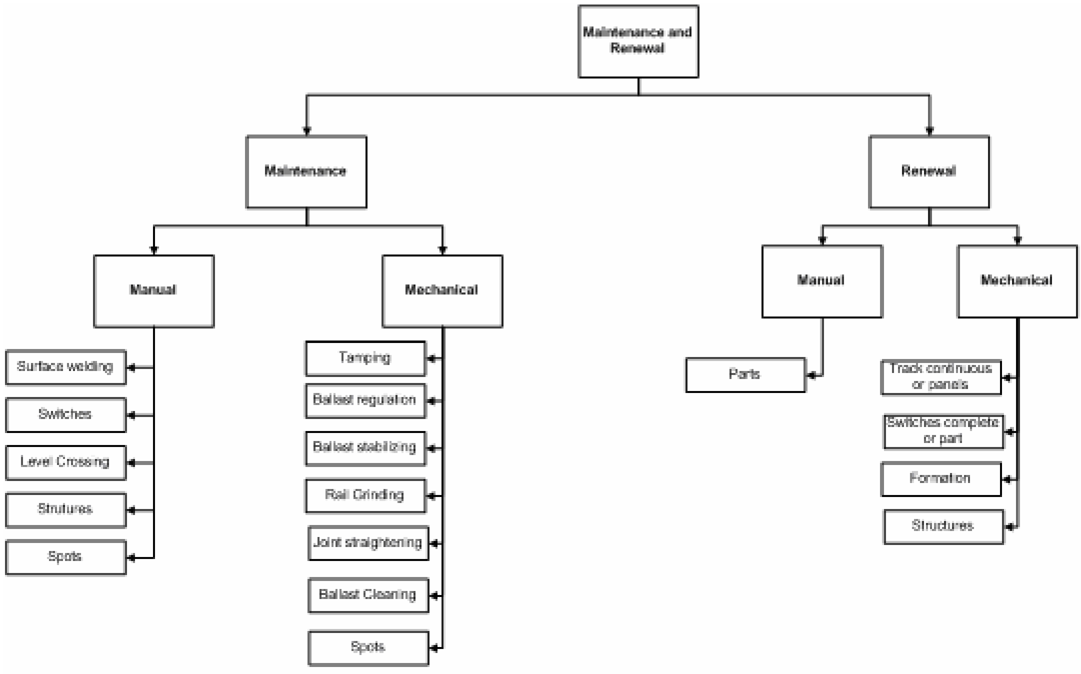


Figure 2-6 Track Renewal & Maintenance Process (Esveld (2001)

Esveld (2001) argues that carrying out maintenance only to requirements including delivering availability, reliability and low costs of ownership (Zoeteman, A. and Braaksma, E. (2001) when indicated by measured data or inspection is current good practice. Figure 2.2 illustrates the track renewal and maintenance process. The process has been broken down into four main areas including manual maintenance, mechanical maintenance and manual renewal and mechanical renewal. The manual maintenance process could consist of surface welding, switches, level crossing and structures maintenance and some spot maintenance. Mechanical maintenance would involve tamping, ballast regulating, ballast stabilizing, joint straightening, ballast cleaning and also some spot maintenance. The manual renewal process would involve the renewal of certain parts whereas the mechanical renewal process would involve the renewal of track continuous or panels, switches complete or part, the formation and some structures.

2.3.3 Availability

The European Commission (2000) emphasise that to attract more traffic to rail, the quality features "availability and reliability of the track infrastructure and of the trains" plays a major role. Stalder (2002) argues that performance related issues concerning ‘reliability’ and ‘availability’ (together with maintainability and safety) are key aspects of infrastructure quality. He further suggests that these performance aspects and their value to the customers (train operators and end-customers) are as relevant as cost, and this is particularly true in highly congested areas where railways increasingly have service quality and punctuality problems. Unavailability patterns can be observed by a combination of different failure rates and different downtimes per failure type. The "penalty cost" of unreliable or unavailable infrastructure is suggested as becoming increasingly an issue. These ‘penalty costs include delay costs. Possession costs should also be included as major availability cost driver. Stalder (2002) claims that ‘unreliability’ is a hidden cost driver and also suggested there is a need for a commercial framework to assess the cost of reliability. This will give guidance for decision making and add an additional element in a wider whole life cycle Cost view which performance-oriented maintenance strategies can be developed. (Zoeteman and Braaksma (2001) suggest ‘availability’ is the time that the infrastructure is available for operations per calendar period. The ‘unavailability’ of the infrastructure can be attributed to planned possessions (preventive maintenance), to infrastructure failures (corrective maintenance), possession over-runs or external factors, such as vandalism and bad weather. They also suggest **‘**reliability**’** is the time that the infrastructure is available for operations during the operation periods agreed. Here only the unplanned maintenance and repair is considered. The reliability depends on e.g. the asset quality and the ease, at which it can be maintained, as well as the amount of preventive maintenance, and the failures restore times.

Safety, noise, vibrations and riding comfort are also areas of conceren and are related to maintenance thresholds (e.g. geometry control limits), and inspection and failure response strategies (e.g. inspection frequencies and speed restrictions. The use of ‘Safety Cases’ are used to analyse the railway safety provided (Zoeteman and Braaksma (2001).

2.3.4 Deterioration of Track Geometry / Defects

A major debate within the literature is one concerning prediction of track deterioration in order to predict future maintenance and renewal requirements and therefore the costs. Track geometry deteriorates under the weight of different track loads. In most circumstances, the level of track quality controls the decision on whether or not to renewal or apply maintenance to the track. Considering the track quality requirements the cheapest option over the life is the most desirable strategy. Hargrove *et al.* (1991) argue that physical deterioration relationships are central to the development of any life-cycle costing and maintenance planning tool. The literature discusses two main approaches to predicting the deterioration these include tonnage/age based and condition based.

2.3.5 Age/Tonnage Based Approach

Both Zoeteman, A. (2003) and Shenton, M. and Tunna, J. (1991) discuss the idea that rail renewal or maintenance is performed using a correlation between the amount of tonnage passed over the asset and its age. The higher the amount of tonnage the more frequent maintenance or renewals will occur. Andersson, M, (2002) have the same view that deterioration models for rail wear is a function of traffic load, rail fatigue is a function of repeated loading cycles, ballast and sleepers deterioration as a function of loading. They suggest cost is calculated through the estimation of life cycles of the various components based on the deterioration rates from the individual models and total costs for maintenance activities to restore the track quality. The authors also split traffic related deterioration factors into three main groups; dynamic effects, speeds and loads. However, the main issues when intervening with renewal or maintenance, based on life expectancy due to traffic loading, is the asset may be still in a good condition and have useful life left. Cost saving would be made by allowing the assets to extend its life.

2.3.6 Condition Based Approach

State of the art infrastructure management systems use probabilistic deterioration models, which use accurate data of the condition of the asset. Data concerning the condition of the asset and the track geometry can be inspected visually (human) or by measuring machines/devices. The visual inspection machines can be attached to trains and can analyse rail images to determine rail size and wear (Izbinsky and Gillanders (1991) and (McNeil *et al.* (1991). Andersson, M, (2002), Trask, E. and Fraticelli, C. (1991) argue that obtaining an accurate and complete human visual inspection of the rail surface is time consuming and costly and the quality and consistency of typical visual inspection data is highly dependent on the training, experience, motivation and tenacity of the inspector. As an alternative to visual inspection (McNeil, S. *et al.* (1991)

propose an automated system for high speed inspection of the rail surface with the aim of using the data to develop more informed grinding strategies.

Studies by Trask *et al.* (1991), Mesnick (1991), Esveld (2001), Esor and Zarembski (1992), and Acharya *et al.* (1991) investigate the deterioration mechanisms and possibilities of controlling this occurrence by implementing improved maintenance strategies and polices. They also argue that developing deterioration models improves the ability to plan track repairs also suggest that the models which predict deterioration are only as good as the input base deterioration data and the engineering model used.

Larsson, D. (2002) discusses a study that investigated the development of a model to predict the degradation costs of Track. The model simulated degradation of the sleeper ballast and rail. The model was validated against three other similar models identified from the literature, the Track Maintenance Planning Model, Total Right of Way Analysis and Costing System (TRACS), and the Damage Exponent Heavy Axle Load Analysis. The output from the model were related to the output from the three models identified.

2.3.7 Historical Developments

Concerns of maintaining and renewing the railways within budget constraints have changed little since 1935. The first discussion within the literature of a need to improve maintenance and renewal practice to meet budgets dates back to 1935. Geyer (1935) suggests that up to 25% of the annual budget can be 'dead money'. He suggest this 'dead money' can be attributed to a high turn over of staff, therefore losing capability with experienced staff leave. Having low productivity with new staff and the labour cost involved when work is disbanded for a period of time as well as damage to equipment that has been left at sites. He also interestingly proposes the need to analysis alternative maintenance machines and identify which will be the most economic over its life. However, offers no suggestion on how best to perform this analysis. Data collection is also discussed and the need for a dedicated individual to capture data from time sheets is proposed.

Comparing Geyer (1935) concerns to those of Zarembski (1989), (who was the first to publish research discussing economic benefit analysis using lifecycle techniques), fifty-four years later, it is interesting to observe the similarities between them. These similar concerns include the need to analysis alterative options for the most economic over the whole life, and the need to collect appropriate data which historically has not been done. Furthermore, the main renewal and maintenance requirements have changed little since 1935. There is still a major requirement to provide a safe, reliable and economic service however is is suggested that over the last 10 years more pressure has been put in place to reduce expenditure however, still improving performance (Zeoteman and Esveld (1999).

The proposal of using a track degradation model to plan maintenance and renewal activity was first discussed by Trask, and Fraticelli, (1991). He discussed a model which used the current condition as a base and predicted the service lives over 5 years for the rail and ties. With an understanding of the service lives, the user would abe able to plan the required renewal or maintenance.

The newest approach to reduce costs of maintenance activities observed in the literature is published by (Stirling *et al* (2000). They trail and converse an Expert systems, which based on defined rules chooses the most appropriate remedial work based on the condition of the asset They argue that this will reduce maintenance costs because it will provide the most optimised remedial process to be performed.

Over all the historical debates within maintenance and renewal have stayed consistent. There is a need for methodologies, which provide an understanding of future maintenance and renewal activity so to plan and produce budgets, and a need to investigate areas of renewal and maintenance process, which can be optimised to reduce costs however, always considering the safety requirements of the assets. Furthermore, a need to understand the most economical option over the life of the asset is required. Observations of what has changed historically are the techniques that have been applied to address these debates and issues, which manly involve the statistical modelling requiring historical empirical data.

2.3.8 Life Cycle Cost Analysis

The main cost estimating approach debated within the Railway renewal and maintenance literature is whole life cycle costing. Zoeteman and Van der Heijden (2000) suggest that the life cycle costing approach is used for making maintenance and design decisions. They suggest that the reduction of government funds has made it necessary to reduce total costs and to increase the control costs and that this approach will provide a means to reach this aim. As previously mentioned the need for a whole life view of an asset is discussed as far back as 1935 however, there has only been interest in applying methodologies that take a whole life view of costs within the Railway industry within the last 10years.

Zoeteman and Esveld (1999) suggest that to address issues concerning the Infrastructure Manager, such as the optimal long-term strategy for the railway system, the consequences of these strategic decisions need to be assessed. They suggest that the LCCA methodology can provide a framework to assess these decisions in terms of life cycle costs (LCC). Schlickman (2002) reiterates this view and suggests that due to the restructuring of the railways and increasing efficiency requirements in many countries, the role and responsibilities of the infrastructure manager has evolved now requiring long term strategic planning. There are several definitions of life cycle cost (LCC). Schlickman (2002) proposes the following definition: *"the life cycle cost of an item is the sum of all funds expended in support of the item from its conception and fabrication through its operation to end of the usual life"*. He suggests that the LCC of an asset starts when it is acquired to when it is finally taken out of service for disposal or redeployment. A new life cycle begins once the process is completed. He argues that reducing maintenance cost and delay time without reducing the safety level is the main objective of the LCC methodology.

2.3.8.1 Life Cycle Cost Analysis Process

Dhillon (1989) supports a view that LCCA has been applied to many domains including manufacturing, engineering and maintenance. Dhillon (1989), Fabrycky and Blanchard (1991) emphasise that due to the many different domains and problem environments that the LLCA is applied to, the many different items being analysed and the different data collection techniques used there is not a single standard life cycle cost model. However, Dhillon (1989) suggests there are two general types of life cycle cost model these include:

- Conceptual - Relationships between variables are given by qualitative methods
- Analytical - Total cost models, design trade off models

Observations of the Railway renewal and maintenance literature indicate that many of the discussed life cycle models can be grouped in to Dhillon's (1989) analytical type models (UNIFE LCC Group (1997), (Steinmetz and Ashmore (1997), (Zoeteman *et al.*

(2001), (Larsson, D and Gunnarsson (2001), (Vatn (2002), (Schlickman (2002), (Veit (2002) and (Stalder (2002).

He argues that the basic uses of life cycle costs can be classified in the groups, as shown in Figure 2.1.

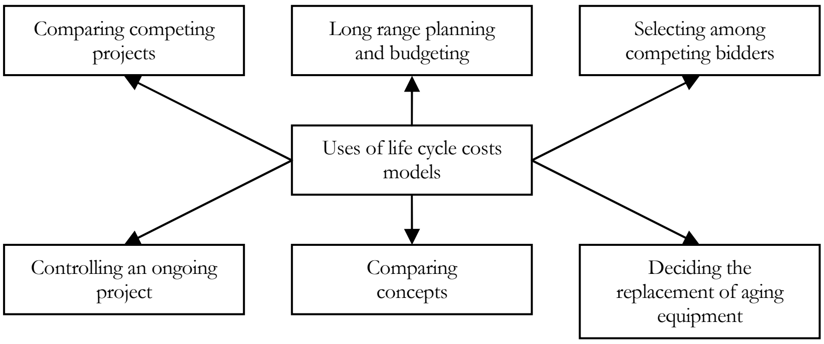


Figure 2-7: Basic Uses of Life Cycle Cost (Dhillon (1989)

Within the railway literature, the issues researchers are mainly concerned with surround 'long range planning and budgeting', 'comparing concepts' and 'deciding the replacement of aging equipment'. The 'comparison of concepts', is commonly called "what if analysis" within the literature and is used to model and test alternative scenarios that has costs associated with them. An economic analysis of the scenarios is then performed. (Roney and WcIlveen (1991), (Hide *et al.* (1991), (Chrismer and Selig (1991), (Zarembski (1989), (Zinck and Tudor (1991), (Hargrove and Martland (1991), (McCarthy and Lees (1991), (Trask and Fraticelli (1991), (Mesnick (1991), and (Shenton and Tunna (1991)

Dhillon (1989) suggests that the life cycle cost approach includes several activities, including:

1. Identify life of the item.
2. Identify operation and maintenance costs.
3. Identify the item final value.
4. Subtract the final value from the ownership cost of the item.

5. Discount the final amount of step 4 to present value.
6. Add procurement cost to final amount from step 5.
7. Final life cycle costs.
8. Repeat steps 1-7 for each item under analysis.
9. Make comparisons of life cycle costs.
10. Purchase item with least life cycle cost.

He suggests the life cycle cost model inputs can consist of the following: cost of training, values of mean time between failures, mean time to repair, items listed price, Cost of labour, Warranty, Logistics, Installation costs, spares, and average material cost for a failure.

Whereas Janz and Sihn (2005) suggest the following nine steps are involved in life cycle cost analysis including.

1. Identify cost drivers
2. Develop cost estimating relationships
3. Develop escalated and discounted life cycle costs.
4. Define an items or product life cycle.
5. Define activities that generate ownership costs.
6. Perform sensitivity analysis
7. Establish cost profile.
8. Determine cause-and effect relationships.
9. Establish an accounting breakdown structure.

You can see that both approaches are slightly different further supporting the idea proposed by Dhillon (1989), Fabrycky and Blanchard (1991) that there is no standard method. Janz and Sihn (2005) suggest that sensitivity analysis should be one key step when conducting Life Cycle Cost Analysis. However, the models discussed in the Railway specific literature seem to have overlooked this type of analysis.

The key sources of research concerning life cycle cost analysis within the Railway literature is mainly authored by Zoeteman. (Zoeteman and Esveld (1999) propose the following steps in order to develop a railway specific life cycle model.

1. Understand traffic volumes
2. Estimate volumes of maintenance and renewal based on predicted track quality due to traffic volume
3. Estimate possessions, speed restriction hours based on maintenance and renewal volumes.
4. Track possessions and speed restrictions are converted into an estimation of train delay minutes and cancellations.
5. Costs are estimated for renewal and maintenance and there influence on delays.
6. Costs are discounted over life
7. Options are compared.

(Zoeteman and Esveld's (1999) approach most closely resembles Dhillon (1989) suggested approach. It is noted that the early steps in both Dhillon (1989), (Zoeteman and Esveld (1999) and Janz and Sihn (2005) are key to the success of the model and the accuracy of the estaimte. These stages are also the most difficult to conduct and require large amounts of data, this is especially apparent with the model which fall in to Dhillon's (1989) suggested analytical type models.

2.3.8.2 Current Life Cycle Cost Models

(Zoeteman *et al.* (1999), (Veit (2002), (Schlickman (2002), (Vatn (2002) all converge on a similar arguement. That there are few structured quantitiave cost estaimting methods within Railway renewal and maintenance organisations which produced cost estimates over the life of an asset. In addition they suggest due to this lack of methods most renewal and maintenance cost estimates were produced by unstructured expert judgment.

Table 2.4 and 2.5 below summarise the identified Life Cycle Cost studies/models for comparison. Presented in table 2.4 are an overview of the published research and a comparison of the papers by location, methods used and present an overview of each paper. Whereas Table 2.5 compare the model input and outputs.

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Table 2-4 Life Cycle Cost Analysis Overview - Comparison Matrix

Year	Reference	Location	Methods used/approach	Comments
1997	UNIFE LLC Group		Propose a LLC model	The study proposed an Excel based model developed to analysis Rolling stock costs, Modelled items included - reliability (MTBF), availability (op time), maintainability (MTTRestore), safety (hazard failure rate), security (protective measures), Logistics (labour)
1997	Steinmetz and Asmore	UK	Literature review, questionnaire (Delphi) to develop model.	The study discusses the developed of a model to compare different light Rapid Transport systems. Inputs included capacity and cost performance (capital, operating and whole life), and environmental impact, passenger acceptability and institutional factors. The model also used risk-modelling techniques using the @RISK software package. The study did not provide a detailed description on the structure of the model
1999	Zoeteman and Esveld	Netherlands	Validation of LCCA model using two case studies both related to the choice of a track structure.	They suggest that the drivers influencing the life cycle cost include labour costs, sub grade, maintenance slots regime, traffic intensities and characteristics, maintenance concepts (e.g. balancing maintenance and renewal) and risks. They suggest that LLCA is means to systematically consider the pros and cons of the track structures involved. And argue it can provide a means for discussions on so-called 'unproven technology'.
1999	Zoeteman and Esveld	Netherlands	Validation of LLCA model using a Dutch high speed rail link case study	The aim of the study was to validate a LCCA decision support tool developed to analysis track structures. They suggest the planning process does not yet fit the changing railway environment and therefore this model was required. The results support the case that the model helps optimise the design and maintenance strategies and showed that a 10% decrease in costs can be achieved. The paper modelled- timetable (tonnage), R&M requirements, (Cost of R&M), Penalties (possessions, delays, cancellations), Overheads,
2001	Jovanovi and Zoeteman	Netherlands	Case study approach	The aim of the study was to investigate the combination of a LLCA model with the ECOTRACK approach, which is a widely used European track maintenance management system.

2001	Zoeteman and Braaksma	Netherlands	Analyse and optimise the performance of the rail system using a LCCA model	They conclude that a systematic analysis of the costs and availability impacts, long term, are still an exception at the design phase. During the Tender Phase most engineers were not used to doing this type of analysis. Some doubts on the reliability of data because it concerned the use of innovative technology and partly because it was difficult to obtain benchmark data during the tender.
2001	Larsson and Gunnarsson	Sweden	Evaluation of increased axle load	The model uses both track and vehicle data as well as subjective information from field inspections. The model did not deal with the effects of changes in maintenance strategies but instead focuses on effects due to changes in traffic including vehicle performance, speed and load. The study modelled the impact of an increase in the axle loads from 22.5 to 25 tonnes on normal lines.
2002	Veit	Austria	Evaluating different track structures	The research considered Track structures as well as bridges and level crossings strategies. No details of the models structure were discussed.
2002	Vant	Norway	Development and validation of model using case studies. Comparison of alternative projects.	Inputs into the model include track quality, safety, delays, maintenance and operating costs, life of assets. A large validation study was performed using 100 projects
2002	Stalder		Benchmarking study	This research involved the Benchmarking of maintenance and renewal costs from European and international countries. The study provided a toolbox for cost improvements.

From the results of the comparison matrix presented in Table 2.4 it is observed that research papers published by Zoeteman *et al* (1999, 2001) have individually discussed the developments of a Life Cycle Cost model, validation of this model using three case studies and a study investigating the combination of the proposed model with ECOTRACK (a track maintenance management system). The models scope included track structures and used a combination of inputs including labour costs, sub grade, maintenance slots regimes, traffic, maintenance concepts (e.g. balancing maintenance and renewal) and risks.

Zoeteman and Braaksma (2001) argues that the strengths of using LCCA techniques are that it allows the consideration of pros and cons of the assets under analysis, backing the claims by Dhillon (1989), also it allows discussion on 'unproven technology', and allows communication between department experts and different stakeholders. Zoeteman *et al.* (1999) also suggest that the main issue in conducting a life cycle cost analysis was the collection of reliable maintenance data. Also argued is that estimates produced by Life Cycle Cost models can be convincing and provide effective justification for decisions when in discussions with other stakeholders, e.g. the government. Data can also be an issue when conducting analysis on new technologies because there has not been sufficient time to collect historical data.

Following Zoeteman's first published work two years earlier , Zoeteman *et al.* (2001) then published a study which extended their proposed model by integrating it into ECOTRACK, a European wide decision support maintenance management software system. The software system aims to determine whether, when, where, and how to intervene with either a renewal or maintenance strategy, and deciding on optimum allocations of resources and minimizing the costs of the track system. ECOTRACK is based on the principles of 'Expert Systems'. They suggest that different track sections tend to behave differently under the effects of loading and that decision-making processes for renewal and maintenance works are closely interrelated technically and economically. Also suggested is renewal and maintenance plans are based on large quantities of qualitative and quantitative data. They argue that the strengths of integrating LCCA with ECOTRACK were that rules can be created that are specific to the particular Railway environment. However, they argue that the key weaknesses observed were the quality and reliability of data, the data was fragmented, and often improperly referenced, and that data was not always in a digital format and was not always self explanatory. Additionally major limitation to the work included the development of reliable maintenance estimates, the collection and use of regional specific track quality data and the standardisation of the track quality data.

Viet (2002) developed a model to analysis renewal and maintenance of track structures and optimise renewal and maintenance strategies, similar to Zoeteman *et al.* (2001), model, however; he extended renewal and maintenance cost estimating research by also introducing analysis of bridges and level crossing. The paper however does not provide details of the structure of the model so a comparison of inputs and output cannot be made with Zoeteman's proposed model.

Viet's (2002) research identified the optimal strategies for plain line track: main line, secondary and branch lines, research into the quality performance of the track structure alongside strategy for points and crossings, bridges and level crossings. He suggested, to optimise the strategy, three key points should be considered; there should be high initial track quality, that the speed restricted areas are uneconomical and life extension of the assets should be aimed for. Limitations of the study are concerned with the use of an expert attended workshop to collect work cycle data. Robson suggest the results from workshops may be prone to bias due to dominate personalities. The use of quantitative data may have provided the results with more accuracy.

Both Viet's (2002) and Zoeteman *et al.* (2001) models try to understand the impact of changing renewal and maintenance strategies on costs. Larsson and Gunnarsson (2001) however developed a model to understand the impact of changing traffic including, vehicle performance, speed and load such as increasing the vehicle tonnage from 22.5 to 25 on costs. The model they propose is different to that developed by Zoeteman *et al.* (2001) and Viet (2002) because they suggest the use of a degradation model as a means the predict maintenance and renewal requirements and therefore the costs**.** The degradation model uses track and vehicle data as well as qualitative information from field inspections. They also suggest the the model creates links between practical and theoretical excising research consisting of experiences, technical data on components and research results.

Both the UNIFE LCC Group (1997) and Steinmetz and Asmore (1997) propose models to understand life cycle costs of rolling stock. Comparing the two models Steinmetz and Asmore (1997) have decided that environmental impacts and passenger acceptability are important drivers and have included these in the model. They have also introduced risk-modelling techniques, which are required to understand the uncertainties. UNIFE LCC Group (1997) describe in detail the inputs and methodology used to develop the model however there is limited discussion on this from Steinmetz and Asmore (1997) and therefore a comparison of drivers and approach can not be conducted.

Steinmetz and Ashmore (1997). The study investigated comparison analysis of different Light Rapid Transport (LRT) modes of transport. They argue that it is difficult to get state funding due to current cost estimates being over optimistic and so argue there is a need to understand the amount of economic risk involved with funding LRT, They suggest that a cost benefit analysis should be conducted. The model uses quantitative data, such as capability and cost performance, and qualitative indicators such as environment impact, passenger acceptability, and institutional factors. The outputs of the model is the ability to discuss different modes of transport in terms of their advantages and disadvantages. Costs associated to each mode and cost reducing approaches for each mode are additional outputs. An observed weakness of the study was that the sample used was very small. Using a bigger sample size would have provided more insight into the comparisons of different urban transport. However, data issues inhibited the sample size.

UNIFE LCC Group (1997) suggests that the Railway operators require products that are reliable and can be easily maintained during their lifetime. They argue that the decision to purchase is controlled by the initial cost and by the operating and maintenance cost during its life time. They suggest that Life Cycle Cost methodology can be used to give a cost value to compare these different product alternatives over there lives

Vatn (2002) propose a life cycle cost model for prioritisation of renewal and maintenance projects. His arguments, that cost drivers within the model should include costs for safety, punctuality, costs due to increased residual life length and project costs. More then one hundred projects were used to validate the model. The aim of the model was to conduct a cost benefit analysis of the different projects analysed. The advantages of the work were that all renewal and maintenance projects are evaluated similarly, by a set of evaluation criteria that was agreed upon within the entire organisation. The best project can be selected in situations were there are budget constraints.

“The Cost of Railway Infrastructure (InfraCost) is the title of a study presented by Stalder (2002). The study was an international benchmarking project of railway infrastructure costs. It was designed to help infrastructure managers in analysing and optimising their own infrastructure costs. Stalder (2002) suggested life cycle costs for fourteen Western Railways, six North American, and four East Asian Railways. The costs consisted of, investment in new lines or extension/upgrading and major renewals, renewal and maintenance cost, and the cost of network operations. Stalder (2002) argued the use of a ‘harmonisation methodology’ in order to compare the different railway networks. Some key outcomes of the study were ‘Good Practice’ life cycle costs in Europe are 30 - 40% lower then the average life cycle costs, and average maintenance costs in Europe have decreased by some 10% between 1994 and 2000. The impact of these outcome show that there are lessons to be learned and applied to the UK industry in an attempt to lower their Life Cycle costs. Collection of reliable data was problematic.

It is interesting to observe that all the Life cycle models are developed and applied in different countries. This may suggest that due to different operating procedures within each country a specific model is required.

All the life cycle models discussed have been a similar aim, to optimise strategies and plans by investigating the impact of changes to these strategies or plans.

Life Cycle Cost Analysis of Track Structures and Rolling Stock modelling are observed to be of most interest to the Railway Industry; this may be because of the large expenditure required for these types of renewal and maintenance projects, This may also be because more data may be available on these types of assets when compared to telecoms or signalling.

Table 2-5 Life Cycle Cost Analysis Model Inputs Comparison Matrix

Year	Author	Aims	Model Structure	General Inputs	General Outputs	Validation/ Case studies
1997	Steinmetz and Asmore	Ascertain the risks associated with each urban transport mode in terms of cost and benefits	N/A	Operational costs (staff wages, vehicle and infrastructure maintenance including depot costs, and company administration charges). Benefits are calculated by estimating system rider ship associated with a particular fare and quantifying the improvements in journey times and safty and multiplying these by an appropriate financial value	NPV , Costs thresholds as upper and lower limits (Risk analysis)	N/A
2001	Larsson and Gunnarsson	Predict maintenance costs of track when the traffic was increased from 22.5 ton to 25 ton vehicles.	Modelled degradation of the rail, by using a formula which pinpointed how axle load, speed and track geometry affects dynamic wheel rail forces.	Track, (Track length, Track quality, Friction coeffiecients), Vehicles, (Axle loads, coefficients of wear contribution, coefficients of fatigue contribution, speed profile as a function of curvature, height to centre of gravity) Traffic, annual miles per vehicle set) Maintenance activities, Experiences annual traffic dependant. Independent maintenance costs) and research.	Deterioration rates and cost changes based on different scenarios	N/A

1999	Zoeteman and Esveld	Predict life cycle costs of track structures	N/A	Time tables (timetable up to 2034, tonnage data, scheduled journey time). Maintenance thresholds (frequencies of renewals and major overhauls, small maintenance and incidents). Maintenance impacts (renewal and overhaul costs, costs of small maintenance, possession hours, speed restriction hours). Penalties (contribution of signalling and power, train delay minutes and cancellations). Total cost indication (construction, overhead, specific risks, interest costs)	need revenue, cost breakdown availability level. Revision of track maintenance policy	Case study,
2002	Veit	Economic optimisation of track investment and maintenance	N/A	N/A	Optimal Plain line track, points and crossing, bridge strategies.	N/A
2002	Vant	develop a model to priorities maintenance and renewal projects	developed a model using a hazard rate, which defines the rate that an item will fail in small time interval from time t-t.	Qualitative information (measurements and analysis of track quality, trends) Safety (risk model- number of crack in rail relating to accident consequence) Punctuality (line speed, speed restrictions, increase in travelling time) Project Costs, Cost Parameters (interest rate, Monterey value of safety consequences, Cost per minute delay freight and passenger trains,	Safety considerations, Punctuality costs, maintenance and operations costs, extended life length, project costs, cost benefit ratio.	Case study

Table 2.5 above compares the models by general inputs and outputs. The models suggested by Larrsson and Gunnarsson (2001), Zoeteman and Esveld (1999) and Vant (2002) have as part of there main aim a requirement to understand costs of renewal and maintenance of track structure. They have all suggested different approaches to estimate required maintenance activities. Vant (2002) has adopted the use of a 'Hazard rate' whereas, Larrsson and Gunnarsson (2001), chose to use a degradation model and Zoeteman and Esveld (1999) used tonnage and expert judgement as well as Failure Mode and Effect Analysis to estimate renewal and maintenance requirements. Considering the different maintenance approaches adopted and the different main aims of each study, this vastly impacts on the data inputs required for each model. In terms of inputs Vant (2002) and Zoeteman and Esveld (1999) models are most similar. Both consider Traffic, Maintenance, Penalties and additional project costs such as construction and overheads. Interestingly Vant (2002) has been the only researcher to considered 'Safety 'as a key input. Safety in the context of Vant (2002) research means relating cracks within the rail to accident consequences. None of the models presented in Table 2.5 consider noise or pollution costs.

To estimate degradation of the track and therefore predict renewal and maintenance requirements two approaches are suggested, a degradation model (Larrsson and Gunnarsson (2001), and a tonnage based approach (Zoeteman and Esveld (1999). The tonnage-based approach is the more simplistic of the two and uses a correlation between tonnage run over the track with the degradation of the track i.e. the more tonnage run over the route the more degradation and maintenance requirements needed. This is a commonly used approach when there is little data available. The degradation model is a more accurate approach to predict the degradation however; it requires detailed data on the track and vehicles, which is not always readily available.

Like many domains, challenges surround collecting accurate and meaningful data to feed into the models.

The above discussion has compared the research, highlighted the key areas of concern and debate within the Railway renewal and maintenance cost estimating literature. The review has discussed many models, which aim to predict future renewal or maintenance requirements or perform cost benefit analysis of different renewal and maintenance options. Also presented have been the historical developments of the topic.

2.3.9 Key Observations

- The review of the literature has suggested that' Availability and Reliability' are key drivers to attract more traffic to Rail (Stalder (2002). Penalty costs for unavailable and unreliable infrastructure and possession costs are major availability cost drivers. These drivers are important when estimating renewal and maintenance costs, and are relevant to this research, and should be considered in the proposed approach that this thesis proposes.
- The literature has highlighted two approaches to understand degradation of the asset. Degradation is important in understanding renewal and maintenance frequencies. Degradation models require data on track and vehicle parameters, which may not be available at the early stages of a project. These degradation models are therefore limited in there use at the early stages. However, the age or tonnage based approach could be relevant to this research and used at the early stages, as only one parameter e.g. tonnage is required as input. However, they are not a very accurate prediction of asset life due to the use of averaging and require a large amount of data to develop the relationships.
- The main cost drivers within the Railway literature are 'corrective maintenance and preventative maintenance costs, availability costs (these include possessions and delay costs).
- The most commonly debated cost estimating approach within the railway specific literature is the application of Life cycle cost analysis. This is because it is argued that it can provide the infrastructure manager with the optimal renewal and maintenance long-term strategies for the railway system (Schlickman (2002).
- Many of the models discussed can only be applied to the situation they were developed for. These models are not generic in nature due to the differences in the problem environment (Wahby *et al* (2001).

- When quantitative data is unavailable renewal and maintenance cost are based on unstructured expert 'best guess' (Zoeteman *et al.* (1999), (Veit *(2002)*, (Schlickman (2002), and (Vatn (2002).
- Much of the literature focuses on discussing models, which aim to predict future maintenance requirements. Unit costs are assigned to these predicted requirements and aggregated to give an estimate of cost.

2.4 Key Challenges in Renewal and Maintenance Cost Estimating

The review of the literature has identified the key issues and debates within renewal and maintenance cost estimating literature. The following summarises the renewal and maintenance literature review key challenges.

- Historically challenges with optimising renewal and maintenance processes to reduce costs, performing cost benefit analysis of different options and taking a whole life view can date back to 1935. These are still major challenges today and it has only been in the last 25 years that researchers across all domains have started to publish work addressing these challenges.
- Within the Railway domain, developing models that take a whole life view of the asset have been a major challenge. Development of these models has only become of interest to the Railways only within the last 10 years.
- Collection of quantitative cost and engineering data needed to produce cost estimates is a major challenge as it can be limited, fragmented, improperly referenced, might not be in a digital format, might not be self explanatory or not available at all (Zoeteman *et al.* (2001).
- The deficiency of available quantitative cost data has not been addressed in the literature, suggesting there is a distinct lack of methodologies that produce renewal and maintenance cost estimates when there is limited or no quantitative cost data available. A major challenge is the development of a model which estimates costs when there is a lack of data.

- Budgets are produced at the early stages in a project life cycle. A major challenge is that literature lacks methodologies that address the problem of estimating renewal and maintenance costs at the early project life cycle stages.

The above discussion of the literature review has highlighted that many model are proposed to estimate renewal and maintenance costs. The review has identified that the availability of data is a major challenge. However, the review has also shown that there is no formal scientific research discussed in the literature addressing estimation of renewal and maintenance costs when quantitative data is limited or unavailable. Considering these observations the following research gap has been identified to require further research and address some of the challenges discussed.

1. *There is a lack of an appropriate structured methodology to estimate renewal and maintenance costs, during the early project life cycle stages, when quantitative data is limited or not available'*

Considering the need for the research gap presented the author returned to the literature to investigate whether the work of others might be able to contribute to achieving the main research aim. The next sections of this chapter discuss 'knowledge capture and reuse approaches, cost engineering and estimating state of the art techniques and focuses on reviewing analogy based estimating.

2.5 Knowledge Capture and Reuse Approaches

Knowledge management is now widely used in many organisations. Buckman, (2004) defines 'Knowledge Management' as the use of practices by organisations to identify, create, represent, and distribute knowledge for reuse, awareness and learning. O'leary (1998) suggests that' Knowledge Management' is concerned with classifying and categorising knowledge according to a pre-specified but evolving ontology into structured and semi-structured data and knowledge bases (database).

In order to define 'knowledge' we must first define 'data' and 'information'. Ackoff (1989) defines data as raw and consisting of symbols. Blackwell (2003) suggests data is simply a collection of numbers or facts.

Information on the other hand is data that has been given meaning by relational connection. Blackwell (2003) also suggests information is data that has been processed in a meaningful way. This may be in the form of reports and graphs that add an interpretation and meaning to the data. Information is also explicit. Ackoff (1989) suggests this meaning does not have to be useful. A relational database makes information from the data stored within it.

Knowledge however is defined as information combined with experience, context, interpretation, and reflection (Eldridge *et al* (2004). Ackoff (1989) suggest knowledge is the appropriate collection of information, such that its intent is to be useful. Blackwell (2003) suggests knowledge is created by the experience of carrying out an action, or acting on information, in this sense knowledge can be seen as actionable information emphasising knowledge as relating to human action.

Eldridge *et al* (2004) suggests that there are many different approaches to defining knowledge however suggests that most authors converge with a view on two types of knowledge, these include tacit and explicit. Eldridge *et al* (2004) argue that tacit knowledge is knowledge that exists in the human mind whereas explicit knowledge is knowledge that is documented, is public and shared through information technology. Explicit knowledge can be presented as words and numbers and shared in the form of data, scientific formulae, specifications or manuals. Eldridge *et al* (2004) argue four methods of transferring knowledge these include:

1. Socialisation (tacit to tacit), through coaching and on-the-job training.
2. Internalisation (explicit to tacit), learning from the analysis of explicit knowledge.
3. Externalisation (tacit to explicit), the articulation of tacit knowledge into procedures or reports that attempt to document experience in context.
4. Combination (explicit to explicit), the combination several elements of explicit knowledge into summary reports.

The literature suggests that ontology’s are used extensively to classifying, categorising, transfer knowledge and standardise the language and terminology of the domain.

Ontology's are argued to provide a shared and common understanding of a domain that can be communicated between people and application systems. Fensel (2001) argues ontology's are the key technology used to describe the semantics of information exchange. He defines an ontology as "specifications of a shared conceptualisation of a particular domain", that provide a shared and common understanding of a domain that can be communicated across people and application systems, and thus facilitate knowledge sharing and reuse. The model proposed in this research aims to capture and develop cost estimates for renewal and maintenance projects by capturing tacit knowledge from an expert and converting this tacit knowledge into a quantitative explicit value (pair wise comparison). The value is then used within a mathematical expression to produce a cost estimate. According to Ackoff's (1989) definitions, the cost estimates would be classed as 'knowledge' as these are perceived as meaningful information.

Introducing 'knowledge management' into this research would therefore involve classifying and categorising the cost estimates according to an ontology for sharing and reuse, however this is out of the scope of this research. Nevertheless, knowledge management and the development of an ontology for sharing and reuse of the captured cost estimating knowledge is an important area to consider for future research and would be an important next step in the evolution of the model proposed in this thesis.

2.6 Cost Engineering/Estimating Definitions

Lewis and Pickerin (2001) suggest that cost engineering contains the following sub level methods and activities; cost estimation, scheduling, risk analysis, cost control, development of cost models, data collection, cost engineering process evaluation, tools evaluation and development, cost estimating methods and processes development, validation of input data, analysis of supplier proposals, cost reduction and improvement, value analysis, design to cost, definition of costing requirements, economic appraisal, preparation and evaluation of business plans, benchmarking, cost as an independent variable (CAIV), participation in integrated product process team, support to participation in cost negotiations, achievement of value for money (from suppliers) communicate findings.

Roy (2003) argues that cost engineering helps companies involved in product development with decision-making, cost management, and budgeting. He suggests that it is a methodology used for predicting the cost of a work activity or output.

The International Cost Engineering Council (2005) suggest that cost engineering attempts to address problems with cost estimation, cost control, and business planning and management science, including project management, planning, scheduling problems, and profitability analysis of engineering projects and processes.

The Association for the Advancement of Cost Engineering (2005) suggests that cost estimation is predicting within a defined scope the cost required to construct and equip a facility to manufacture goods or to provide a service. It argues that cost estimates are produced using experience and or equation calculations using quantitative data. The aim of the cost estimate is to forecast the future cost of resources, methods and management within a scheduled period. Risks and opportunities are often included in these costs. The scope of this research is concerned with cost estimation and therefore the following section will review techniques used.

2.7 Cost Estimating Approaches

This section of the chapter will discuss cost estimating using cost estimating techniques as the organisational theme. The aim of this section is to understand if the work of others can contribute to meeting the research aim. Therefore, a wide review of all cost-estimating techniques follows.

2.7.1 Traditional Costing

Roy (2003) suggests that there are two main estimates in traditional costing: an initial high-level estimate usually based on experts judgement and a detailed estimate. The 'first sight' estimate is done early in the project life cycle, whereas the detailed estimate is done to calculate costs more precisely and is conducted in the latter stages of a project. The 'first sight' estimate is based around the experience of the estimator and is usually produced by the estimator using a past similar project or purely on his or her cost estimating experience. He suggest that 'first sight' estimates are useful for a rough order of magnitude estimate but are too subjective for today's cost conscious environment and so more quantified and justified estimates are required.

2.7.2 *Bottom Up*

NASA (2002) suggest that the Bottom Up cost estimating approach is concerned with identifying and estimating all individual components. The results are then combined to give a total estimate. They also suggest that these types of estimates can be very time consuming because every item in the project needs to be identified. Depending on the size of the project will dictate the length of time it will take to identify every item. This data collection process are therefore not usable within the early stages of the estimating life cycle. However, they can produce estimates with a low level of error.

2.7.3 *Activity Based Costing*

Activity based costing (ABC) is a process for measuring the cost of the activities of an organisation (Edwin) and Cokin (1998). They suggest that it is a qualitative technique used to measure the cost and performance of activities, e.g. maintenance, inspection production processes, and administration. An average cost is associated to each identified activity. The amount of activity a project/product is likely to need is then estimated and costs aggregated.

2.7.4 *Feature Based Costing*

The developments of CADCAM technology and of 3D modelling tools has resulted in the development of feature based costing (FBC) (Roy (2003). The approach uses the products features, (physical structures or element of the product) as a basis for costing during the design phase. Theses physical structures of elements can include holes, flat faces, edges or folds. The principle behind the approach is that each feature will have costs associated during production since the more features it has the more manufacturing will be required. Decisions on what features to include will therefore impact on cost. A major benefit of this approach is that many products have simalr feature and therefore cost information can be used across deferent products (Rush and Roy (2000). (Roy (2003) suggests that the main issues with feature based costing is concerned with the definition of a feature and suggesst that there is no common census concerning what a feature is and that the approach is not fully developed and therefore fully understood.

2.7.5 *Parametric Cost Estimating*

Ntuen and Mallik (1987) argue that the estimating process has become more complex and that the reaction time is becoming shortened as the scope of industrial projects expands.

They suggest that parametric cost estimating has advanced to address these problems. It is suggested that the attributes of a project are identified during the creation of a parametric cost estimate. These attributes are commonly called cost drivers, which are related to costs by cost estimating relationships (CERs). CERs are mathematical formulas. They suggest that the relationships between costs and cost drivers can be made by linguistics statements, although the lack of data or insight prevents these relations from being written using equations. Kahn and Mason (1997) and Bode (1998) argue that parametric cost estimating should only be used as a costing method: when you have quite a few similar cases from the past, when you know precisely which attributes have a cost effect, when cost drivers are few, and when you are quite certain how drivers influence cost.

Neural networks (NN) and fuzzy logic are an area of interest with regard to cost estimating. They aim to computerise the human thought processes. Bode (1998) suggests that NN should only be used as a costing method when there are quite a few similar cases from the past, when the user is quite certain which attributes have a cost effect, when cost drivers are few and when it is not know how drivers influence cost.

2.7.6 Design to Cost

Roy (2003) argues the design to cost (DTC) objective is to make the design unite to a satisfactory cost, rather then letting the cost converge to design. DTC activities, during the conceptual and early design stages, involve identifying the trade-offs between cost and performance for each of the concept alternatives. It is suggested that DTC can produce massive savings on product costs before production begins.

2.7.7 Analogy

Analogy makes use of the similarity of products. Roy (2003) argues the similar products have similar costs. It is possible to achieve a valid and useable estimate by comparing products and adjusting for differences. The method requires the similarities and differences of items to be identified, which can be through the use of experience or databases of historical products. Case-based reasoning is an approach which has evolved from analogy based estimation. Case based reasoning systems contain past cases which have a description of the problem and solution associated to them. The cases are compared with the new project to be estimated using rules and the nearest match is retrieved from the system.

2.7.8 3 Point Estimating

It is not possible to measure or predict everything 100% accurately, due to the quality of the tools used or issue with data collection or data quality. Many outputs will therefore not be 100% accurate and will have some uncertainty within them. NASA (2002) argues that the three point estimate is a methodology that considers uncertainty and outputs a possible range of values rather then a single value. These value ranges include the minimum (worst) to maximum (best) and the most likely value which falls between these two. A probability distribution describes the shape of the variation between the minimum and maximum values. A sanity check, should be performed on the outputs either using expert judgement or a sensitivity analysis (or both) before they can be fully accepted.

Compared with a single point estimate value the 3 Point Estimate allows the 'estimate user' to make more informed decisions considering the uncertainty and risk as more cost information is provided. Furthermore, the use of 3 point estimating can reduce the following biases, Optimism Bias, Rosy Considering and underestimation, which can create errors in estimates when using expert judgement. (These biases are discussed further in the literature review and Section 6.5 of this thesis). The author has therefore suggested the 3 Point estimating approach should be incorporated in to the proposed methodology discussed in Chapter 5.

2.8 Analogy Based Cost Estimating

After review of the cost estimating techniques, the author felt analogy estimating required further investigation because analogy estimation can deal with issues of estimation when there is a lack of data. Whereas, many of the other techniques are not appropriate or require a large amount of data.

This section of the chapter will therefore discuss the literature surrounding analogy estimation. The organisation theme for this section starts with two applications before discussing analogy estimating as a process.

The Oxford Advanced learner's dictionary Oxford (2002) defines analogy as: *'A similar feature, condition state etc shared by two things that are compared.'*

Bardasz and Zeid (1991) suggest that solving problems within mechanical design is one application of analogy. The approach adopted is to use the design goal, a set of design data, and design constraints as the mechanism for retrieval of analogies, in this case a design plan. Cases are stored within a database using episodic memory-organisation packets (EMOP) based on a model on how people might store memory. The authors suggest a process containing seven sections, namely: reminding, modifying, mapping, evaluating, repair, generalizing and storing. A script structure that described a sequence of events that would modify the retrieved case to the current problem these were in the form of if-then rules.

Rintala *et al.* (2001) have investigated the applicability of Analogy Based Estimation to estimating the whole life costs of building services. The authors state that researchers have used Analogy and Case Based Reasoning interchangeably and conclude that Analogy based estimation is estimation by Case based Reasoning. They undertake analysis of whether ABE is a better approach then linear regression, and also conclude that ABE is not an appropriate technique to estimate the costs of building services.

2.8.1 Analogy Process

Literature shows that research has addressed some of the key problems when using analogy reasoning. One such study has investigated "*the method of generating correct generalisations and analogical inferences given correct determination rules*", in other words the study has looked at the process and reasoning for retrieval of analogies based on the inputs from the target problem. Davis and Russell (1987) state that more work needs to be done regarding the determination rule and how and what these might be.

Whitaker *et al.* (1989) explore the different qualitative and qualitative / quantities methods to relieve analogies from a database. They conclude that there currently is no understanding of what is the optimal or best total solution for the similarity problem.

Kolodner (1993) defines a case as *"A contextualised piece of knowledge representing an experience that teaches a lesson fundamental to achieving the goals of the reasoner"*
Another area of importance and discussed within the effort estimation literature, is that of how can a person select what should be the attributes that are used to search and retrieve the similar case. Hornby (1996) suggests that one possible way is to classify this with the following six main elements:

1. "Goal – objective of the domain
2. Resources – elements existing within the domain to use to meet the goal
3. Operators – actions that can be taken in the domain
4. Constraints – limiting factors on actions and resources
5. Solution plan – how resources might be used to overcome or manage constraints and achieve the goal
6. Outcome – the desired outcome of achieving the goal (may be the same as the goal)" (Hornby (1996)

Old solutions are never the same and therefore need to be adapted and changed to become more applicable to the current environments problems. Kolodner (1993) suggests an example of an adoption methodology as follows:

- Input
  - A problem description
  - A not quite right solution
  - The problem description
- Output
  - A solution that fits the problem description
- Method
  - Adjust the not quite right solution to make it appropriate as a solution to the described problem.

Within the literature, adaptations are usually in the form of rule based models. Kolodner (1993) argues that there are many different adaptation models and can be classified as:

- Commonsense transformation, these delete replay or add components.
- Model guided repair, these are domain specific and structure modifying adaptations
- Special purpose adaptation and repair, these are controlled by rule based systems and are a way of implementing parameter adjustment, commonsense transformation and model guide repair.
- Derivational replay, these use pieces of solutions and also can be used in the same set of steps as were used to solve a previous solution.

Figure 2.4 illustrates an overview of techniques identified from literature grouped into three main categories; assess similarity techniques, case base / data set structure and modification /adoption techniques. The case base /data set structure techniques grouping summaries the structures proposed by authors to store the data. these include EMOP which is based on a model of how human store memory, Other techniques observed include indexing cases by criteria

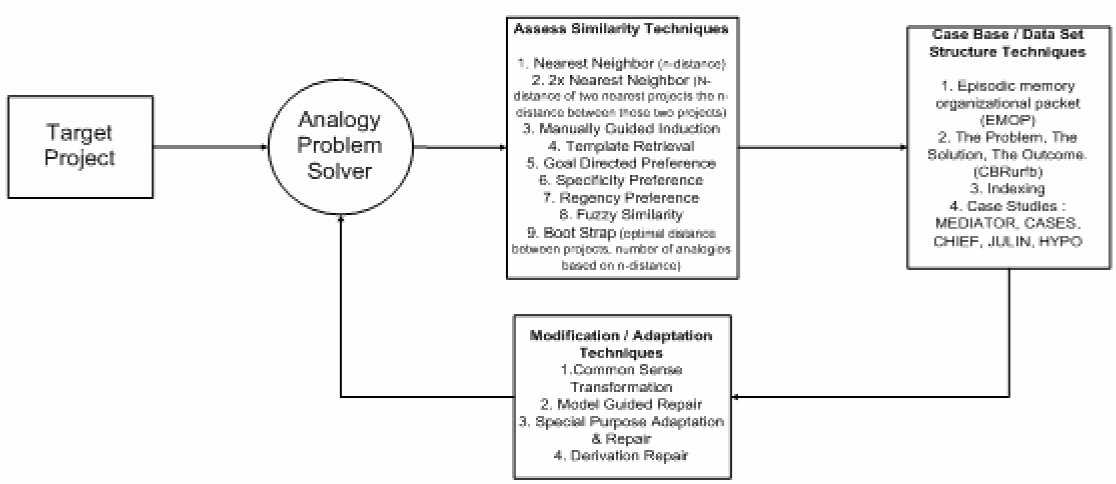


Figure 2-8: Overview of Case Base Reasoning Techniques

Marir and Watson (1995) argue that the problem of whether to refurbish or to redevelop buildings was addressed by the use of analogy. A key area of discussion is that of case representation. The authors suggest that a typical case will comprise the problem, that describes the environment when the case occurred, the solution to the problem and the outcome of the solution. They suggest that the factors that have an impact on cost will be the problem part of the case such as building specification features, and external factors such as the market, and innovation. They suggest that the solution and outcome should contain information on the real costs of the repair work, the lesson learned, and advice on the work itself.

2.8.2 Software Effort Estimation

Literature suggests that the focus of analogy based problem solving applications has been within the software community, in particular effort estimation. Bisio and Malabocchia (1995) argue that predicting the costs of a software project is achieved by identifying the number of man-months the project would take. The authors suggest a solution that identifies features of the software project, and then two types of weighting are associated to the features. Similar cases are then retrieved and a weighting score is presented between 1-100, 100 being the perfect match. The authors suggest a match of 70 and above should be a good project to use as for the estimate.

Another approach to the problem of effort estimation has been with the introduction of a simulation technique called the bootstrap method, the aim of which is to improve the applicability and the reliability of the estimate by analogy. Angelis and Stamelos (2000) and Stamelos *et al.* (2001) suggest the bootstrap method is used to identify the optimal distance between projects, number of analogies, and statistics used to predict effort based on the Euclidean distance in N-dimensional Space measure used to identify the most suitable and closest analogy. Stamelos *et al.* (2001) suggest an expansion of the bootstrap analogy approach by looking at estimating the possible costs of an entire software project portfolio rather than one single project.

cEstor is another software developed on a similar theme by Prietula *et al.* (1996). Shepperd and Schofield (1997) suggested an alternative approach to the effort estimation problem, which is to characterise projects based on their features such as number of interfaces, size, and development method. They have adopted the approach of Euclidean distance in N-dimensional Space to retrieve similar analogies and developed a software tool ANGEL.

A study compares different analogy based effort estimation techniques with each other and a linear regression model. Walkerden and Jeffery (1999) and Myrtveit and Stensrud (1999) conclude that human selection of analogies will give the most accurate results. Another study by Mair *et al.* (2000) compared neural networks, Analogy and rule induction to least square regression. They compare the accuracy, explanatory value and configurability of the approaches and conclude that case based reasoning is best when interacting with end users. A fuzzy Analogy approach was suggested that looked at introducing the use of linguistic quantifiers such as very low, low, high and enabling to estimate when a project is described in numerical or linguistic values. They discuss some techniques for project attribute selection and conclude that it is not possible to use statistical methods to selecting these attributes (Idri *et al.* (2002). Cowderoy and Jenkins (1988) suggest a meta-model is developed with the aim of allowing comparison of estimates that were retrieved using analogy.

Other human performance areas of investigation have been human performance with the aid of historical data, human performance with the aid of history and the analogy tool, and the performance of the analogy tool as suggested by Stensrud and Myrtveit (1998). The authors conclude that human performance improves with historical data and improves further with the aid of historical data and the analogy tool because the analogy tool provided added value but producing more realistic estimates.

Leung (2002) suggest an approach suggested that uses the two nearest neighbours of the target project to estimate. He suggests that once the N-dimensions are identified for the target project then the nearest neighbour within this distance is identified. The data set used is based on maintenance projects. The author also concludes that this approach provides more realistic results when compared to other estimation methods which only use one nearest neighbour.

Mendes *et al.* (2002) explored development effort estimation for web hypermedia applications. Ideas from software effort estimation were used. The work explored the accuracy of using different analogy retrieval mechanisms. From the results of validation using two datasets the authors conclude that Euclidean distance gives the most accurate estimates.

Analogy had been used for predicting software quality. Grosser *et al.* (2003) suggest that analogy is an appropriate methodology to use since there is little theoretical domain knowledge about software stability. The work explores structural similarities between classes, which are expressed as software metrics.

Effort estimation has also discussed the use of the Analytic Hierarchy Process (AHP) as a means of estimation.

2.8.3 Cost Estimating Using the Analytic Hierarchy Process (AHP)

Bhushan, N. and Rai (2004) defined *"The analytical hierarchy process as a systematic approach developed in the 1970s to give decision making based on experience, intuition and heuristics the structure of a well defined methodology derived from sound mathematical principles. It provides a formalised approach where economic justification of the time invested in the decision making process is provided by the better quality of the solutions to complex problems."*

AHP consists of a set of stages that need to be completed for its successful application. Bhushan, N. and Rai (1966) suggest that the stages include:

1. Decomposing the problem into a hierarchy of goal, criteria, sub-criteria, and alternatives.
2. Collecting data from experts corresponding to the hierarchy structure in the pairwise caparisons of alternatives on a qualitative scale.
3. Pairwise comparisons are organised in a square matrix.
4. Add weights to the matrix to show the relative importance of the various criteria.
5. The consistency of the matrix of order n is evaluated.
6. The rating of each alternative is multiplied by weights of the sub criteria and aggregated to get local ratings with respect to each criterion.

Sheppard and Cartwright (2001) suggest a methodology for estimating effort estimation based on the use of pair wise comparisons and an equation that requires the weights identified and one items' known cost. They conclude that there approach is an effective way of estimating effort when there is little quantitative data available.

However, because the use of pair wise comparisons requires expert judgement it is prone to bias; therefore, this next section will discuss some of these bias present when estimating using expert judgement.

2.8.4 Cognitive Bias

Flyvbjerg, *et al* (2002) suggest that one of the reasons for errors in estimates could be due to psychological bias, such as a bias in the mental make up of the estimator. A cognitive bias is any of a wide range of observer effects identified in cognitive science and social psychology including very basic statistical, social attribution, and memory errors that are common to all human beings. There are many categories of cognitive biases. The following categories may suggest some of the reasons why bias is present in cost estaimtes.

2.8.4.1 Optimism bias

Lovallo and Kahneman (2003) suggest optimism bias is the preference for people to be over-optimistic about the outcome of actions. Optimism bias arises in relation to estimates of costs and benefits and duration of tasks. Optimism bias typically results in cost overruns, benefit shortfalls, and delays, when plans are implemented. Flyvbjerg (2003) acknowledges the existence of optimism bias but suggests that optimism bias may on closer examination be strategic misrepresentation. Estimators may deliberately underestimate costs and overestimate benefits in order to get their projects approved, especially when projects are large and when organizational and political pressures are high. Studies have shown that the more difficult and uncertain a task, the more prevalent the optimism bias (Hammond *et al.* (1998).

2.8.4.2 Rosy Retrospection

Mitchell and Thompson (1994) suggest 'Rosy Retrospection' refers to the finding that subjects later rate past events more positively than they had actually rated them when the event occurred, reminiscent of the Latin phrase *memoria praeteritorum bonorum* ("The past is always well remembered.") This bias may influence the estimator into remembering the past project scenario to have less issues then it was in reality leading to an underestimation in its cost.

2.8.4.3 Subadditivity effect

Tversky and Koehler (1994), Fox and Levav (2000), Sloman *et al* (2004) all suggest that the subadditivity effect is the tendency to judge probability of costs for the whole to be less than the probabilities of the parts. This raises the issue concerning the project structure discussed in Section 5.2.5 and its appropriate level of granularity. This form of bias suggests the estimator may underestimate items in the project structure which are at a higher level of granularity and over estimate items which are at a detailed level of granularity.

2.8.4.4 Memory bias

Heitger (2007) and Roediger and McDermott (1995) suggest it is common that human memory may be unreliable. The proposed approach in this research requires an estimator to recall historical projects to estimate the current project, suggesting that the recall of the past historical project may be remembered incorrectly.

2.8.4.5 Lack of Experience

Error within cost estimates base on expert judgment may be due to the lack of experience the respondents has of estimating a similar project which the respondent uses as a reference to estimate the new project being estimated. The recalled historical project may not have had closely matching attributes. Gray *et al* (1999) suggests this type of bias may be difficult to assess. Furthermore, they suggest a lack of understanding of the characteristics of the new project to be estimated may be apparent. (e.g, some features may be seen as simple by a particular estimator but in reality requires substantial development effort). Additionally, changes in technology many also make the selection of a similar project difficult. If a new technology is used there is no historical information for the estimator to recall.

2.8.4.6 Underestimation

A study conducted by Flyvbjerg, *et al* (2002) suggests that during the cost estimation of railway projects actual costs were 45% higher then the estimate. They suggest that this underestimation can be explained by four groups including: (1) Technical, such as imperfect techniques, inadequate data, honest mistakes and a lack of experience. (2) Economic, such as self interest. A company may be able to influence the outcomes so to make the project go ahead. (3) Psychological, such as a bias in the mental make up of the estimator and, finally (4) Political, were estimates are influenced to promote self interest and power. They finally conclude that cost underestimating can not be explained by error but suggest it is done by strategic misrepresentation.

The literature suggests that analogy can provide a good approach to the cost estimating problem by using similar past project. Rintala *et al.* (2001) suggests that the term analogy and case based reasoning are used interchangeably. In addition, there have been nine suggested techniques for the assessment and retrieval of similar projects. Four techniques suggested for the data structure and four techniques suggested for modification and adaptation of retrieved similar projects.

Analogy based estimation has been applied to three main areas including mechanical design and building services cost problems and software effort estimation. Within the software effort estimating domain, quantitative data can also be fragmented, improperly referenced, or not available at all (Sheppard *et al.* (2001). Within the Railway renewal and maintenance domain, quantitative data can be fragmented, improperly referenced, data might not be in a digital format, might not be self explanatory or not available at all (Zoeteman, A. *et al.* (2001). Therefore, software effort estimation has similar estimation problems as Railway renewal and maintenance estimation.

Sheppard *et al.* (2001) propose a framework that addresses problems regarding software effort estimating. Software effort estimating has similar problems to Railway infrastructure renewal and maintenance estimating. Therefore, the framework might address Railway infrastructure renewal and maintenance estimating problems.

2.9 Research Gap Analysis

It has been concluded that there is a need for the following research gap to be investigated further.

1. *'There is a lack of an appropriate structured methodology to estimate renewal and maintenance costs, during the early project life cycle stages, when quantitative data is not available or limited.*

It has also been concluded that the renewal and maintenance cost estimation domain have similar problems to software effort estimation domain. Therefore this research will explore a framework using a pair wise comparison technique, proposed by Sheppard *et al.* (2001) to address software effort estimation, and investigate this frameworks applicability to estimate Railway infrastructure renewal and maintenance costs. Considering this a hypothesis was developed. Robson (2002) suggest a hypothesis is a predicted answer to a research question. He also suggests that a hypothesis should only be generated after data collection during a qualitative study. Burns (2000) agrees, and suggests that generation of a hypothesis follows logically from the literature review. Additionally they both argue that a hypothesis should be stated so it can be confirmed or rejected. The subsequent chapters in this thesis investigate the following hypothesis:

2.10 Hypothesis

A Pair wise comparison technique can be applied to the early project life cycle stages of Railway Infrastructure renewal and maintenance projects and produce cost estimates that fall within an error range dictated by industry"

The above discussion has highlighted the importance of estimating renewal and maintenance costs for the purpose of strategy and budget development. It reviews a wide range of renewal and maintenance models, which manly use historical quantitative data as input. However, it has also identified that there is no research to address cost estimates when quantitative data is unavailable which is observed to be a common issue. The technique proposed in this study extends previous models by provided a structure method to formalise quantitative judgements and produce renewal and maintenance cost estimates.

CHAPTER 3. RESEARCH OBJECTIVES AND METHODOLOGY

3.1 Introduction

In the previous chapter a structured review of renewal and maintenance cost estimating literature is discussed. The chapter concludes with the identification of the research gap that needs further investigation.

This chapter presents the research objectives and methodology chosen to achieve them. The author discusses available research approaches, quantitative and qualitative. The most appropriate research strategy and research design for the successful completion of this study is then selected. The chapter concludes with a discussion of the issues of the chosen methodology.

3.2 Chapter Aim

To present the research methodology used to successfully complete the research aims and objectives.

Section 3.3 recalls the research objectives and aim. Section 3.4 presents the research questions which have guided this study. Section 3.5 discusses two research approaches and discusses their strengths and weaknesses. A discussion on the most appropriate research strategy is presented in Section 3.6. Section 3.7 is concerned with data collection in case studies. The chapter then concludes with the research methodology adopted based on the discussion in the previous sections.

3.3 Research Aim and Objectives

Section 2.13 stated that a research gap has been identified:

'There is a lack of an appropriate structured methodology to estimate renewal and maintenance costs, during the early project life cycle stages, when quantitative data is not available or fragmented.'

Considering the research gap the following research aim was developed:

'To develop a structured framework that estimates Railway Infrastructure renewal and maintenance costs when there is a lack of quantitative cost data at the early stages of the project life cycle.'

The research objectives are to:

- Identify and understand renewal and maintenance cost estimating issues.
- Understand the current renewal and maintenance cost estimating practice within the Rail industry
- Develop a Railway renewal and maintenance cost estimating methodology suitable for the initial stages of a project life cycle and when there is a lack of data.
- Develop a prototype software system based on the proposed methodology.
- Validate the proposed methodology using three industrial case studies

3.4 Research Questions

The research project has been guided by sixteen research questions illustrated in Figure 3.1. These research questions have been developed in order to successful complete the research objectives.

3.5 Research Approaches

There are two types of research approach. Generally these approaches are called quantitative and qualitative, although they are also called fixed and flexible designs.

3.5.1 Quantitative Design

Creswell (2002) agues that quantitative research is concerned with the investigator primarily developing knowledge using viewpoints such as the cause and effect, reduction in specific variables, use of measurement and observation, and the testing of theories. The most common quantitative research techniques include Observation, sometimes called descriptive, and Experimentation techniques. In observational studies, behaviour or conditions that are being measured are not changed; they are observed as they are. In experimentation studies measurements are taken, variables are changed, and then measurements are taken again to see what has happened. Robson (2002) suggests that experiments are the main type of quantitative design and refers to them as fixed designs. He suggests that a good indication of a fixed research design is that a large amount about what you are going to do and how you are going to do it is predefined at the beginning of the study. The main aim of quantitative research is to show how one item (variable) affects another in a population.

Strengths and weaknesses

Burns (2000) suggests that precision and control are primary strengths of the quantitative research approach. The quantitative research design satisfies the control aspects and reliable measurements satisfy the precision aspects. An additional strength includes quantitative research leading to identification of causation by limiting or controlling variables. Additionally, answers from a quantitative study are suggested to have much more of a concrete basis. Limitations of the quantitative research approach are suggested by Burns (2000) to be concerned with degrading humans individuality and their ability to think. He argues that this approach leads to answers which imply that this is true for all cases, all of the time. Burns (2000) also argues that this approach can produce trivial findings due to controlling variables.

3.5.2 Qualitative Research

Qualitative research is suggested by Creswell (2002) to be concerned with the inquirer making claims based on viewpoints such as the multiple meanings of individual experiences with the aim of developing a theory or pattern. Wisker (2001) and Strauss and Corbin (1998) both suggest that qualitative research involves the collection of people's options and feelings. Robson (2002) suggests that qualitative research mainly produces results as qualitative data. Qualitative data in most cases is words. Data collection during qualitative research tends to take the form of interviews, surveys, and observation. Fields including education research, health related research, social work research, business research, and management research, and disciplines including psychology, sociology, and anthropology tend to use qualitative research approaches Robson (2002). Robson suggests that flexible designs are similar to qualitative research designs because they produce qualitative results. There is less predefinition about what and how the work is to be done; rather when engaged in the research, the design develops over the course of time. Robson (2002) also argues that flexible design is a

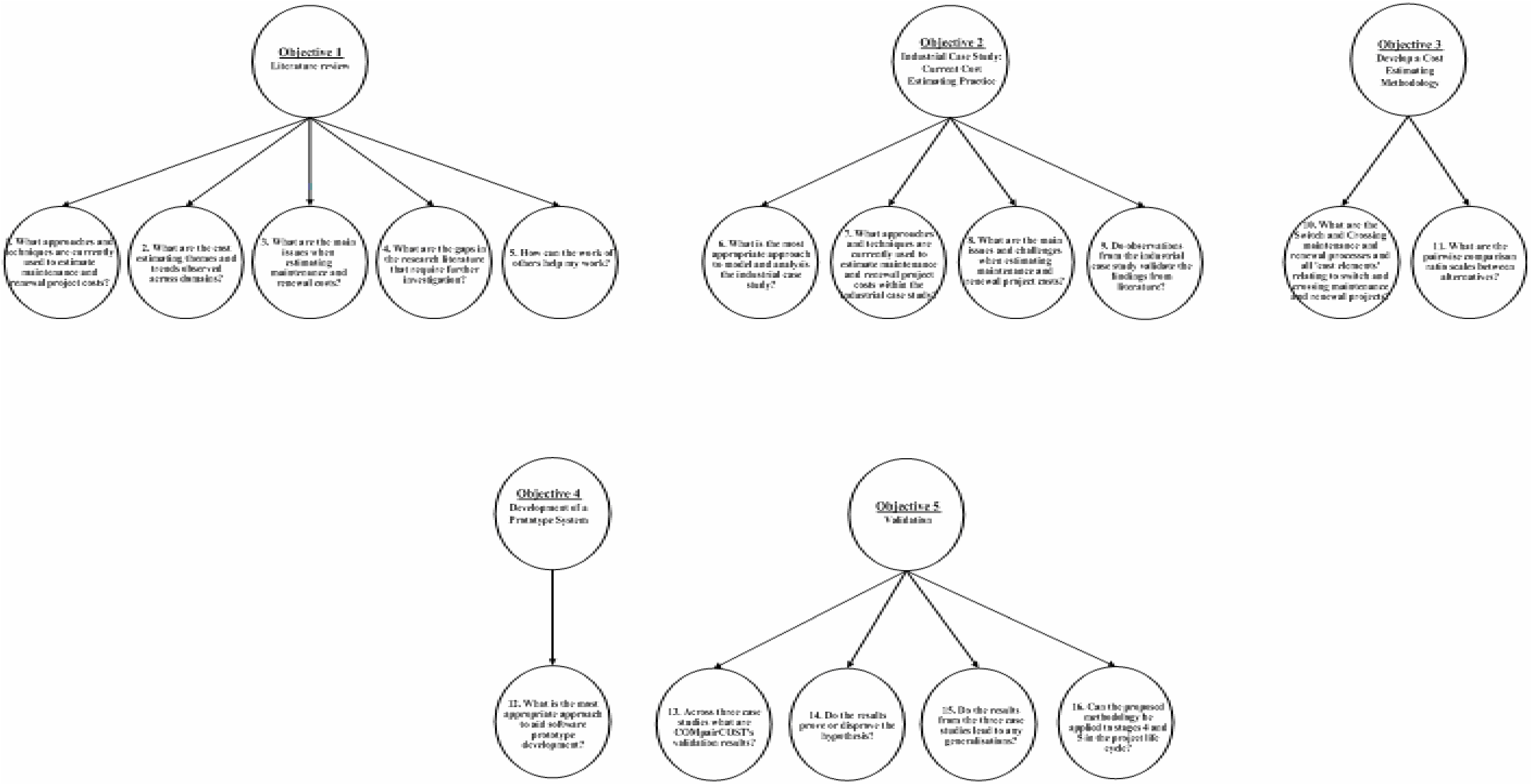


Figure 3-1 Research Questions

more appropriate name since these designs often draw on both qualitative and quantitative data (words and numbers) and so the term qualitative can be misleading as it implies just qualitative data.

Strengths and Weaknesses

Burns (2000) argues that the main strengths of the qualitative research approach include the fact that the researcher has a close connection with the participants and activities of the study so allows an 'insider view' of the field. This insider view allows for the researcher to record social interaction, which can not be achieved by quantitative studies. The main limitations of qualitative research include validity and reliability. Burns (2000) suggests that, due to the subjective nature of qualitative data and because the data is based within a single context, it can be difficult to replicate and produce generalisations to a wider context. He also argues that the time needed for data collection, analysis, and interpretation can be considerable, while the researcher's presence in the environment can affect the subject of study. Bias from both the researchers and the participant's perspectives should also be addressed. Burns (2000) suggests there are some key differences in qualitative and quantitative research as shown in Table 3.1.

Table 3-1 Comparison of Qualitative and Quantitative Methods (Burns (2000)

Qualitative	**Quantitative**
Assumptions	
Reality socially constructed	Facts and data have an objective reality
Variables complex and interwoven; difficult to measure.	Variables can be measured and identified
Events viewed from informant's perspective	Events viewed from outsider's perspective
Dynamic quality to life	Static reality to life
Purpose	
Interpretation	Prediction
Contextualisation	Generalisation
Understanding the perspectives of others	Casual explanation
Method	
Data collection using participant observation, unstructured interviews.	Testing and measuring

3.6 Selection of the Appropriate Research Strategy

Yin (2003) argues that exploratory, explanatory, and descriptive are the three main research motives. Exploratory research attempts to develop hypothesis and further inquiry by answering the “what” research questions. Explanatory research attempts to explain the “how” and “why” research questions. Descriptive research aims to describe the “who, what, when, where,” and “how” research questions of the phenomenon being studied. Considering the research questions presented in Figure 9 (page 48) are ‘what’ questions, and so the research motive is exploratory. Exploratory research is conducted to familiarise the researcher with the problems or ideas that are to be studied. Robson (2002) suggests that exploratory research is always conducted using a flexible research design, while Yin (2003) argues that exploratory studies can use many different research strategies including experiment, survey, archival analysis, history, and case study.

3.6.1 Research Design

Robson (2002) suggests that the research design is the overall framework of a research project. Yin (2003) argues that a research design is the logic that links the data collection and the conclusion to the research questions. Robson (2002) further suggests that research designs are about the aims, purpose, involvement, and plans of the research considering any project restrictions. He suggests a research design should contain five main components, namely:

1. Purpose of the study,
2. Theory, how to understand the findings from the study and what framework links the phenomena being studied.
3. Research questions, questions the study aims to answer,
4. Methods to collect data and analyse data,
5. Sampling Strategy, who to collect the data from.

He suggests that these five components should be considered and thought about throughout the duration of the research project. It is also suggested that the research designs will become more detailed as the research evolves during a flexible design whereas a detailed research design is developed before conducting data collection during a fixed design approach. Considering the aims, research questions, and the research motive to be exploratory, a flexible design approach is the most appropriate strategy.

3.6.2 Research Strategy

Robson (2002) argues that the research strategy is concerned with how the research questions are going to be answered. Both Robson (2002) and Yin (2003) also suggest that the research strategy selected is linked to the type of research questions posed.

There are three main types of research strategy within a flexible research design: Case Study, Ethnographic Study and Grounded Theory Study. Robson (2002) definitions of the three strategies are as follows:

1. Case study: *"Development of detailed, intensive knowledge about a single 'case', or of a small number of related 'cases'.*

2. Ethnographic Study: *"Seeks to capture, interpret and explain how a group, organisation or community live, experience and make sense of their live and their world".*

3. Grounded Theory Study: *"The central aim is to generate theory from data collected during the study".*

Table 3-2 Comparing Research Traditions in Qualitative Research (Robson (2002)

	Grounded Theory	**Ethnography**	**Case study**
Focus	Developing a theory grounded in data from the field.	Describing and interpreting a cultural and social group	Developing an in-depth analysis of a single case or multiple cases
Discipline origin	Sociology	Cultural anthropology, sociology	Political Science, sociology, evaluation, urban studies, many other social sciences.
Data Collection	Typically interviews with 20-30 individuals to saturate categories and detailed theory.	Primary observation and interviews during extended time in the field	Multiple sources- documents, archival records, interviews, observations, physical artefacts
Data Analysis	Open coding, axial coding, selective coding, conditional matrix	Description, analysis, interpretation	Description, themes, assertions
Narrative form	Theory or theoretical model	Description of the cultural behaviour of the group	In-depth study of a 'case' or 'cases'.

Table 3.2 presents the key features of the three main research strategies, case study, ethnography study, and grounded theory. Based on the statements made in Table 3, case study is the most appropriate strategy for this study. The focus of this research project is to understand and improve renewal and maintenance cost estimating as a process rather then describe a social group, which is the focus of Ethnography, or to develop a new theory, which is the aim of grounded theory. The research is also sponsored, which meant access to specific 'indusial cases' was possible.

Case Study

Yin (2003) argues that the case study is an empirical enquiry that "*investigates a contemporary phenomenon within its real life context especially when the boundaries between phenomenon and context are not clearly evident.*" In order for a case study to be successful four areas of concern need to be addressed; including:

1. Construct validity,
2. Internal validity,
3. External validity,
4. Reliability.

Yin (2003) suggests case study research designs can be single case or multiple cases. Robson (2002) argues that the case under investigation could be an individual, group or organisation. He suggests that a case study involves multiple methods of data collection including both quantitative and qualitative data.

Validity

Validity is concerned with trying to provide evidence that the research is true, accurate, and correct. It is suggested by Burns (2000) and Creswell (2002) that it may be impossible because in social science studies many of the influences on an environment or person can not be measured. However, the aim is to provide, as much as possible reliable, evidence of the validity of the research. Robson (2002) suggests three main types of risk involved in flexible design validity are:

1. Reactivity, which is concerned with the impact of the researcher on the phenomenon being studied.

2. Researcher bias, which is concerned with what perspectives the researcher brings to the study and how they might affect the study.

3. Respondent bias, which is concerned with what perspectives the respondent brings to the study and how they might affect the study.

Table 3.3 presents some strategies that can be used to reduce some of the above risks.

Table 3-3 Strategies to Reduce Risk Involved in Flexible Design Validity

Strategy	Reactivity	Researcher bias	Respondent bias
Prolonged involvement – Researcher is involved in the research setting for up to years.	Reduces treat	Increases treat	Reduces threat
Triangulation – uses multiple sources of data, such as different data collection techniques, using more then one observer, combining qualitative and quantitative approaches, using multiple theories or perspectives.	Reduces threat	Reduces threat	Reduces threat
Peer debriefing / support – people of similar status collectively have debriefing session to reduce bias and give support.	No effect	Reduces threat	No effect
Member checking – returning materials to respondents to check content is correct.	Reduces threat	Reduces treat	Reduces treat
Negative case studies – look for instances that will disprove your theory.	No effect	Reduces treat	No effect
Audit trail – keep full records of your activities when conducting the study.	No effect	Reduces treat	No effect

Quality in Case Studies

Four tests have been developed for the purpose of quality assessment of qualitative research as shown in Table 3.4.

Table 3-4 Case Study Tactics for Four Design Tests (Yin (2003)

Tests	**Case Study Tactic**	**Phase of research in which tactic occurs**
Construct validity	(1) Use multiple sources of evidence. (2) Establish chain of evidence. (3) Have key informants review draft case study report.	Data collection
Internal validity (explanatory or casual studies only)	(1) Do pattern matching. (2) Do explanation-building. (3) Address rival explanations. (4) Use logic models.	Data Analysis
External validity	(1) Use theory in single case studies. (2) Use replication in multiple case studies.	Research design
Reliability	(1) Use case study protocol. (2) Develop case study database	Data collection

These tests are common to all qualitative research. Yin (2003) argues that Construct validity is concerned with developing a set of measures regarding the area of study and justifying why these measures have been used for the study. Internal validation is concerned with the development of causal relationships and providing evidence of whether event A caused event B. External validity is suggested by Robson (2002) to be concerned with generalization and how the conclusions from the case study can be generalised outside of the particular case within the domain of study. Yin (2003) suggests that a theory should be generated from the first case study and then performed within one or two other case studies in order to see if the same results or conclusion occur. This might lead to a generalisation of the theory.

Would the conclusions and findings be the same if another study was conducted using the same approach and on the same case study. If the answer is yes then the study would be reliable. Yin (2003) suggests that the minimizing of errors and bias is the main goal of reliability. Robson (2002) suggests that being thorough, honest and careful as well as being able to show evidence an audit trail has been used can lead to reliable research.

3.7 Data Collection in Case Studies

Robson (2002) and Burns (2000) suggest that the selection of the appropriate research methods is based on the source, information type, and circumstances. Robson (2002) further suggests that there are three main methods to data collection, namely surveys, interviews, and document content analysis.

3.7.1 Surveys

According to Robson (2002), *'Survey research entails the collection of data on a number of units and usually at a single point, with a view to collecting systematically a body of quantifiable data in respect of a number of variables that are then examined to discern patterns of association'*. Robson (2002) argues that the survey is viewed as producing large amounts of data often of little value and suggests that the results from a survey are based on uninvolved respondents who do not report their true feelings, rather reporting in a way that portrays them in a positive light. Data can also be affected by the respondent's knowledge, experience, and personality. Using a structured questionnaire in a survey can be restrictive in the depth of response is argued by Robson (2002). Considering this, interviews and document content analysis are the most appropriate means of data collection for this research project.

3.7.2 Interviews

Burns (2000) and Robson (2002) both argue that the interview is concerned with asking questions and receiving answers from a respondent. Robson (2002) and May (1993) suggest three possible approaches can be taken when conducting an interview namely, structured, semi-structured and unstructured interviews. Wisker (2001) suggests structured interviews are concerned with the respondent completing a set of structured close ended questions. The respondent's results from this type of interview provide simpler analysis but can be too limiting. Wisker (2001) argues that a semi-structured interview is concerned with asking a set of questions that are open ended and provide a flexible guide to the order and structure of the interview. He also argues that unstructured interviews are based around a conversation with the respondent. Robson (2002) suggest that an unstructured interview allows the respondent to talk freely, although Wisker (2001) argues that there is a risk that this type of interview can easily move away from the point of discussion. Analysis and comparison of unstructured respondent interview results can also be difficult.

Robson (2002) argues that there is a relationship between the depth of response and the approach adopted, suggesting that a less structured approach will provide more flexibility and depth. Table 3.5 presents the advantages and disadvantages of interviews.

Table 3-5 Advantages and Disadvantages of Interviews (Burns (2000)

Advantages	Disadvantages
Flexibility	Expensive and time consuming
High response rate	Only a limited number of respondents may be interviewed due to time and money constraints.
Face to face interaction creates rapport increasing motivation of participants.	Finding skilled interviewers may be difficult.
Beneficial when data is required on complex topics	Interviewer may affect results, bias
Probing used to elicit more complete responses	Respondents may feel they are being put on the spot.
Observation of respondent none verbal communication	Unstructured interviews can be difficult to categorise and evaluate the responses.
Interviewer can control the sequence of items discussed.	
Useful if respondent can not respond in a written format.	
Appreciation can be shown to respondent	

Burns (2000) agues that validity and reliability can be an issue when conducting interviews. He argues that to overcome interview validity (validity meaning: are the questions really measuring what they are supposed to be measuring) one possible method requires people who are familiar with the area to review the items used to measure and identify if they are appropriate. Burns (2000) suggests that reliability could be addressed by two individuals interviewing the interviewee. However, to interview the same interviewee on two occasions within a real world industrial environment is seldom possible due to time and money constraints. Considering the arguments presented, the author chose structured and semi-structured interviews to collect data because unstructured interviews provided too much scope for the interview to move from the main point.

3.7.3 Document Content Analysis

Robson (2002) argues that document content analysis is concerned with the analysis of a written document such as a book, newspaper, company report, letters etc. Wisker (2001) suggests that document analysis is concerned with identifying key issues and themes. May (1993) argues that document content analysis is concerned with identifying how events were constructed at the time and the reasons employed, as well as providing ideas for further investigation. Robson (2002) agues that content analysis of documents is a secondary for data collection. He suggests that there are four main stages to carry out content analysis;

1. Start with a research question,
2. Decide on a sampling strategy, in order to make the task more manageable.
3. Define the recording unit, such as categories or an 'individual word'.
4. Construct categories for analysis.

Table 7 presents the advantages and disadvantages of document content analysis.

Table 3-6 Advantages and Disadvantages of Document Content Analysis (Robson (2002)

Advantages	**Disadvantages**
When used on exiting documents, it is unobtrusive. You can observe without being observed.	The documents may not be limited or partial.
The data are in permanent form and hence can be subject to re-analysis, allowing reliability checks and replication studies.	The document has been written for some purpose other then for the research, and it is difficult or impossible to allow for biases.
It may provide a low cost form of longitudinal analysis when run or series of documents of a particular type is available.	It is very difficult to assess casual relationships. Are the documents causes of the social phenomena you are interested in or reflections of them?

3.7.4 Sampling

The decision to use qualitative or quantitative research methods depends on which sampling strategy is adopted. Both Burns (2000) and May (1993) suggest that quantitative research uses probability sampling. However, when involved in qualitative research non –probability sampling should be used. Burns (2000) suggests two means of non–probability sampling, namely snowball sampling and theoretical sampling. Theoretical sampling is concerned with a theory developing as more information is collected. This theory extends and therefore informs the researcher of which groups are relevant. Snowball sampling is argued by Burns (2000) to involve the identification of a valid member of a group who then informs the researcher of others who fit the requirements. Robson (2002) suggests that the sampling strategy should balance the need to be selective, due to resource constraints with the need to collect all the required data.

3.7.5 Workshops

Fry *et al.* (2003) suggest a workshop is an environment where a group of people openly discuss and reflect on the chosen topic. Robson (2002) suggests that workshops can be used as a primary data collection technique and that they investigate collective phenomena rather then individual ones. Table 3.7 presents advantages and disadvantages of workshops.

Table 3-7 Advantages and Disadvantages of Workshops (Robson (2002)

Advantages	Disadvantages
Effective technique for qualitative data collection as data increases by collection from several people at the same time	Number of questions covered can be limited
Participants tend to provide checks and balances on one another and extreme views are weeded out.	Facilitating the group process can be challenging.
Group dynamics help in focusing into the most important topics and it is easy to assess a shared view.	Interview process needs to be well managed or the less articulate may not scare their views and bias may be caused by domination of one or more people.
Participants tend to enjoy the experience.	Conflicts may arise between personalities
Inexpensive and flexible.	Results can not be generalised as they cannot be regarded as representative of the general population.
Participants are empowered and able to make comments in there own words. While being stimulated by others.	The live and immediate nature of the interaction may lead the researcher to place greater faith in the findings then is warranted.
Contributions can be encouraged from people who are reluctant to be interviewed on there own.	
People who can not read and write are not discriminated against.	

3.8 Research Methodology Adopted

Considering the previous sections in this chapter the research methodology was developed. Figure 3.2 presents the Research methodology. Stage 1 of the research methodology is concerned with identifying the research topic and problem. This research is an industrial sponsored CASE and therefore the topic and problem had been predefined. Cost estimating is the research topic and the research problem is Railway renewal and maintenance cost estimating.

The research questions (Figure 3.1) and objectives of the study, discussed on page 47, were developed during Stage 2. The initial research questions were used to define the scope of the project and to determine what is to be studied. The research objectives are the goals and types of knowledge that the research aims to achieve.

Having developed the research questions and objectives Stage 3 involved the development of the research strategy. Considering the research questions are 'what' questions the research motive is exploratory. Considering the research aim, research questions and motive is exploratory a flexible design approach is the appropriate approach (Robson (2002) (Yin (2003). Furthermore, the focus of this research project is to understand and improve renewal and maintenance cost estimating as a process rather then describe a social group which is the focus of ethnographic, or to develop a new theory which is the aim of grounded theory. Therefore case study, which is the development of detailed intensive knowledge about a case(s), is chosen as the most appropriate strategy for this study.

Types of data, their sources, data collection and cost estimating model construct are the main aims of Stage 4 and 5. Multiple sources of both qualitative and quantitative primary and secondary data are identified to increase the validity of the data. Secondary data includes literature reviews to identify theories, models, research, knowledge gaps and primary data includes industrial case studies. In total four case studies were used. A summary of the data collection methods chosen include workshops, structured and semi-structured interviews and content analysis. The author chose to collect data using semi structured and structured interviews because unstructured interviews provided too much scope for the interview to move from the main point. Workshops were chosen because of the advantages of it increasing the data collected since it is collected from several people at the same time and group dynamics help to focus on the most important topics and make it easier to assess a shared view.

Case Study 1 is concerned with understanding current Railway asset renewal and maintenance cost estimating practice and to identify issues. A snow ball sampling strategy was used to identify suitable respondents. Table 3.8 presents the respondents identify across all the case studies. Respondents A, B, D, E were interviewed in a workshop environment, helped by an additional facilitator, with the aim to construct process models using Xpat (because of it depth of probing) and IDEF0 (because it was developed to model activities of an organisation or system). Triangulation was employed and Respondents A, B and C validated the process models using member checking and semi-structured interviews. All interviews were audio tapped and transcribed to provide an audit trail

Case Study 2 is concerned with the construct of a Switch and crossing renewal cost estimating model which addresses the issues identified from case study 1 and the literature review. Similarly to case study 1 a snow ball sampling strategy was used to identify suitable respondents. Respondents B and E were interviewed using semi structured questionnaires to construct and populate the model. Respondents B and C validated the project structure using member checking and also answered a semi-structured question concerning the models usability. Triangulation was employed to reduce the treat of reactivity, research bias and respondent bias. Five historical Switch and Crossing Renewal projects were used to validate the model.

The construct of a switch and crossing maintenance cost estimating model is the focus of Case Study 3. Respondent P was interviewed using semi structured questionnaires with the aim of modifying the model developed in case study 2 and constructing and populating the new model based on this case. Five historical Switch and Crossing maintenance projects were used to validate the model.

Case Study 4 is concerned with constructing and validating the model developed during case study 2 and 3 however using Track Sidings & Insulated Rail Joint specific data rather then switch and crossing specific case data. Respondent T was interviewed using a semi-structured interview. The reason assets other then switch and crossing were chosen were so the results and conclusions can be generalised outside this domain of study.

Table 3-8 Case Study Respondents

Respondent	Position	Cost Engineering (CE) Experience	Purpose of Data Collection	Type of interview used
Case Study 1				
Respondent A	Head of Estimating	Between 10-15 years	Construct process models,	Workshop,
			Validate process models.	Member checking

Respondent B	Cost Estimating Manager	Between 10-15 years	Construct process models,	Workshop,
			Validate process models.	Member checking
Respondent C	Cost Estimating Manager	More then 15 years	Validate process models.	Member checking
Respondent D	Cost Engineering Consultant	5 years	Construct process models,	Workshop
Respondent E	Rail Consultant	N/A	Construct process models,	Workshop
Case Study 2				
Respondent B	Switch and Crossing Cost Estimating Manager	Between 10-15 years	Model Construct,	Semi-Structured Interview,
			Validate Project Structure	Member checking
			Project Scenario Development	Semi-Structured Questionnaire
			Model Population	Semi Structured Interview
			Usability Validation	Semi structured Interview
Respondent C	Switch and Crossing Cost Estimating Manager	More then 15 years	Usability Validation	Structured Interviews,
			Validate Project Structure	Member checking
Respondent E	Rail Consultant	N/A	Model Construct,	Semi-Structured Interviews,
Case Study 3				
Respondent P	Production Manager	Between 1-5 years	Model Construct, Model Population	Semi-Structured Interviews
Case Study 4				
Respondent T	Senior Estimator	More then 15 years	Model Construct & Model Population	Semi-Structured Interview
			Usability Questionnaire	Semi- Structured Questionnaire

Case study 2 provides that main case study for the construct of the cost estimating model proposed in this research. The model from this case study is then adapted based on the data provided by two case studies 2 and 3.

During all the case studies full records of the research activities were keep these included audio taping and transcribing all interviews so to provide an audit trail. Furthermore, throughout all the case studies content analysis was employed on published and company based literature which formed the Secondary Data Collection activity.

Validation is the aim of Stage 6 in the research methodology. Two main approaches were adopted they include empirical validation and a 'Usability' questionnaire. A prototype software system was developed based on the cost estimating model developed in case studies 2, 3 & 4. The system was developed to aid the empirical and qualitative validation. The empirical validation was performed by using in total 15 historical projects across case studies 2, 3 and 4. Respondents were asked to estimate the projects using the prototype software system. The results were then compared with the historical project costs. Additionally a 'Usability' questionnaire was developed. Respondents B,C,F,G,P,T,H,I,J,K,L,M,N,O as shown in Table 3.9 were interviewed using semi-structured questionnaires with the aim of assessing the prototype systems usability. Results were used to improve the system. The final stage in the research methodology discusses the finding and conclusions.

Table 3-9 Usability Questionnaire Respondents

Respondent	Position	Cost Engineering (CE) Experience	Purpose of Data Collection	Type of interview used
Respondent B	Switch and Crossing Cost Estimating Manager	Between 10-15 years	Usability Validation	Structured Interviews
Respondent C	Switch and Crossing Cost Estimating Manager	More then 15 years	Usability Validation	Semi-Structured Interviews
Respondent F	Cost Engineering Lecturer	N/A	Usability Validation	Semi-Structured Interviews
Respondent G	Cost Engineering Lecturer	N/A	Usability Validation	Semi-Structured Interviews
Respondent P	Maintenance Manager	5-10 years	Usability Validation	Semi-Structured Interviews
Respondent T	Senior Estimator	More the 15 years	Usability Validation	Semi-Structured Interviews
Respondent H	PhD Researcher	N/A	Usability Validation	Semi-Structured Interviews
Respondent I	PhD Researcher	N/A	Usability Validation	Semi-Structured Interviews
Respondent J	PhD Researcher	N/A	Usability Validation	Semi-Structured Interviews
Respondent K	PhD Researcher	N/A	Usability Validation	Semi-Structured Interviews
Respondent L	PhD Researcher	N/A	Usability Validation	Semi-Structured Interviews
Respondent M	PhD Researcher	N/A	Usability Validation	Semi-Structured Interviews
Respondent N	PhD Researcher	N/A	Usability Validation	Semi-Structured Interviews
Respondent O	PhD Researcher	N/A	Usability Validation	Semi-Structured Interviews

The chapters in this thesis have been mainly organised around each case study. Therefore, a summary discussion on the research methodology is also presented at the beginning of these chapters.

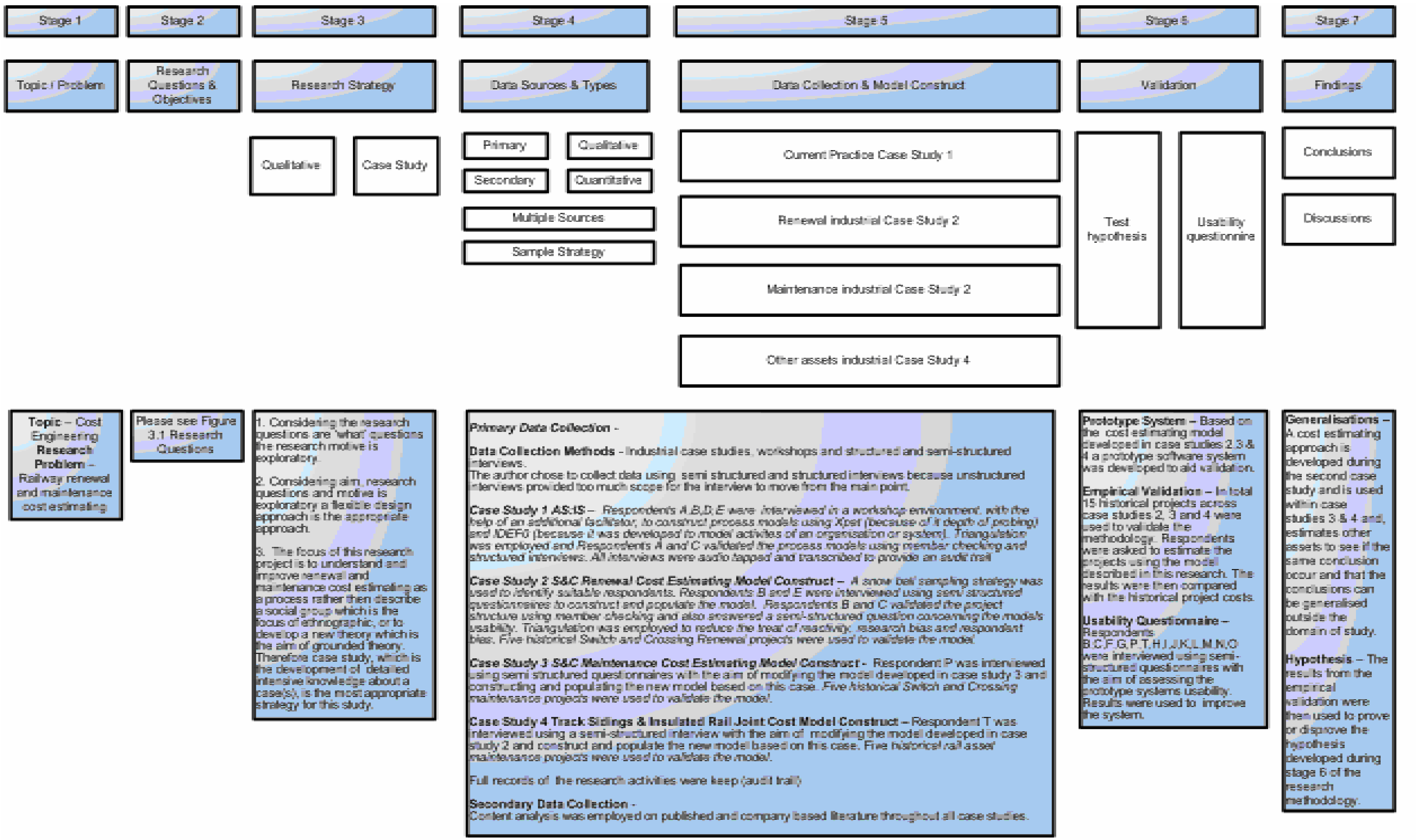


Figure 3-2 Research Methodology

CHAPTER 4. RAILWAY ASSET RENEWAL AND MAINTENANCE COST ESTIMATING: CURRENT PRACTICE

In the previous chapter the research objectives and methodology are discussed. The chapter reviewed available research approaches and argues which approach is the most appropriate for this research project. The chapter concludes with a discussion on the issues concerning the chosen approach.

This chapter discusses the use of qualitative techniques, including interviews and process modelling to collect and analyse renewal and maintenance cost estimating process data. Issues identified from analysis of the elicited current renewal and maintenance estimating processes are also presented.

4.1 Chapter Aim

To present the elicited renewal and maintenance project cost estimating processes using a case study approach.

Section 4.2 discuses Process Modelling and introduces the Integration DEFinition language (IDEF) family of process modelling techniques. This section also explains IDEF0 and gives justification on why this technique was selected as an appropriate approach to visually represent the cost estimating processes. A knowledge elicitation methodology used to capture the process knowledge is also presented. Section 4.3. describes the research methodology used to capture of the process knowledge and concludes with a discussion on how the results from the knowledge capture exercise were validated for trustworthiness. Section 4.3.2 presents IDEF0 diagrams and concludes with a discussion on the issues and challenges identified with the current cost estimating process. This section also presents analysis resulting in identification of the most appropriate cost estimating technique at each stage of the cost estimating process. Section 4.4 compares the results to those from the literature review. The chapter then concludes with a summary and some key observations.

4.2 Process Modelling - the Cost Estimating Processes

The author began this research by identifying the need to understand the current cost estimating processes for renewal and maintenance projects within the railway industry. To understand the cost estimating processes a mechanism that would allow the author to visually represent the processes in an appropriate manner was needed. It was decided that process modelling techniques were an appropriate mechanism to fulfil this need.

4.2.1 AS:IS Process Modelling

Oxford (2002) define process as “a series of actions or tasks performed in order to do, make or achieve” and a model is defined as “a simple description of a system, used for explaining, calculating, etc”

The “AS:IS” model is a model of a current system; it describes the system as it is. AS:IS models would be created to evaluate a current system and identify ways to improve it. For example, a system's cost might be identified as an area needing improvement.

There are many techniques that are used for process knowledge elicitation, including structured, semi-structured, and unstructured interviewing. Other techniques include protocol analysis where the expert is observed performing a specific task “thinking aloud” (Adesola *et al.* (2001). Knowledge can fall into three categories, namely declarative, procedural, and tacit. Declarative is explicit knowledge e.g. standard operating procedures or specifications. Procedural is explicit knowledge e.g. business process, and tacit knowledge is implicit knowledge stored in the heads of people.

4.2.1.1 Integration DEFinition language (IDEF)

IDEF are a family of process modelling techniques developed by Knowledge Based Systems. Inc. The family include IDEF0 through to IDEF5.

- IDEF0 – is a function modelling method designed to model the decisions, actions, and activities of an organisation or system.

- IDEF1 – is an information modelling method designed as a method for analysis and communication in the establishment of requirements.

- IDEF1x – is a data modelling method for designing relational databases.

- IDEF3 – is a process description capture method designed to provide a mechanism for collecting and documenting processes.
- IDEF4 – is an object orientated design method designed to assist in the correct application of this technology
- IDEF5 – is an ontology description capture method designed to assist in creating, modifying, and maintaining ontology's.

4.2.1.2 Integration DEFinition language 0 (IDEF0)

IDEF0 Knowledge Based Systems Inc (1993) was selected as the most appropriate technique to model the renewal and maintenance cost estimating processes. The technique was chosen for a number of reasons. Firstly because the author had had previous training on the methodology, because of it was easy available and supported, and because it is widely used and accepted. Also because the output models are easily understood by persons unfamiliar with the underlying methodology.

IDEF0 produces a "function model" which consists of functions, activities or processes that are represented in a structured way. The technique includes a graphical modelling language and a description of a methodology for developing models. The output from the IDEF0 technique is a model that contains a hierarchical series of diagrams, text, and glossary, and that are cross referenced to each other. Functions and data, and objects are the two main components of IDEF0.

The IFEF0 model is represented using a diagram that contains a number of "boxes" and "arrows". Figure 4.1 illustrates the IDEF0 diagram main syntax.

The "box" represents what is happening in the particular function, whereas the "arrows" represent data or objects related to the function in question. The model contains five main types of information, the function name, which is located within the "box", and

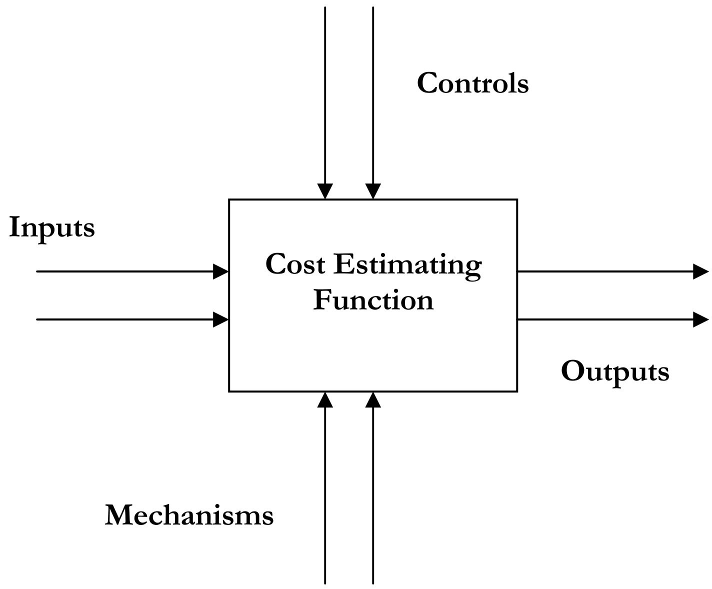


Figure 4-1 Main Syntax of IDEF0 Model

control, input, mechanism, and output information relating to the function in question, as defined below:

- Function – an activity or process that must be accomplished
- Control – conditions required to produce the correct output
- Input – the data or object required by the function
- Mechanism – the means used to perform a function
- Output – the data object produced by the function.

Figure 4.2 provides a simple example of IDEF0. Make a drink is the function in this example. The inputs, objects or data required by the function are sugar, water and teabag; the control information, conditions required to produce the correct output, is 100 degrees C. The mechanisms, the means used to perform the function, are a kettle, cup, and spoon; and finally the output is a hot cup of tea.

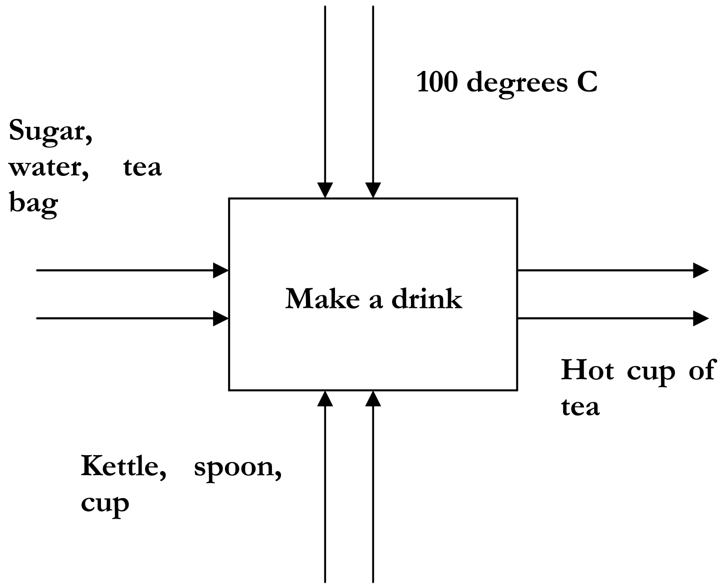


Figure 4-2 Example IDEF0 Diagram

A further important aspect of IDEF0 is the hierarchical series of diagrams that the methodology produces. The methodology presents three types of diagram;

1. A top level context diagram,
2. A child diagram,
3. A parent diagram.

The top level diagram is represented as a single box titled A0. This diagram is used to show the overall focus of the activities, i.e., processes being modelled. The descriptive names at this stage should be general. A child diagram is the top level context diagram decomposed into sub functions.

Each of the sub functions can also be decomposed further. Each sub function provides additional information in the hierarchy. A parent diagram is the functions that are above the child diagram in the hierarchy. However, a child diagram could be a parent diagram to a sub function, and a parent diagram could be a child diagram to a function above it, as shown in Figure 4.3.

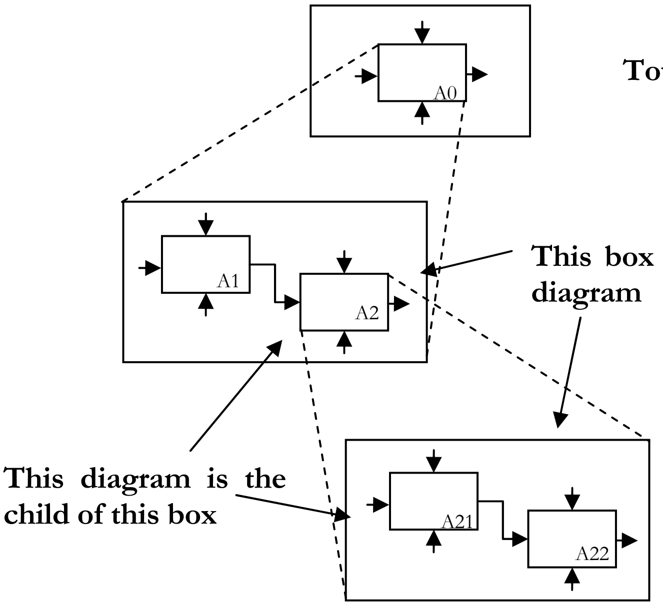


Figure 4-3 IDEF0 Hierarchy Diagram Structure

4.2.1.3 IFEF0 Model Development Process

The author investigated a number of different techniques in order to identify the most appropriate method for elicitation and collection of data enabling the production of the IDEF0 diagrams. These techniques provided a structured process (Roy *et al.* (1999) consisting of questions that were used to elicit the data needed for each of the five main information areas of an IDEF0 model including the function, outputs, inputs, mechanisms, and controls. However, a methodology named Expert Process Knowledge Analysis Tool (XPat) (Adesola *et al.* (2001) was identified as the most appropriate approach in eliciting the required information for production of the IDEF0 models. This was due to the approach provided a high degree of depth in its probing (Adesola (2002) of the subject under analysis.

4.2.1.4 Expert Process Knowledge Analysis Tool (XPat)

Knowledge elicitation can be a challenging exercise and a heavy burden on resources, both in terms of intellectually from the point of view of the expert the knowledge is being elicited from and in terms of time need to complete the activity. XPat (Adesola *et al.* (2001) was developed to address the problem of how to capture tacit process knowledge from a domain expert/s. The approach is divided into the following stages;

1. Pre analysis,

2. Identify the problem,
3. Collect and interpret the knowledge,
4. Analyse knowledge elicited and finally,
5. Design further elicitation techniques.

Stage 1 pre-analysis is concerned with identifying the scope and issues of the project in question. An organisational chart, feasibility study, businesses case and initial project definition are outputs at this stage.

Identify the problem, Stage 2, is concerned with understanding the knowledge intensive task, sources of knowledge, and types of knowledge involved. Stage 3, interpret knowledge, involves interviewing an expert/s using structured techniques. A set of probe questions have been developed for this purpose.

The probe questions have been developed to identify three main categories of process information

1. The inputs to the process, internal and external,
2. The processes themselves
3. The outputs from the processes.

Table 4-1 Probe Questions used to Elicit Input Knowledge

Probe Identity	**Probe Questions**	**Rationale for a probe question**
I1	List all input to the process?	To identify specific inputs to the process in terms of information needs, states, problem and material. To define types of input. To provide support for constructing $IDEF_0$ process model.
I2	Why would you need that input?	To generate rules for input information. IF <condition> THEN <action>
I3	How would you get that input?	To determine acquisition process
I4	How would you use that input?	To generate detail level rule. IF <condition> THEN <action>
I5	What is the source of	To identify sources of input and interactions

	input?	
I6	What is the frequency of input?	To determine the dynamic nature of input (e.g. time relative to input – Hourly, Daily, Weekly, as and when required)
I7	When would you generate this input?	To reveal specific or generic frequency of inputs. To generate a detail level rule specific or generic input. IF <condition> THEN <action>
I8	What is the relationship between inputs and output elements?	To reveal the nature of relationships as either specific or generic.

Table 4.1 presents the probe question used to identify the inputs to the processes. The data collected using the probe questions should be reviewed concurrently with the elicitation process. The outputs at this stage are flip charts and post-it notes as shown in Figure 4.4.

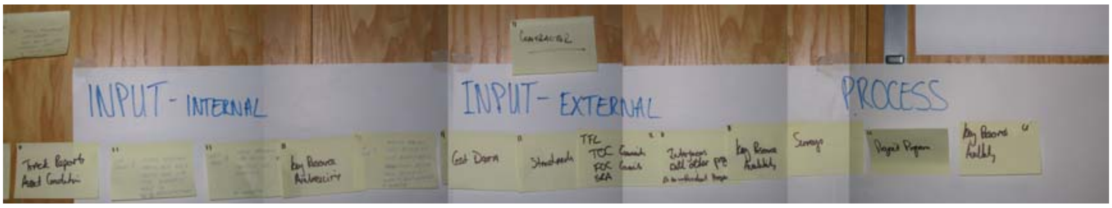


Figure 4-4 Visualization of Data Elicited using Flip Charts & Post-it Notes

Analysis of the data elicited is the aim of Stage 4 and is concerned with how best to structure the knowledge. The inputs, processes, and outputs elicited will be defined

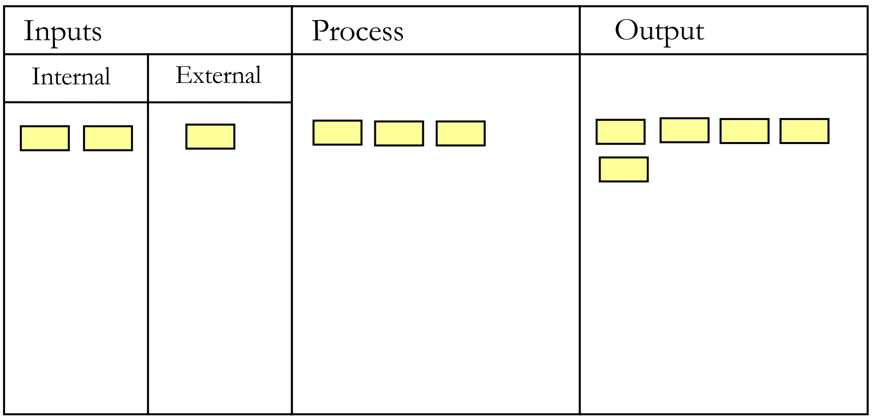


Figure 4-5 Inputs, Output, and Process Knowledge Flipchart and Post-it Note Structure

and structured in a graphical format a shown in Figure 4.5. All inputs, processes, and outputs are linked to one another as appropriate.

The resulting structure is then easily transferable into a set of IDEF0 diagrams. Finally, Stage 5 is concerned with designing further elicitation techniques should, following analysis, more process knowledge be required.

4.3 Research Methodology

This section discusses the research methodology used to collect data needed to construct the renewal and maintenance cost estimating process models.

Table 4.2 presents the sample used to collect primary data needed to develop and validate the process models. The table presents the respondent interviewed, their job position, their cost engineering experience, the reason they were interviewed and the type of interview used. The secondary sources of data collected included internal company documents.

Table 4-2 Primary Data Collection

Respondent	Position	Cost Engineering (CE) Experience	Purpose of Data Collection	Type of interview used
Respondent A	Head of Estimating	Between 10-15 years	Construct process models,	Workshop,
			Validate process models.	Member checking
Respondent B	Cost Estimating Manager	Between 10-15 years	Construct process models,	Workshop,
			Validate process models.	Member checking
Respondent C	Cost Estimating Manager	More then 15 years	Validate process models.	Member checking
Respondent D	Cost Engineering Consultant	5 years	Construct process models,	Workshop
Respondent E	Rail Consultant	N/A	Construct process models,	Workshop

The threat to validity of the data presented in this chapter, including reactivity, researcher bias, and respondent bias is reduced by the use of triangulation and member checking (refer to Chapter 3, Table 4). Multiple sources, including primary and secondary data, and the combined use of data collection techniques, including workshop interviews and document content analysis, are used to construct the process models and provide construct validity. The developed process model have been returned to respondents in order to check the content is correct. This process reduced the risks to validity. Validation of the proposed model employed structured interviews. All interviews were audio taped and transcribed which increases the reliability of the data presented and reduces researcher bias. However, issues with audio taping are that it can inhibit responses or person may not say what they truly think (Robson (2002).

Two four hour workshops were organised with the aim of eliciting renewal and maintenance cost estimating processes. The first workshop was attended by all four renewal and maintenance cost estimation experts, including a consultant from a leading cost estimation software vender, a railway infrastructure renewal and maintenance Cost Estimation Manager, the Head of Railway infrastructure Cost Estimating, and a Railway infrastructure Engineering Consultant. The second workshop was attended by only Respondent B. The author acted as the main facilitator throughout the workshops. Robson (2002) suggests that to facilitate effectively a balance between an active and passive role is required. He argues the facilitator needs to generate interest in the topic of interest without guiding them to a prior hypothesis. Furthermore, the facilitation task can be too large for one person to manage. The author therefore employed the help of an additional facilitator. The second facilitator provided additional guidance and made some notes on who was speaking during the workshops. The first stages of the workshop are the preparation stages. All materials needed, location, and time are to be considered at this stage (Fry *et al.* (2003). The second stage involved the workshop activities. The facilitator introduced himself and all attendees. The aim, the methods that were to be used, and the workshop procedure were then introduced. The time period was then defined, allowing for regular breaks so to reduce loss of concentration (Rush (2003). Attendees were given a work pack (see Appendix 2) that contained all relevant information required for successful completion of the aim. The attendees were asked to complete a simple questionnaire that requested some background information on each attendee, such as name, and job function. XPat, the process to elicit the renewal and maintenance cost estimating processes, was then explained in detail with a practical example. Once all attendees had expressed an understanding of Xpat's procedure, the facilitator started to elicit the cost estimating processes, inputs, controls, outputs, and mechanisms using the probe questions provided by the methodology. The elicited information was then imputed into a software tool named A10 Win 6.2 where the final

IDEF0 diagrams were produced (see Appendix 1 for full IDEF0 diagrams). These diagrams were then used for validation and analysis with a view of improvement. The author also conducted content analysis on company documents which provide additional data.

4.3.1.1 Validation

IDEF0 diagrams were produced once all the data had been elicited to an appropriate level of detail. For the author to have confidence in the trustworthiness of the knowledge elicited the results needed to be validated. Member checking was used for the purpose of validation. Two, two hour interviews were organised with the aim of validating the knowledge contained within the IDEF0 diagrams. The interviewees consisted of two renewal and maintenance Cost Estimating Managers (Respondent B & C) and the author facilitated the interview session. The interview was structured into three main stages. Firstly the facilitator, aims, objectives, and time frames for the interview were introduced. This stage also involved the dissemination of a work pack (see Appendix 3) containing all relevant information, including copies of the IDEF0 diagrams and a structured questionnaire. The second stage was concerned with reviewing the IDEF0 models. The facilitator presented the IDEF0 syntax and then "walked through" the information contained within the diagrams, giving opportunity for questions to clarify misunderstood information from the interviewee. Once the facilitator and the interviewee were happy that the information within the diagrams had been presented sufficiently and was clearly understood, the interviewee was asked to complete the structured questionnaire provided. The interview was audio taped and transcribed.

4.3.2 Findings –Renewal and Maintenance Cost Estimating Processes

The elicited estimating process has a structure consisting of five stages, as illustrated in Figure 4.6. The stages involved, include the Order of Magnitude Estimate, the Budget Estimate, the Feasibility Estimate, and the Definitive Estimate. Both the Order of Magnitude Estimate and the Budget Estimate are ideas that are developed based on a business need, a response to a route strategy or a customer's requirement. The Feasibility estimates are based on clearly defined strategic objectives and a business case. A Definitive estimate is produced when the project reaches the delivery stage. More data becomes available as the estimate moves though the stages to Stage 5 and hence the production of a more realistic estimate can be generated. Decision making is conducted up to the feasibility estimate and is concerned with what is the most cost effective and appropriate method to complete the project based on requirements. Therefore, it is essential to have accurate cost estimates available at these stages.

Figure 4.7 illustrates the estimate production process (Network Rail (2003). This process should be followed for each of the five estimate stages. The process requires inputs from five types of employee, namely the Estimate Originator, the Estimator, the Estimate Manager, the Project Commercial Manager, and the Chief Estimator. Each employee is responsible for a stage/s within the process e.g. the Chief Estimator is responsible for the updating the estimating database whereas the Estimating manager is responsible for the validation of the estimate. The production process contains fourteen main activities. 'Request Estimate' and 'Record Estimate' are the first two activities in the production process. The estimate originator will provide a remit defining the scope of the work to be estimated. They will notify the Estimating Manager and will obtain a unique identification for all reports and documents. 'Define Information Requirements' and 'Ensure Accesses to Information Owners' are the next two activities and are concerned with the Estimating Manager identifying what data is required for the estimate. Also the Estimate Originator should also insure that the Estimator has access to the relevant data. The 'Hold Kick off Meeting' activity is concerned with inviting all appropriate people to discuss the identity of the scope of the estimate and how the estimator will obtain all relevant data. The Estimator should receive and be sent all relevant data at the 'Provide and Receive Information' activity. The 'Identify Resources' and 'Components of Cost' activities are concerned with the quantifying resources and components of cost.

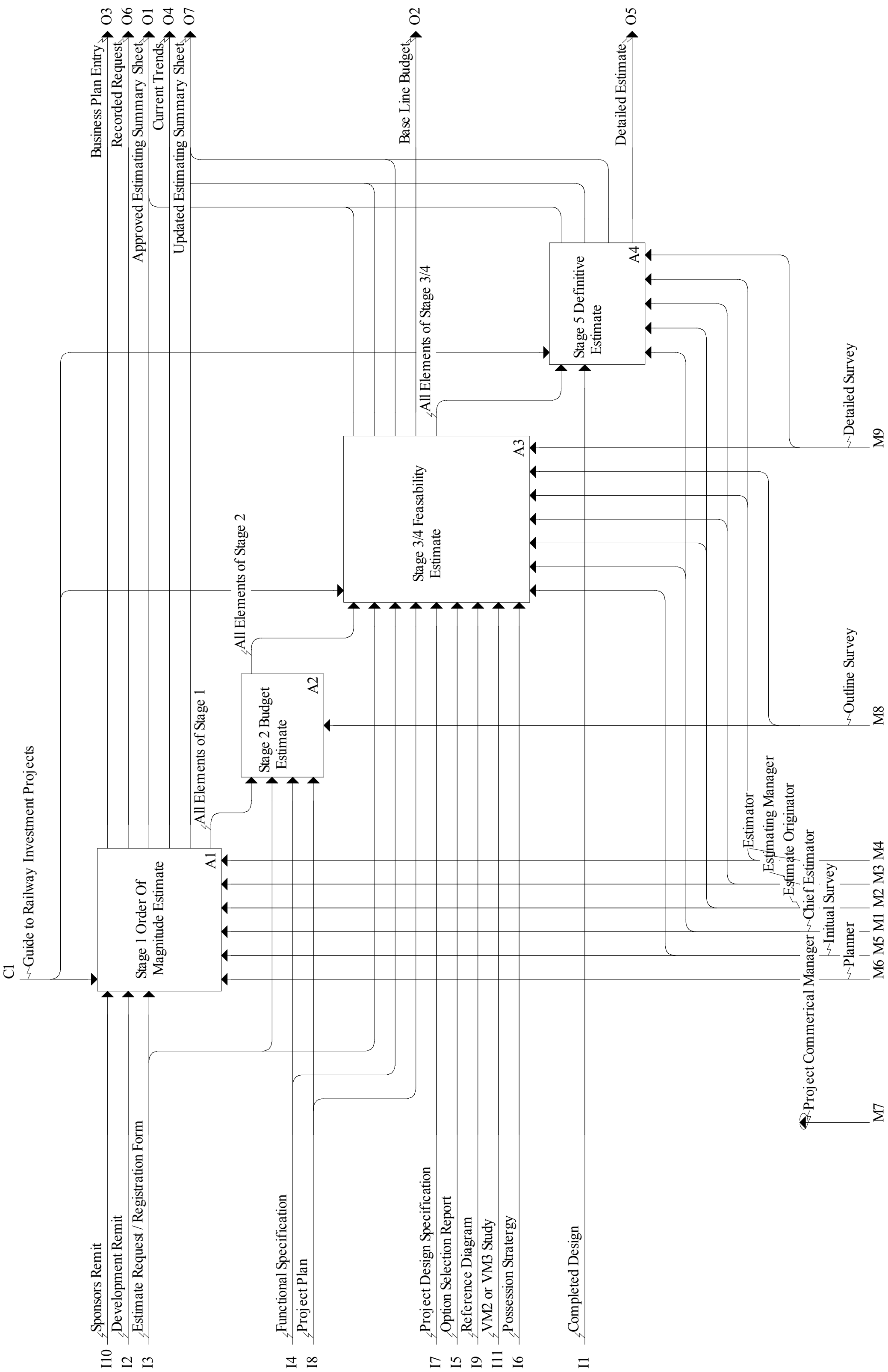


Figure 4-6 Cost Estimate Production Stages

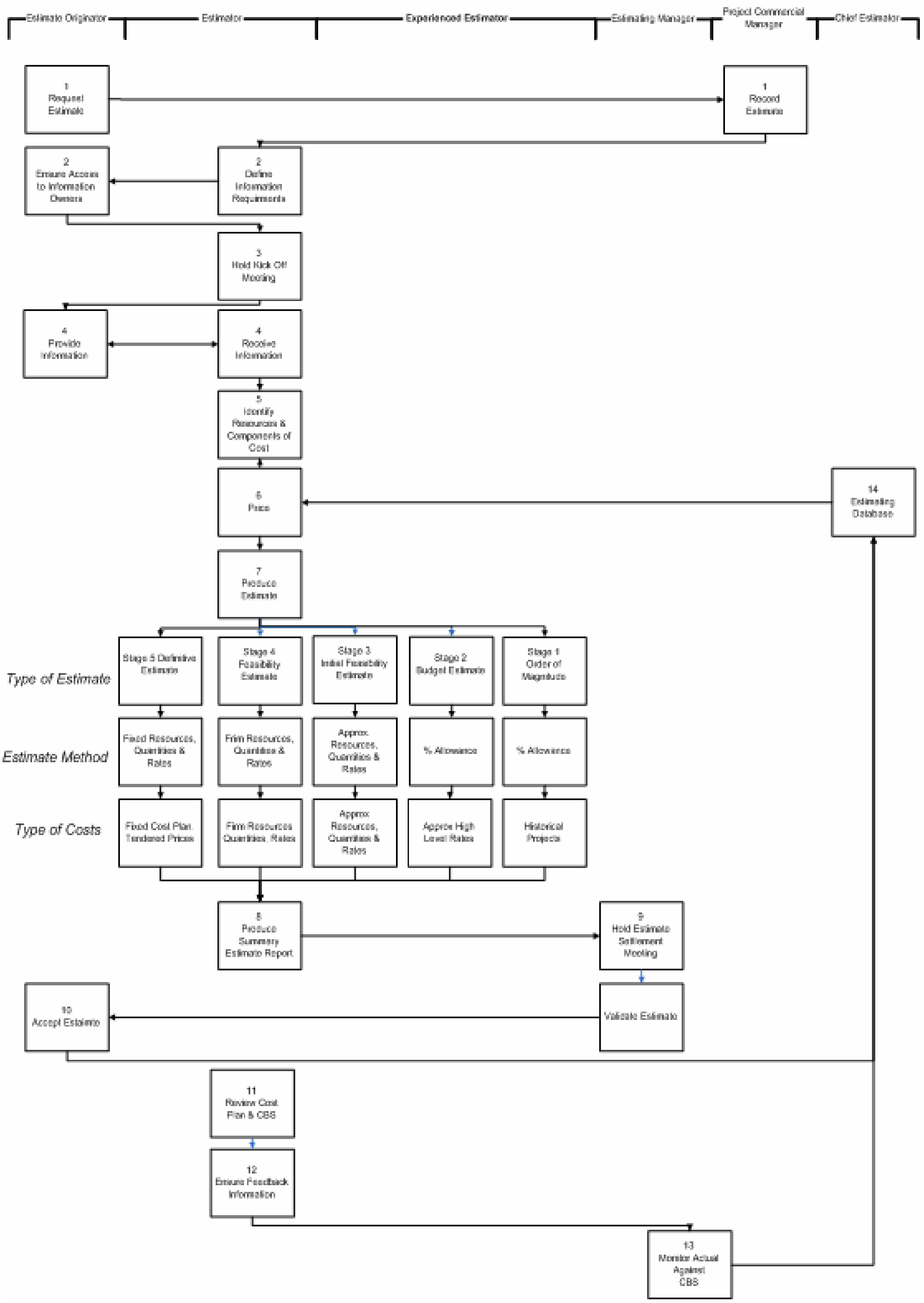


Figure 4-7 Estimate Production Process

All quantities shall be recorded and scheduled to a level of detail appropriate for the stage. ‘Price’ is concerned with identifying the costs of all materials and resources required. The ‘Produce Estimate’ activity also requires a Quantitative Risk Assessment. Once an estimate is produced an estimating summary sheet is also produced. Activity nine, Estimate Settlement Meeting is concerned with reviewing all costs and risk evaluations. The costs and contingencies are also refined to obtain a final cost for the investment authority. The approval by the Estimate Originator is the main aim of activity ten. The ‘Review Cost Breakdown Structure’ activity is concerned with the Estimator ensuring that the ‘Cost Breakdown Structure’ is in a format that allows cost and feedback data thought-out the project stages to project close. The Estimator should apply resources to ensure activity twelve, Ensure Feedback Information. Activity thirteen, ‘Monitor Actual against Cost Breakdown Structure’, is the responsibility of the Project Commercial Manager. Finally the, ‘Estimating Database’ activity, is concerned with holding all estimating information including lessons learned supply chain, and industry trends in the estimating database.

4.3.2.1 Analysis of Cost Estimating Processes

The UK railway industry has recently encountered dramatic changes in which the previously outsourced renewal and maintenance contracts have been returned to in-house, making the infrastructure owner directly responsible for all asset related works. However, due to the restructuring of the industry, accurate cost data for realistic life cycle cost analysis is fragmented and difficult to obtain. Therefore renewal and maintenance estimates have often been based on “best guess” unstructured expert estimates. The following issue has been identified:

- The need for a structured cost estimation methodology

The industrial case has not collected historical cost data. This is due to the maintenance activities being the responsibility of the contactor. Additionally there was previously no requirement for the collection of renewal and maintenance cost data. However, since maintenance has now been brought in-house, there is a need for the collection of this data.

The production of realistic cost estimates at all stages of the project life cycle require historical data to be collected; in order to collect this data there needs to be a structure to collect the data against enabling analysis of project by project costs. The following issue has been identified:

- The need for a Cost Element Structure

The process presented in Figure 4.7 currently has no automation. Validation is required by an expert and novice estimators have a large learning curve when attempting to understand the complexities of the quantities that are required for the renewal and maintenance activities. The following issue has been identified:

- The need for a transparent automated validation methodology.

Until the database is populated fully unstructured best guess is applied at Stage 1 of the estimating process. The expected level of error in the estimate at this stage is 50%. Business decisions are made at the early stages of the project life cycle. The following issue has been identified:

- The need for a cost estimating methodology to decrease the level of error in the estimate at the early stages of the project life cycle.

The process output is currently a point estimate. Due to risks and uncertainties in the estimate it does not accurately represent the possible cost variations. The following issue has been identified:

- The need for an approach which addressed uncertainties and risks in the cost estimates.

In addition to the above analysis, the author also investigated which would be the most appropriate cost model applied at each stage of the cost estimating process. The availability and access to relevant Switch and Crossing experts within the sponsoring company meant that Switch and crossing renewal and maintenance was chosen as an appropriate case study for this analysis. Based on the available data, the current environment, and the context within the company, the author was able to produce a matrix that identifies what cost estimating model is most applicable at each stage in the process as illustrated in Table 4.4.

Table 4-3 Suggested Cost Estimating Model Applied at Different Stages in the Estimating Process

Switch & Crossing Case Study	**Stage 1 Order of Magnitude**	**Stage 2 Budget Estimate**	**Stage 3/4 Feasibility**	**Stage 5 Definitive Estimate**	
Lifecycle Cost Model	X	X	X	x	**Lack of historical data**
Parametric Model	X	X	X	x	**Lack of historical data**
Analogy Model	√	√	X	x	**Have some past projects, sparse data**
Bottom Up Model	X	X	√	√	**Currently done need tools to eliminate expert, speed up process. Lack of data**

The results presented in Table 4.4, show that, due to a lack of historical data within the case study both LCCA and Parametric Cost Analysis are not currently achievable. The current approach used the sponsoring company is a Bottom Up cost estimating technique and is applied at the later stages of the process; This bottom up process hinges on the cost data available in the cost estimating database, however, there is a lack of available cost data. The results indicate that Analogy would be an appropriate method to estimating cost at the early stages, since it can cope with the issue of the availability of limited quantitative data (Sheppard *et al.* (2001).

4.4 Comparison to the Literature Review Findings

Findings from the analysis of the industrial case study have shown that there are issues concerning a lack of historical data to produce cost estimates. Analysis has also shown that current early project life cycle cost estimates are based on unstructured "best guess". The review of literature suggested that a lack of historical data to produce estimates was also a primary concern. Furthermore, the review of literature concluded that there is a need for a structured cost estimating methodology at the early project life cycle stage. Considering this, the findings from the industrial case study support the claims from the review of literature and this increase the justification and need for this research. Table 4.5 presents a comparison of the Literature Review and Industrial Case findings.

Table 4-4 Comparison of Literature and the Industrial Case Study Findings

Literature	Industrial Case
There have been a range of techniques used to estimate renewal and maintenance costs including: equations Muiga *et al.* (1979) Clark *et al.* (2002), bottom up Myers *et al.* (1778), regression analysis Wahby *et al.* (2001), and Life Cycle Cost Analysis Zoeteman, A. *et al.* (1999).	Analogy would be an appropriate method to estimating cost at the early stages as it can cope with the issue limited available quantitative data (Sheppard *et al.* (2001).
Life cycle cost analysis is current 'best practice'.	The need for a structured cost estimation methodology
There is a distinct lack of methodologies that produce renewal and maintenance cost estimates when there is limited or no quantitative cost data available.	Cost data needed is fragmented or incomplete
Literature lacks methodologies that address the problem of estimating renewal and maintenance costs at the early project life cycle stages	The need for a cost estimating methodology to decrease the level of error in the estimate at the early stages of the project life cycle.
Many of the models discussed can only be applied to the situation they were developed for. These models are not generic in nature due to the differences in the problem environment (Wahby *et al.* (2001).	The need for a Cost Element Structure
There is a distinct lack of research within the Railway infrastructure renewal and maintenance cost estimating domain.	The need for a transparent automated validation methodology.
Software effort estimation has similar estimation problems as Railway renewal and maintenance estimation.	Early project life cycle cost estimates are currently based on unstructured best guess
Sheppard *et al.* (2001) propose a framework which addresses problems regarding Software effort estimating. Software effort estimating has similar problems to Railway infrastructure renewal and maintenance estimating. Therefore, the framework may address Railway infrastructure renewal and maintenance estimating problems.	The need for an approach which addressed uncertainties and risks in the cost estimates.

4.5 Summary and Key Observations

In summary, this chapter has presented the current cost estimating processes for renewal and maintenance projects within the sponsoring company using a case study approach. Two four hours workshops were used to elicit the cost estimating process knowledge. Some of the key findings from the analysis of the cost estimating process support the claims of the related literature.

In Section 4.1, 4.2 and 4.3 the author discussed the aim of this chapter. Section 4.4 discusses process modelling with a view of explaining the Integration DEFinition Language (IDEF) family of modelling techniques. The author discusses in particular IDEF0, a function modelling technique, which the author has identified as the most appropriate method to represent the cost estimating processes. The author additionally discusses the justification for the choice of this approach. Expert Process Knowledge Analysis Tool (XPat) is also discussed in this section. XPat was chosen as the most appropriate methodology in the elicitation of the renewal and maintenance cost estimating knowledge. The author presents the methodology and discusses how it was applied in the context of data collection for the production of the IDEF0 diagrams.

In section 4.4.1 the author discusses the methods of data collection used. In this section the author discusses the workshop process used, who attended the workshops and the reasons why this methods were chosen. Furthermore, to show trustworthiness and validly of the results the validation process is also discussed.

Five main issues and needs are identified from the analysis of the cost estimating process they include: (1) the need for a structured cost estimating methodology, (2) due to a lack of cost data at all stages in the project life cycle the need for a cost estimating structure, (3) the need for a transparent automated validation methodology. (4) the modelling of risk is not present in the current process therefore the there is a need for a three point estimating methodology.

Furthermore, the analysis of the cost estimating process suggested that there is an expected level of error of 50% in the cost estimates at the early project life cycle stages. Therefore the following hypothesis is produced.

"A Pair wise comparison technique can be applied to the early project life cycle stages of Railway Infrastructure renewal and maintenance projects and produce cost estimates with a 50% or lower level of error"

The author presents the results of the knowledge elicitation exercise in the form of IDEF0 diagrams in Section 4.5.2. These diagrams were developed using a software tool named A10 WIN 6.2 and were validated during a workshop.

This chapter has discussed the collection and analysis of renewal and maintenance cost estimating processes using a case study approach. The next chapter will discuss the development of an infrastructure renewal cost estimating methodology.

CHAPTER 5. COST MODELLING OF INFRASTRUCTURE RENEWAL AND MAINTENANCE

The previous chapter discussed the collection and production of renewal and maintenance cost estimating processes within an industrial case study, It also presented issues observed from analysis of these processes.

This chapter presents the development details and validation of two costs models, for both railway infrastructure renewal and maintenance. A study aimed at investigating the models applicability to the later stages in the project life cycle then concludes this chapter.

5.1 Chapter Aim

To develop a Railway Infrastructure renewal and maintenance cost estimating methodology using two Switch and Crossing case studies.

In section 5.1 and 5.2, the author discusses the chapter aim, Section 5.3 discusses the development of a switch and crossing renewal model using an industrial case study. Section 5.3.8 discusses the results from a sensitivity analysis and section 5.3.9 presented the results from an empirical validation of the proposed cost model. Section 5.4 then discuses the application of the model to a switch and crossing maintenance case study, investigates maintenance costs and presents the validation results. Section 5.5 explores the cost models applicability to the later stages in the project life cycle. Finally section 5.6 presents the key observations.

5.2 Switch and Crossing Renewal Model Construct – Case Study One

The following sections in this chapter will discuss the data collection, model construct and validation of a cost estimating methodology using a switch and crossing renewal case study.

5.2.1 Research Methodology

Table 5.1 presents the sample used to collect the primary data needed to construct and validate the proposed model. The table presents the Respondent interviewed, their job position, their cost engineering experience, the reason they were interviewed and the type of interview used. Published literature was used as the secondary source of data collection. A snowball sampling strategy was employed (see section 3.7.4)

Table 5-1 Primary Data Collection

Respondent	Position	Cost Engineering (CE) Experience	Purpose of Data Collection	Type of interview used
Respondent B	Switch and Crossing Cost Estimating Manager	Between 10-15 years	Model Construct,	Semi-Structured Interview,
			Validate Project Structure	Member checking
			Project Scenario Development	Structured Questionnaire
			Model Population	Semi Structured Interview
			Usability Validation	Semi structured Interview
Respondent C	Switch and Crossing Cost Estimating Manager	More then 15 years	Usability Validation	Structured Interviews,
			Validate Project Structure	Member checking
Respondent E	Rail Consultant	N/A	Model Construct,	Semi-Structured Interviews,

Triangulation was employed to reduce the treat of reactivity, researcher bias and respondent bias and therefore increase the validity of the project structure developed during this chapter. Different sources of data collection were used to construct the project structure including published and company based literature and also data captured from two experts suggesting that the project structure presented is generic. Once the project structure had been developed Member Checking was employed. The project structure was returned to respondents B and C to check is contents were correct. Results from the usability validation can be seen in Section 6.2.1.

5.2.2 The Developed Approach for Renewal Cost Estimation

The motivation for choosing Switch and Crossing as the case study was due to the availability and access to industrial experts with knowledge of this particular type of asset. Considering the research gap and the research aim a model was developed using this asset. The following section discusses the construct of this model.

5.2.3 Switch and Crossing Renewal Process

In order to understand the case study domain an investigation into switch and crossings was undertaken. The high number of components within a switch and crossing unit make them prone to failure. High loading from trains and, in some cases, poor maintenance and previous renewal work can also lead to the need for S&C renewal action to take place.

The layout of a crossing contains a point rail, a splice rail, two wing rails, and two checkrails as shown in Figure 5.1. All S&C layouts contain one or more switches, an acute or common crossing which permits wheels to cross another running rail, and occasionally an obtuse crossing which permits wheels to cross another running rail and occur where one track crosses another without there being a connection between the two (Cope and Ellis (2002).

Switch and crossings are the components that allow a train to be directed from one track to another; they come in a range of designs and types, including turnouts, crossovers, double junctions, diamond, three throw, tandem, and four throw. Figure 5.2 illustrates a turnout, crossover, double junction, and cross section through a switch and crossing installation.

The process of renewing a switch and crossing unit consists of three main stages. The first is to lift out the Switch & Crossing, and can be broken further into three main areas; lift out the Switch & Crossing, and stack at the access in one unit, lift out the old Switch & Crossing in fragmented parts, and lift out the Switch & Crossing in individual components. The next stage is to position and install the new S&C, which is also broken into three sub levels: position and install in one unit, position and install in fragmented parts, and position and install in components. Finally, the generic work process, which all projects will include, contains activities ranging from disconnecting and removing signalling and telecoms to giving up the possession. Figure 5.3 provides an overview of the switch and crossing renewal process.

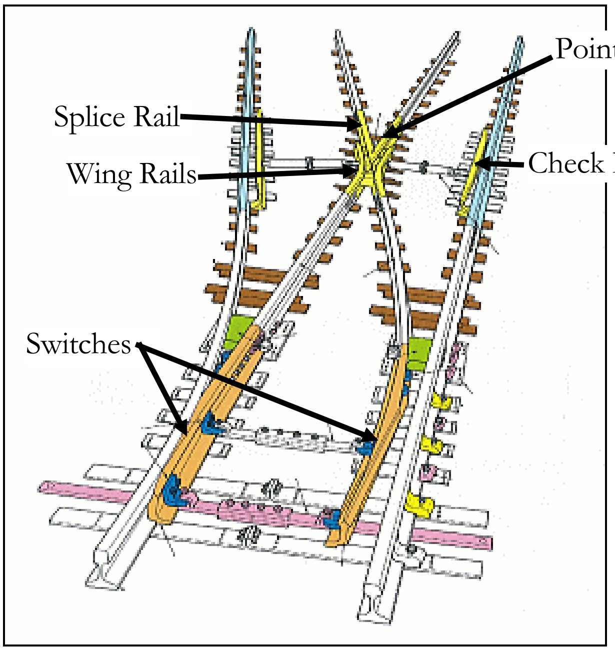
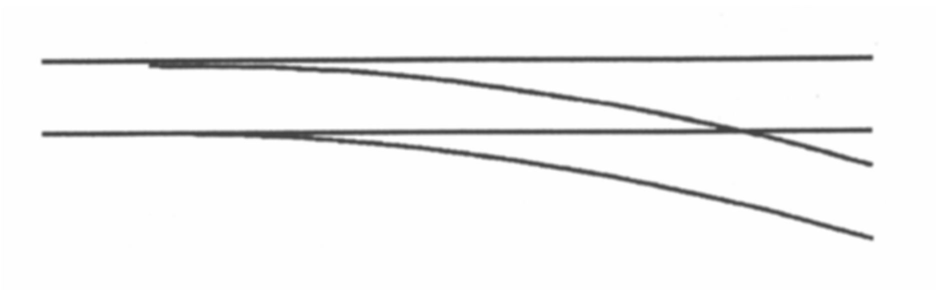
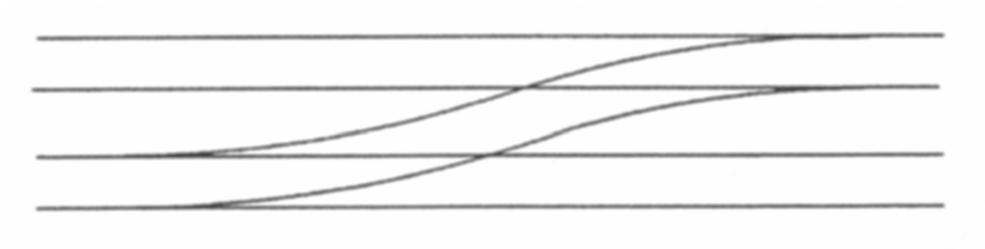


Figure 5-1 Layout of a Crossing



(a)



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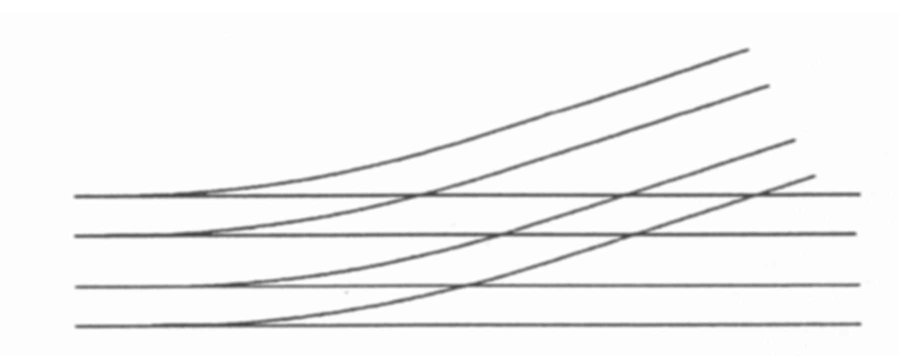

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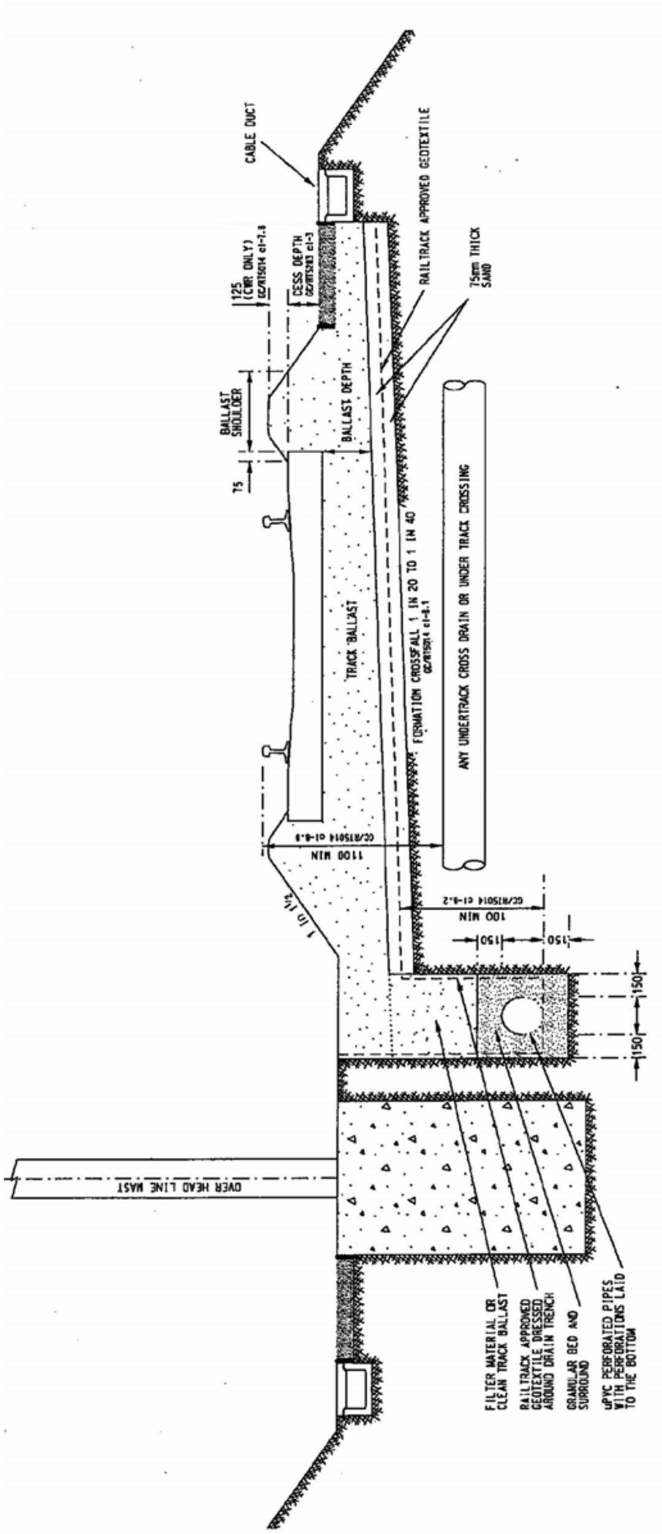


(d)

Figure 5-2 (a) Turnout, (b) Crossover, (c) Double Junction, (d) Typical Cross section through a Switch and Crossing Installation

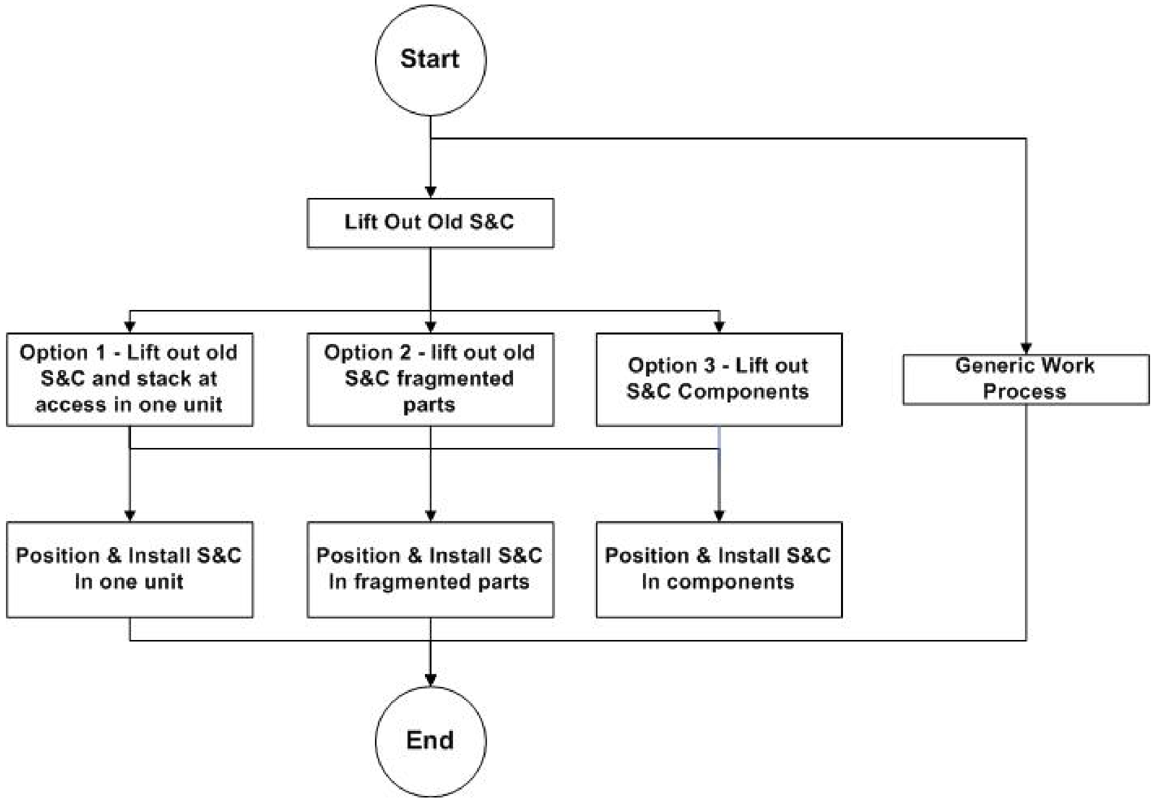


Figure 5-3 Switch and Crossing Renewal Process

5.2.4 The Proposed Cost Estimating Approach

An early cost estimating approach for Railway renewal projects has been developed. A model has been developed based on ideas from Saaty's Analytic Hierarchy Process (Saaty (1990). The approach developed by Saaty, which is discussed in detail by Bhushan and Rai Bhushan, N. *et al.* (2004), draws on subjective judgements and experience of experts who compare alternative project elements with one another and award them a score of importance to the project criteria. The model consists of creating a structure of cost drivers, which are then compared with one another within a matrix and given a score from a ratio scale (Saaty (1990)**.** For each alternative, a weighting is then produced. Finally a cost estimate is produced by applying an algorithmic technique suggested by Sheppard and Cartwright Sheppard *et al.* (2001) which incorporates the produced weighting and one alternatives "known cost"**.** They suggest an approach which aims to predict software effort. Software effort estimation is concerned with predicting the total project effort for the development of software; usually in person-hours.

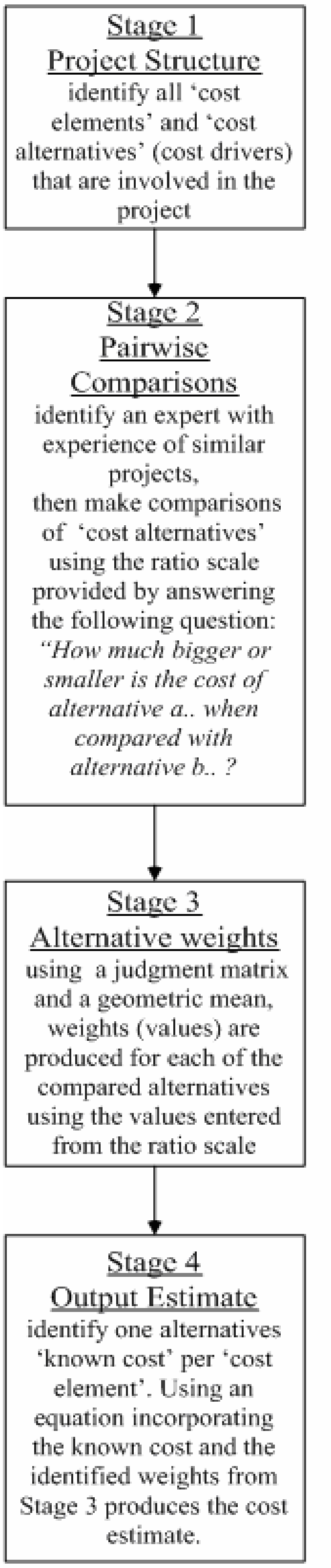


Figure 5-4 Four Main Stages Underlying the Proposed Methodology

It has been observed that software development projects have similar problems of little or no quantitative data for estimation as do Railway infrastructure renewal projects. Therefore, the approach might address Railway infrastructure renewal estimating problems. Possible project alternatives for each criterion are compared not whole projects as suggested by Sheppard and Cartwright and a range estimation technique is introduced. The methodology underlying the model is composed of four stages, namely project structure, pairwise comparisons, alternative weights and the output estimate as shown in Figure 5.4. Detailed descriptions of each stage in the methodology are set out in the following sections.

5.2.5 Project Structure

The main aim at this stage is to produce a structure that describes all cost drivers involved in any Switch and Crossing renewal project. Seven main high level Switch and Crossing cost drivers were identified including Access, Possession, Survey, Site Restrictions, Track Output, Logistics and Work Process.

Literature was firstly studied and cost drivers were identified. During a 2 hour interview with Respondent B and E, the main areas of switch and crossing cost knowledge were identified using a semi structured interview approach. The author asked the respondents to review the cost drivers identified from literature and then to write down on post-it notes any other Switch and Crossing cost drivers they felt were missing. All cost drivers were then grouped into a hierarchy around the seven main high level drivers using brown paper. The results can be seen in Figure 5.5.

Figure 5.5 describes the project structure suggested by the Analytic Hierarchy Process Bhushan, N. *et al.* (2004), which is populated with switch and crossing renewal cost driver data collected during the semi structured interviews.

The structure is similar to a work breakdown structure. The top level of the structure deals with the goal, which concerns estimating the costs of the switch and crossing renewal project. Access, surveys, possession, site restrictions, track outputs, work process, and logistics are the next level in the structure. These are the project ‘Criteria’, which are the key, main high level cost drivers for an S&C renewal project. The ‘Alternatives’ under each criterion are the final levels in the structure. A combination of

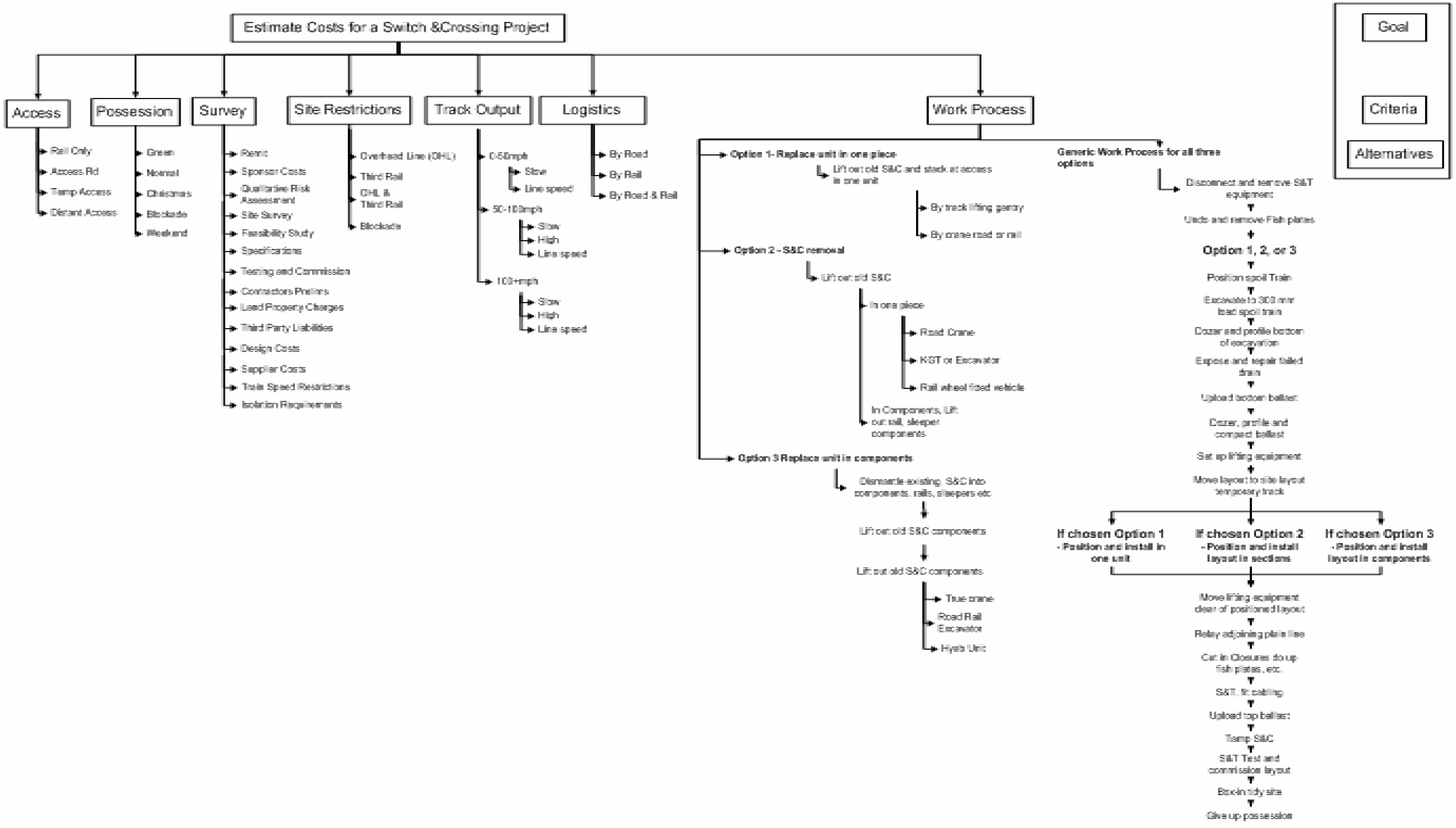


Figure 5-5 Project Structure Populated with Switch and Crossing Cost Driver Data

'Criteria', a selection of Survey 'Alternatives' and one 'Alternative' from the remanding criterion would total a switch and crossing project.

Figure 5.5 presents the four access options within a switch and crossing project including: access to the renewal site, by rail, access road, with a temp access or with a distant access. The possession options are also presented and include; green, normal, Christmas or blockade possession. A possession is a renewal and maintenance window within the train operation schedule. These are pre booked with the train operating companies and are normally done during the night. The whole rail line could be un-operational or only one line could be un-operational during the possession. Items that are required for a survey are presented and include development of a remit, the sponsor costs, a qualitative risk assessment, site survey, specifications, testing and commission, contractors prelims, land property charges, third party liabilities, design costs, supplier costs, train speed restrictions and isolation requirements. The site restriction options are presented they include the use of overhead line or there is a third electrified rail in use. The logistics of material, personal, include by road, by rail or by both road and rail. Finally the work process is presented. The work process contains three options. Option 1 is to replace and position the switch and Crossing in one unit using either a track lifting gantry or road or rail crane, Option 2 is concerned with removing the switch and crossing, either in one piece by road crane, KGT excavator or Excavator or a Rail wheel fitted vehicle, or to lift out the rail, sleeper and components separately. Then the unit would be replaced in sections. Option 3 is concerned with removing the unit in components, either by true crane, road rail excavator or hyab unit. The installation of the unit would also be done in components. A generic work process is also presented. This process would be followed for all the three options and includes: disconnecting and removing the Signalling and telecoms equipment, undo and remove fishplates, one of the three renewal options is then chosen, then position the spoil train, excavate to 300mm and load spoil train, dozer and profile bottom of excavation, expose and repair failed drain, upload bottom ballast, dozer profile and compact ballast, set up lifting equipment, move new layout to temporary track, position and install new switch and crossing depending on what option was used to remove the unit, remove temporary track if applicable, move lifting equipment clear of positioned layout, relay adjoining plain line track, cut in closures and do up fish plates etc, fit cabling and reconnect signalling and telecoms, upload top ballast, tamp switch and crossing, signalling and telecoms test and commission layout, box in tidy site, and finally give up the possession.

5.2.6 Pairwise Comparisons

Identification of an expert with experience of switch and crossing estimating projects should be done prior to the use of this methodology. It is their tacit domain knowledge (Nonaka and Konno (1998) that is required as the input data to the methodology. They are the users of the cost estimating methodology.

This stage involves collecting pairwise comparison data from a Switch and Crossing expert. Comparisons are made between the alternatives under each criterion as shown in Figure 5.5. Each alternative is compared against all other alternatives under the specific criteria e.g. access and awarded a score using the relative value and reciprocal shown in Table 5.2. The scores are based on the experience and judgements of similar past switch and crossing renewal projects that the expert has been involved in. Based on the experts answer to the following question they enter a value from the ratio scale presented in Table 5.2.

"Considering the context of the new project to be estimated, based on your experience of estimating switch and crossing renewal projects. How much bigger or smaller is the cost of alternative e.g. rail when compared with other alternatives e.g. access road?"

Range-estimating techniques have been introduced into the matrix. Rather than, provide a single point judgement the expert is asked to provide the minimal, most likely and the maximum score for each comparison. This provides a spread of the likely cost and hence a more realistic estimate. The pairwise comparison data is then used to populate a square matrix for each criterion.

Table 5-2 Verbal Scale (Saaty (1990)

Definition	Explanation	Relative Value	Reciprocal
Equal size	The two entitles are roughly the same size	1	1
Slightly Bigger	One entity is being bigger	3	.33
Bigger	One entity is definitely bigger	5	.2
Much Bigger	Very strong difference in size	7	.14
Extremely Bigger	The difference between entity is of an order of magnitude	9	.11

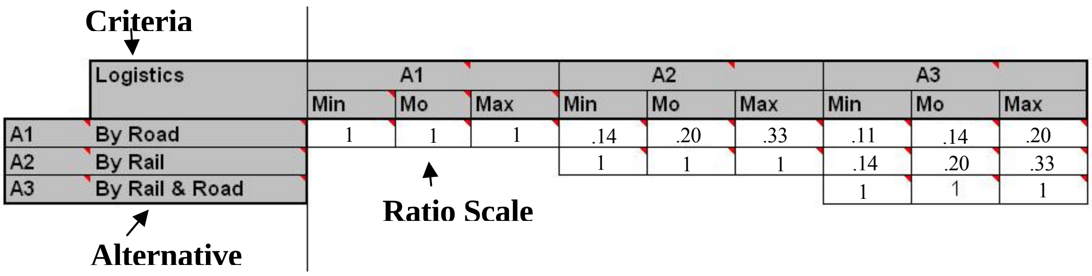


Figure 5-6 Logistics Criteria Square Matrix

Figure 5.6 illustrates the logistic criterion square matrix populated with pairwise comparison data concerning the minimum, mostly likely and maximum values for each alternative. The figure illustrates a square matrix containing all the alternatives for the logistics criteria, by road, by rail and by road and rail. Each alternative is compared against the other and a value from Table 5.3 is entered into the matrix based on the expert's tacit knowledge of estimating switch and crossing renewal projects. For example, in Figure 5.6, by road (A1) alternative is compared against itself, judged to be of equal size and is given a minimum, most likely and max value of one. By road alternative is compared with by rail (A2) and is judged to be most likely smaller hence the value 0.2 is awarded. However, this comparison has been judged to possibly be slightly smaller hence the minimum value of .14 and possibly bigger hence the max value .33. Finally, by road alternative is compared with by road and rail (A3) and is much smaller hence, the most likely value .14 is assigned. Again using the three point estimating feature the comparison has been judged to have a minimum value of 0.11, extremely smaller, and a max value of .20, slightly bigger. This process is carried out until all alternatives have been compared against one another and minimum, most likely and maximum values have been entered. The process of entering the value is relatively easy however it can be time consuming especially when a large project is being estimated because of the amount of comparison that need to be made. However a prototype system using implementing the proposed methodology, as discussed in Chapter 6, can reuse comparisons which will greatly speed up the process.

5.2.7 Alternative weightings

Producing the weightings for each alternative based on the pairwise comparison data produced by the expert is the focus of this stage. Judgement matrices for long term planning is discussed by Williams and Crawford (1980). They propose the use of a normalised geometric mean to produce the weightings for the alternatives. Moreover, the following equations are used in the developed model to produce the weight contribution to the criteria:

1. Calculate the geometric mean of the alternatives

Equation 5-1

$$v_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$$

where

v_i Geometric mean

a_{ij} Judgements

n Size of judgement matrix

2. Normalise the geometric means

Equation 5-2

$$r_i = \frac{v_i}{\sum_{l=1}^{n} v_l}$$

where

r_i Ratio scale

Additionally Saaty suggests a means of producing the weights for the alternatives based on the pairwise comparisons. His approach is to use an "eigenvector" technique. However, this technique is prone to the problem of rank reversal (Triantaphyllou (2001). Rank reversal is a situation where the order of preference is, for example, A, B, C then D. But if C is eliminated, the order of A and B could be reversed so that the resulting priority is then B, A, then D. Therefore, the geometric mean has been chosen as the appropriate method. Besides, it is the simpler of the two methods to implement and understand.

5.2.8 Output Estimate

Once the geometric means are produced for each alternative this stage is concerned with using the means within an equation to generate the cost estimate. Prior to this stage a known cost for one alternative per criteria must be identified. The following equation was developed by Sheppard and Cartwright (2001) to calculate the size of the alternatives:

Equation 5-3

$$C_e\, i = \left[K_c * \frac{r_i}{r_c} \right]$$

where

$C_e\, i$ Cost estimate of alternative i

K_c Known cost of alternative

r_i Ratio scale of alternative i

r_c Ratio scale of K_c

Given a reference cost (known cost) K_c , the expression $C_e\, i = K_c * (r_i / r_c)$ is used to calculate the cost of alternatives.

The selection of an alternative with a known cost is very important. The alternative with a cost that leans towards the extreme ends of the scale should be avoided as this can increase the bias that may affect the judgements. Therefore it is better to choose an alternative that has a cost that is approximately in the middle of all the alternative costs within that criteria (Miranda (2000)). Based on the methodology presented a prototype system is developed. A description of the prototype system is discussed in Chapter 6.

5.2.9 Users of the Proposed Methodology

The methodology can only be used by experienced experts who have cost estimating knowledge of the domain being estimated. These may include Managers, Engineers and Cost Estimators. As previously discussed it is their experience and knowledge that is captured in a structured way which produces the cost estimate.

5.2.10 Sensitivity Analysis

A Monte Carlo and Sensitivity analysis were carried out on a project scenario namely, Doncaster South Yorkshire Junction (see Table 5.4) using Crystal Ball software. The aim of performing the spreadsheet simulations was to investigate the uncertainty of the pair wise comparison scores and identify the certainty of a cost estimate for each alternative within a range of possible cost outputs. The sensitivity analysis would identify what were the important pair wise comparisons within the model and how much they affect the resulting estimate.

Figure 5.7 illustrates the characteristics of the forecasted alternative 0-50 line speed using a Monte Carlo simulation.

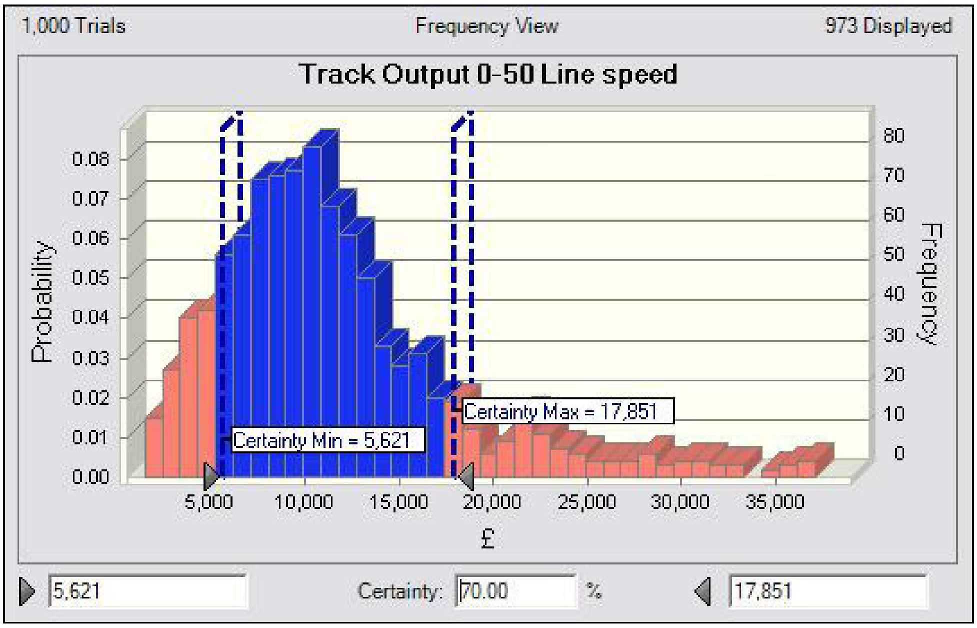


Figure 5-7 Track Output Criteria Monte Carlo Analysis

The graph displays a range of costs and the corresponding certainty of a cost within that range. The results from the simulation suggest that the alternative 'Track Output 0-50 Line Speed' when populated by an S&C expert with pair wise comparison scores would fall within a cost range of between £5,621 and £17,851 with a certainty of 70%. Results for all the alternatives in the Doncaster South Yorkshire Junction scenario can be found in Appendix 4. This information is useful because it suggests the certainty of the estimate falling within the spread of costs while dealing with the uncertainty in the ratio scores populated by the S&C expert.

Finally, a sensitivity analysis was performed for each alternative in the Doncaster South Yorkshire Junction scenario. Figure 5.8 displays the results from the Overhead line alternative under the site restriction criteria. The graph also illustrates the pairwise comparison between alternatives third rail and Overhead Line (OHL) to be the most sensitive and accounts for approx -17.2% of the variance in the cost estimate, meaning that this comparison could vary the resulting estimate by reducing it by 17.2%. Therefore, it can be considered as the most important comparison within the Site Restriction criteria. Additionally the graph displays the least sensitive pairwise comparisons. However, the results indicate the sensitivity of all the comparisons are similar, suggesting that care should be taken for all the comparison.

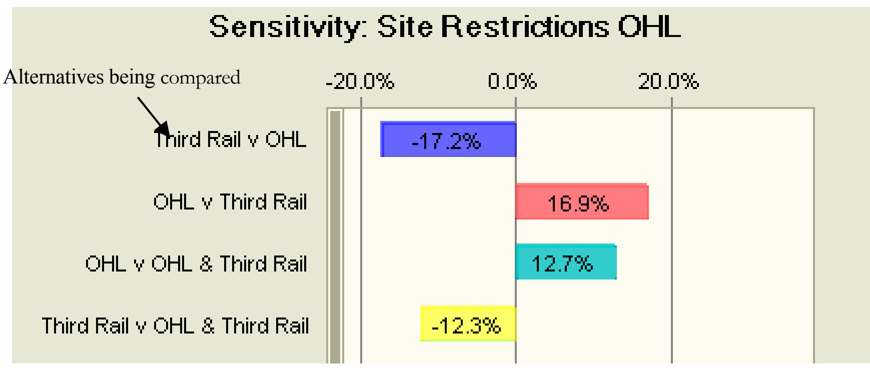


Figure 5-8 Site Restriction Overhead Line Sensitive Analysis

5.2.11 Empirical Validation of the Developed Model

In order to successfully validate the developed model, five historical switch and crossing renewal project data sets were employed. The project scenarios ranged in the location of the work, the number of units used, price of the project, the work process, and access and possession constraints, as shown in Table 5.3.

The project scenarios were incomplete in their description of the work done. Therefore, a structured questionnaire was developed and a switch and crossing estimating Manager was interviewed. The questionnaire identified the criteria involved in each of the project scenarios and can be seen in Appendix 5. Figure 5.9 illustrates the validation process. Estimates produced by the methodology are compared with a consultant’s estimate and the real project costs.

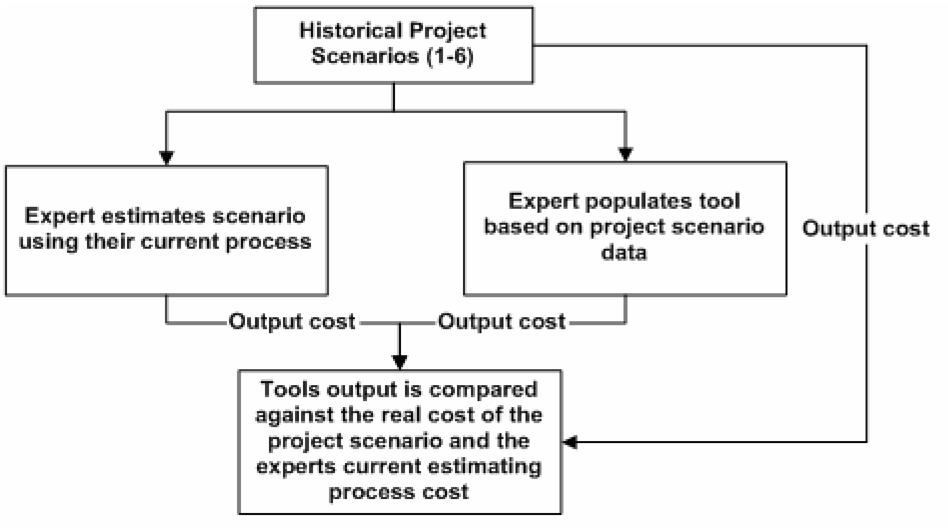


Figure 5-9 Validation Process

Table 5.3 presents the five project scenarios used to validate the model. They include a project scenario located in Gainsborough, were one N0.C11 crossover, RT60 was renewed. The project involved a detailed survey; a temporary access to the site was also constructed. The possession window arranged was at the weekend, there were no site restrictions, the speed requirements of the track after the renewal was 0-50 mph slow and the old S&C was lifted out the new one installed in one piece using a KGT excavator and a rail road excavator.

Table 5-3 Project Scenarios

Location	Units	Survey	Access	Possession	Site Restriction	Output	Work Process
Gainsborough	1 No.C11 crossover, RT60	Detailed	Temp Access	Normal (Weekend)		0-50 slow	Life out One Piece KGT Excavator,Road Rail Excavator
Hatfield South	1No., Gvs28 crossover, RT60	Detailed	Temp Access	Normal (Weekend)	Over Head Line	50-100 Slow	Track Lifting Gear
Stoke summit	2 No.E17.25 crossovers,2 No.G26.75 turnouts	Detailed	Distant Access	Normal (Weekend)	Over Head Line	50-100 Slow	Track Lifting Gear
Welwyn G City	8No.D13.5 crossovers, 1 No.E17.25 crossover,2 No.D12.5 turnouts, 2 No. C11 turnouts	Detailed	Temp Access	Christmas	Over Head Line	50-100 Slow	Track Lifting Gear, Road Crane
Doncaster South Yorkshire Jct	3 No. Cvs9.25 crossovers, 4 No. Cvs9.25 turnouts, 1 No.Bv trap	Detailed	Temp Access	Christmas	Over Head Line	0-50 Line speed	Track Lifting Gear, Road Crane

The second scenario was located at Hatfield South and involved the renewal of one No.Gvs crossover, RT60. A detailed survey was conducted, a temporary access was constructed, the work was done during a weekend possession, there were overhead lines restricting the site, the track output once the work was complete was 50-100 mph slow and track lifting gear was used to remove and install the crossover.

Stoke summit was the location of the third project scenario. This scenario involved the renewal of two E17.25 crossovers and two G26.75 turnouts. A detailed survey was conducted, access to the site was over a large distance and the possession window was at the weekend. Additionally, the site had over head lines and the requirements of the track, after the work was done, was to be operational at 50-100mph slow. Track lifting gear was also used for removal and installation of the units. The fourth scenario was located in Welwyn garden city were eight D13.5 crossovers, one E17.25 crossover, two

D12.5 turnouts and two C11 turnouts were renewed. A detailed survey was conducted, temporary access to the site was constructed, the possession window was at Christmas, and an overhead line was restricting the site. The track outputs were 50-100mph slow and track lifting gear and a road crane were used.

The final scenario was located in Doncaster South Yorkshire were three CVs9.25 crossovers, four CVs9.25 turnouts and one BVtrap were renewed. Again a detailed survey was conducted and a temporary access constructed. The possession was done over the Christmas period. The project involved a site restriction of overhead lines and the track output requirements were 0-50 line speed. Similarly to scenario four track lifting gear and a road crane were used to remove and install the units.

Data collection was conducted during an expert attended workshop. Renewal cost estimate experts populated and assessed a prototype system. The prototype system named 'COMpairCOST', was developed based on the methodology discussed in this chapter and was implemented using Microsoft Excel. The prototype is discussed in more detail in Chapter 6. A Switch and Crossing cost estimation expert were asked to populate the prototype based on the five project scenarios. Due to time restrictions only the most likely costs were populated. The workshop involved a short presentation (approx 15mins) from the author who introduced the aims of the workshop and gave an overview of the prototype software system and how to use it. Respondents B was then shown the project scenarios one by one and asked to populate the square matrixes with ratio scores considering the context of the scenarios. The respondent was given two hours to complete this task. Table 5.4 presents the Survey criteria square matrix populated with ratio scores by respondent B. The full set of square matrixes for each project scenario can be seen in Appendix 8. Due to a lack of available data the alternative of 'know cost' was difficult to identify from historical data therefore Respondents B and C were asked to give a subjective estimate. The average from both respondents' estimates was then used at the 'known cost'.

Prior to the workshop, a switch and crossing renewal estimation consultant estimated the five project scenarios based on their current method of estimation which was a

Table 5-4 Ratio Score Results for Survey Criteria

Cost	Survey																																							
			A1			A2			A3			A4			A5			A6			A7			A8			A9			A10			A11			A12			A13	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Remit		1.00			1.00			0.50			0.14			0.20			0.20						0.11			0.11									1.00				
A2	Sponsor Costs		1.00			1.00			1.00			5.00			0.50			0.20						0.11			0.20									1.00				
A3	QRA		2.00			1.00			1.00			1.00			2.00			0.50						0.14			0.25									5.00				
A4	Site Surveys		7.00			0.20			1.00			1.00			2.00			1.00						0.25			0.25									5.00				
A5	Feasibility Surveys		5.00			2.00			0.50			0.50			1.00			0.50						0.14			0.14									3.00				
A6	Specifications		5.00			5.00			2.00			1.00			2.00			1.00						0.25			0.33									3.00				
A7	Testing and Commission																																							
A8	Contractors Preliminaries		9.00			9.00			7.00			4.00			7.00			4.00						1.00			1.00									9.00				
A9	Design Costs		9.00			5.00			4.00			4.00			7.00			3.00						1.00			1.00									9.00				
A10	Supplier Costs																																							
A11	TSR/PSR Costs																																							
A12	Isolation Costs		1.00			1.00			0.20			0.20			0.33			0.33						0.11			0.11									1.00				
A13	TWA Costs																																							

Table 5-5 Cost Estimate Results from Methodology, Consultants Estaimtes and Real Project Price

			Units	Survey	Access	Possession	Site Restriction	Output	Work Process	Total Cost £
Senario 1	Gainsborough		1 No.C11 crossover, RT60	Detailed	Temp Access	Normal (Weekend)		0-50 slow	Life out One Piece KGT Excavator,Road Rail Excavator	
		Real Price	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1,681,704
		COMpairCost	107,240	171,864	5,000	1,000,000	N/A	10,000	286,398	1,580,502
		Consultant	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1,212,105
Senario 2	Hatfield South		1No., Gvs28 crossover, RT60	Detailed	Temp Access	Normal (Weekend)	Over Head Line	50-100 Slow	Track Lifting Gear	
		Real Price	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2,555,615
		COMpairCost	211,450	161,592	5,000	2,500,000	53,633	10,000	328,121	3,269,796
		Consultant	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1,531,188
Senario 3	Stoke summit		2 No.E17.25 crossovers,2 No.G26.75 turnouts	Detailed	Distant Access	Normal (Weekend)	Over Head Line	50-100 Slow	Track Lifting Gear	
		Real Price	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3,512,968
		COMpairCost	605,440	161,592	1,094	2,500,000	17,878	10,000	328,121	3,624,125
		Consultant	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3,552,678
Senario 4	Welwyn G City		8No.D13.5 crossovers, 1 No.E17.25 crossover,2 No.D12.5 turnouts, 2 No. C11 turnouts	Detailed	Temp Access	Christmas	Over Head Line	50-100 Slow	Track Lifting Gear, Road Crane	
		Real Price	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10,569,911
		COMpairCost	1,329,570	161,592	5,000	4,204,482	196,655	10,000	328,121	6,235,240
		Consultant	N/A	N/A	N/A	N/A	N/A	N/A	N/A	8,331,306
Senario 5	Doncaster South Yorkshire Jct		3 No. Cvs9.25 crossovers, 4 No. Cvs9.25 turnouts, 1 No.Bv trap	Detailed	Temp Access	Christmas	Over Head Line	0-50 Line speed	Track Lifting Gear, Road Crane	
		Real Price	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3,860,213
		COMpairCost	370,710	175,618	5,000	2,378,414	196,655	5,000	311,455	3,442,851
		Consultant	N/A	N/A	N/A	N/A	N/A	N/A	N/A	4,434,187

percentage allowance approach. The percentage allowance approach involves assigning a percentage value to items relating to the project including Design, Preliminaries, Testing and Commission, Possession Management, Management costs, Sponsor Cost, TOC Compensation (possession overruns) and, Land property purchase. These items would be broken down in to percentages of the total cost. A historical project is then used as a reference for one of the items. The output from the tool, the consultants estimate and the real project cost were then all compared. Table 5.5 presents a matrix containing the cost estimates produced by the methodology grouped under the project 'criteria'. Please refer to Table 5.4 for full scenario and criteria information. The matrix also presents the total cost estimate produced by the consultant and the real scenario prices. Due to data issues a breakdown of the consultant's estimates into the project criteria was not possible. The results indicate that the units (material) and possessions contribute a higher proportion of cost suggesting they are the main cost drivers in renewal projects. The remaining costs for each criterion across the five scenarios do not seem to vary greatly. Figure 5.10 illustrates the estimate results based on the five scenarios using the process, the S&C renewal consultant's technique and the real project costs. Figure 5.11 illustrates the estimate results as a percentage error.

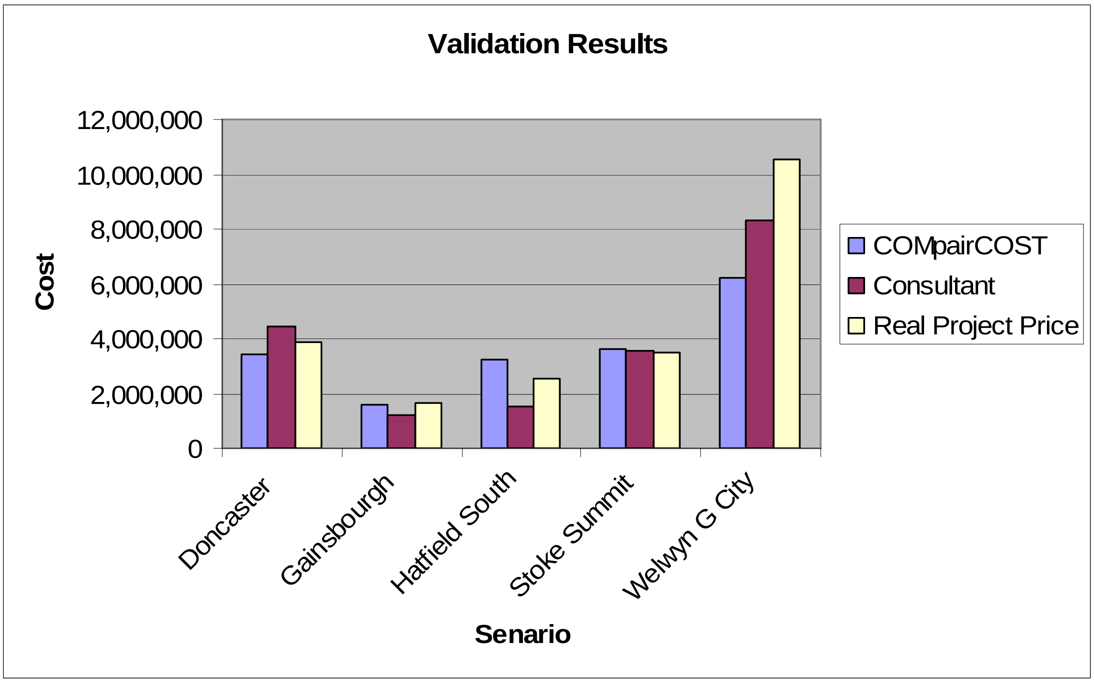


Figure 5-10 Renewal Cost Estimate Results

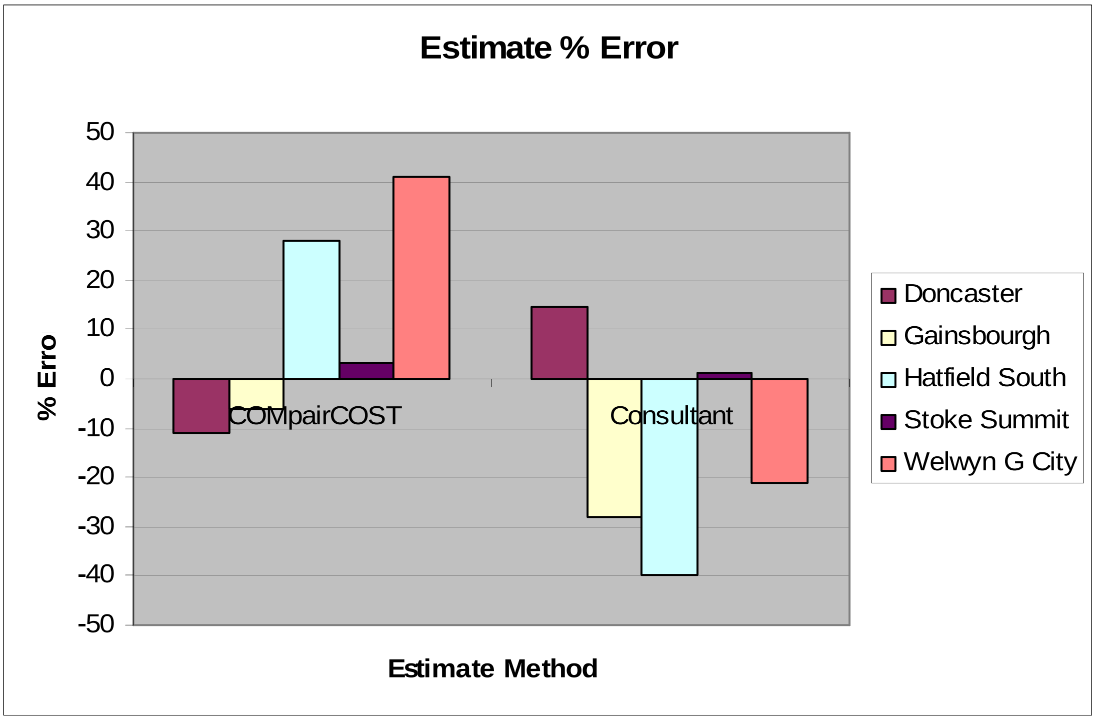


Figure 5-11 Renewal Cost Estimate Percentage Error against Real Project Price

Figure 5.11 illustrates that on most occasions the consultants estimates were underestimated whereas the estimates produced by the methodology were over estimated. The possible reasons why these estimates were underestimates is discussed in Section 6.5.1.

The results presented in Table 5.6 suggest that three of the scenarios estimates by COMpairCost were more accurate than the cost estimates produced by the consultants. COMpairCost performed best during the Stoke summit scenario with only 3.1% error The Doncaster Scenario had an error of - 10%, Gainsbourgh had an error of -6 % Hatfield South has an error 28% and Welwyn garden city scenario performed the worst with 41% error. Following analysis of the results presented in Table 5.5 the work process criteria cost estimate, within the Welwyn garden city scenario, does not appear to be related to the number of units renewed. The results suggest that the cost of the work to renew thirteen units within the Welwyn garden city scenario is the same as one unit within the Hatfield South scenario. Assuming this result to be wrong, if the work process cost estimate produced during the Welwyn garden City scenario is multiplied by the number of units (13) this gives a value of £4,915,573. This estimate added to the additional project cost estimates for the Welwyn garden city scenario totals £10,822,872 and only has a 2% error from the real project cost. The cost estimate produced by the methodology for the Hatfield South scenario also has a high degree of error at 28%. Following analysis of the results in Table 5.5 it is observed that the possession cost for this scenario may be too high. A comparison of the Hatfield South and Stoke Summit scenario indicate that the possession costs are the same however, the number of units renewed in the projects are very different. Hatfield South renewed one unit whereas, Stoke Summit renewed four units. The renewal of less units would suggest less time was required and therefore a smaller possession was needed. However, this assumes that there was equal labour for each scenario. The results in Table 5.5 also suggest that some of the criteria and alternatives are the same across the project scenario.

Table 5-6 Comparison of COMpairCOST, Consultants Estimates with Real Project Price as a Percentage Error.

Scenario	COMpairCOST	% error	Consultant	% error	Real Project
Doncaster	3,442,851	-10.8	4,434,187	14.8	3,860,213
Gainsbourgh	1580502	-6	1,212,105	-27.9	1,681,704
Hatfield South	3269796	27.9	1,531,188	-40	2,555,615
Stoke Summit	3624125	3.1	3,552,678	1.1	3,512,968
Welwyn G City	6235240	41	8,331,306	-21.1	10,569,911

The real projects costs were not broken down into a sufficient amount of detail to provide an analysis concerning which were the easiest and most difficult comparisons to produce. Easy comparisons' would be defined as comparisons that are close to the real cost and difficult 'comparisons' would be defined as comparisons that have a high degree of error. Should there have been a breakdown of real costs comparative analysis could be performed. The comparative analysis would identify across the project scenarios what criteria consistently showed a high or low degree of error. The author then may be able to conclude that e.g. that 'Access' across the five scenarios had a high degree of error and therefore is difficult to compare .Unfortunately, due to this lack of data the author could not investigate this in detail. However, possible factors that may affect the accuracy at this stage could be due to the expert's ability to recall a similar project. The expert may have been involved in a similar project recently and be able to recall through memory the project very easily whereas if the similar project was done five years it may provide more difficult to recall the project accuracy. Other factors that may influence the accuracy could include manual error concerning the input ratio scales. The expert during the population may have lost concentration and therefore may have made errors.

5.3 Switch and Crossing Maintenance Model Construct – Case Study Two

This section will discuss the development of a maintenance cost estimating model using the methodology discussed in the previous sections of this chapter. A Switch and Crossing has also been used as the case study.

This section will discuss the research methodology used for the maintenance model construct and validation. Exactly the same methodology has been used as described in Section 5.5. However, a snowball sampling strategy was not feasible due the limiting access to experts within the case study company. Table 5.7 presents the primary sources of data whereas the secondary sources of data collection include content analysis of internal company documents.

Table 5-7 Primary Data Collection

Respondent	Position	Cost Engineering (CE) Experience	Purpose of Data Collection	Type of Interview used
Respondent P	Production Manager	Between 1-5 years	Model Construct, Model Population	Semi-Structured Interviews

5.3.1 Switch and Crossing Maintenance Process

The Switch and Crossing maintenance process is concerned with the effective use of materials and a maintenance technique to enable an S&C to extend its operational life. It is concerned with replacement of the items such as the components that make up an S&C layout rather than the whole replacement of the layout which is the aim of a switch and crossing renewal. To effectively maintain an S&C there must be an understanding of the S&C layout, its geometry and characteristics plus a fundamental understanding of track maintenance. Chapter 2 Section 4 discusses the maintenance process in more detail.

5.3.2 Project Structure

In order to construct the maintenance cost estimating model the identification of switch and crossing maintenance cost drivers is required. These drivers are then converted into the project structure as discussed in Section 5.3.5. Figure 5.12 presents the project structure populated with the identified switch and crossing maintenance cost drivers.

During a semi-structured interview with Respondent P and content analysis of internal company documents. the switch and crossing maintenance cost drivers were identified. During the interview the author presented the cost estimating methodology/prototype, outlined the aim of the interview and discussed the data requirements. Internal company documents were then analysed for drivers and discussed with Respondent P. Any additional drivers were then elicited from the respondent.

Because a prototype software systems had been already developed during case study one it was used to aid validation during case study two. The developed maintenance project structure replaced the renewal project structure within the prototype system. This involved producing square matrixes for all the criteria. However, only the cost alternatives presented in the maintenance project scenarios (Table 5.8) are compared in the matrixes, unlike the first case study were all possible cost alternatives (Table 5.5) for a renewal project were compared. This was because a generic project structure for switch and crossing maintenance project was not developed. Furthermore, similarly to case study one only the most likely values were populated with ratio scales presented in Table 5.2 .This was due to the time restrictions imposed with the experts. Historical cost data was fragmented however; there was sufficient data to identify an alternative of 'know cost' for each scenario.

5.3.3 Empirical Validation of the Developed Maintenance Model

Five historical maintenance projects were used to validate the model. These project scenarios ranged in the size and complexity of work done. Historical cost data was limited. The historical cost data only provided a total project cost and did not break costs down for individual project criteria. Table 5.8 presents the project scenarios use to

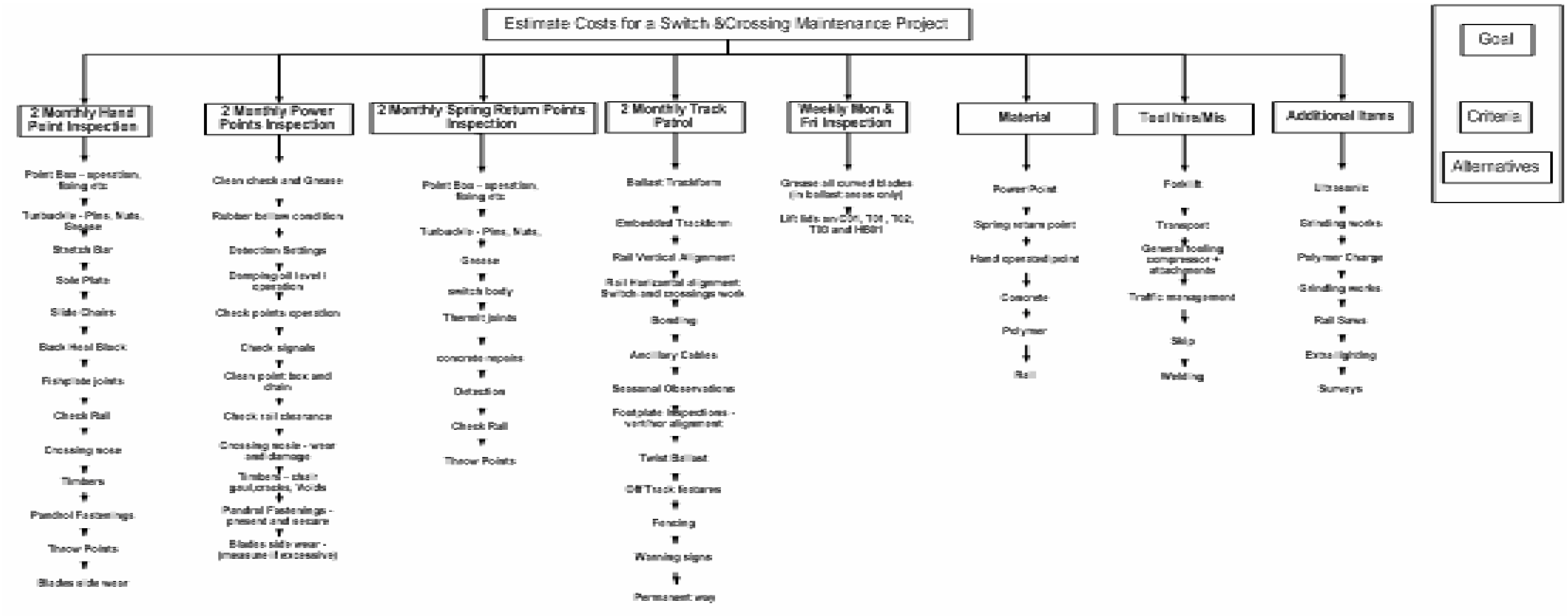


Figure 5-12 Project Structure Populated with Switch and Crossing Maintenance Cost Drivers

Table 5-8 Ratio Score Results for 2 Monthly Spring Return Point Inspection Criteria

Cost		A1			A2			A3			A4			A5			A6			A7		
	2 Monthly Spring Return Points Inspec	Min	**Mo**	Max	Min	**Mo**	Max	Min	**Mo**	Max	Min	**Mo**	Max	Min	**Mo**	Max	Min	**Mo**	Max	Min	**Mo**	Max
A1	Rail		1.00			1.00			9.00			9.00			9.00			9.00			9.00	
A2	labour		1.00			1.00			9.00			9.00			9.00			9.00			9.00	
A3	plant hire forklift		0.11			0.11			1.00			1.00			1.50			0.50			1.50	
A4	scrap skip		0.11			0.11			1.00			1.00			1.50			0.50			2.00	
A5	extra lighting		0.11			0.11			0.67			0.67			1.00			0.33			1.50	
A6	pandrol clips		0.11			0.11			2.00			2.00			3.00			1.00			4.00	
A7	rail saws x2		0.11			0.11			0.67			0.50			0.67			0.25			1.00	

Table 5-9 Maintenance Scenario Cost Estimate Results Produced by COMpairCost and Compared with Real Project Price

					COMpairCost £	Real Project £
Senario 1	Lo2 Switch Body Maintenance	2 Monthly Spring Return Points Inspec	Additional Items	Point Box - operation, fixing etc	1200	N/A
				Turbuckle - Pins, Nuts, Grease	1175	N/A
				switch body	1123	N/A
				thermit joints	1041	N/A
				concrete repairs	927	N/A
				detection	648	N/A
				Check Rail	613	N/A
				Throw Points	294	N/A
				Blades side wear	216	N/A
				Total	7237	N/A
			Tool Hire	forklift	250	N/A
				transport	248	N/A
				general tooling compresser + attachments	355	N/A
				trafic management	204	N/A
				Total	1057	N/A
				Grand Total	**8294**	**12000**
Senario 2	Shirlano Lane Rail Maintenance/	2 Monthly Power Points Inspection	Additional Items	Rail	4000	N/A
				labour	3967	N/A
				extra lighting	826	N/A
				pandrol clips	151	N/A
				rail saws x2	193	N/A
				Total	9137	N/A
			Tool Hire	plant hire forklift	679	N/A
				scrap skip	262	N/A
				Total	941	N/A
				Grand Total	**10078**	**11000**
Senario 3	Cathedral Switch Body Maintenance	2 Monthly Spring Return Points Inspection	Additional Items	contractor	7000	N/A
				polymer charge	6942	N/A
				switch body	9928	N/A
				switch blades	2009	N/A
				Total	25879	N/A
			Tool Hire	transport	5710	N/A
				other plant hire	8447	N/A
				Total	14157	N/A
			Materials	concrete	8764	N/A
				Grand Total	**48800**	**39000**
Senario 4	Rail Reclamation by Welding	2 Monthly Hand Point Inspection	Additional Items	labour	3915	N/A
				prework surveys	4260	N/A
				feul gas & deseil	2447	N/A
				ultrasonic testing work pre-post	3620	N/A
				grinding works	4613	N/A
				Total	18855	N/A
			Tool Hire	materials (weilding)	2976	N/A
				Total	2976	N/A
				Grand Total	**21830**	**12000**
Senario 5	Cathedral Rail Maintenance	2 Monthly Power Points Inspection	Materials	polymer	24794	N/A
				rail	12495	N/A
				concrete	3392	N/A
				road transport	7166	N/A
				Total	47847	N/A
			Tool Hire	plant hire	20443	N/A
				trafiic management	8698	N/A
				weilding	12500	N/A
				Total	41641	N/A
			Additional Items	surveys	2975	N/A
				isolations	5957	N/A
				labour	25000	N/A
				Total	33932	N/A
				Grand Total	**123420**	**110000**

populate the model. The validation process involved a data collection interview were an expert with maintenance cost estimating experience populated the square matrixes within the prototype system with ratio scores, based on the context of the five scenarios. The outputs from the models are compared with the total project cost identified from the historical projects. The results can be seen in Table 5.10 and Figure 5.12. Figure 5.13 presents the level of error in the results produced by the methodology (prototype system).

Table 5.8 presents five maintenance project scenarios. Project scenario one involved the maintenance of Lo2 Switch Body and two monthly spring return point inspections. The project required a fork lift, transport for personal and tools, general tooling a compressor and attachments and traffic management. The project also required a switch body, thermit joints, some concrete repairs, detection equipment, a check rail, throw points and blades side wear

Table 5-10 Maintenance Project Scenarios

Project	Type	Tool Hire/ Mis	Materials	Additional Items	Total Costs
Lo2 Switch Body Maintenance	2 Monthly Spring return points Inpec	Forklift, Transport General tooling compressor and attachments, Traffic management		Switch Body, Thermit joints, Concrete repairs, Detection, Check Rail, Throw Points, Blade side wear	£12,000
Shirlano Lane Rail Maintenance Replacement	2 Monthly Power Points Inspection	Forklift, Skip		Rail, Labour, Extra lighting, Pandrol clips, Rail saws	£11,000
Cathedral Switch Body Maintenance	2 Monthly Spring return points Inpec	Plant Transport	Concrete	Contractor, Polymer charge, Switch Body, Switch Blades	£39,000
Rail Reclamation by Welding	2 Monthly Hand point Inspection	Wielding		Labour prework. Surveys fuel gas & diesel. Ultrasonic testing work pre-post Grinding works.	£12,000
Cathedral Rail Maintenance	2 Monthly Power Points Inspection	Plant Hire, Traffic management, Transport	Polymer, Rail, Concrete	Labour, Welding, Surveys, Isolations	£110,000

Project scenario two involved a rail maintenance and replacement located at Shirlano lane. This Project involved a two monthly power point inspection, required a forklift and skip and, required rail, extra lighting, pandrol clips and rail saw.

The maintenance of a body switch was the aim of project scenario three and involved two monthly spring return points inspection. Plant and transport was required for the project as well as concrete, polymer charge, switch body and switch blades.

Project scenario four was concerned with a rail reclamation by welding. This project required a two monthly hand point inspection, some welding, pre-work on site, surveys, fuel gas and diesel, ultrasonic testing, post work and grinding works.

Finally project scenario five involved the maintenance of rail at Cathedral. A two monthly power points inspection was required as well as plant hire, traffic management, and transport. Polymer, rail and concrete were also required. Surveys, welding additional labour and isolations were also required.

Table 5.10 presents the cost estimate results produced by the methodology. The cost estimates are broken down into drivers. The total costs are then compared with the real project prices. Table 5.9 presents the 2 monthly spring return point inspection from Lo2 Switch Body Maintenance scenario. The full detailed matrixes contained the ratio scales populated by the expert can be seen in Appendix 8.

A comparison of the costs grouped under the criteria for each project is presented in Table 5.11.

Table 5-11 Comparison of Project Scenario Cost Estimates by Criteria

Project Scenario	Tool/Hire	Materials	Additional Items	COMPairCost	Real Project Cost	Level of error %
Lo2 Switch Body Maintenance	1,057		7,237	8294	12000	-31
Shirlano Lane Rail Maintenance/ Replacement	941		9,137	10078	11000	-8
Cathedral Switch Body Maintenance	14,157	8,764	25,879	48801	39000	25
Rail Reclamation by Welding	2,976		18,855	21830	12000	82
Cathedral Rail Maintenance	41,641	47,847	33,932	123420	110000	12

Figure 5.13 compares the maintenance project scenario cost estimate results, produced by the methodology, with the real project costs.

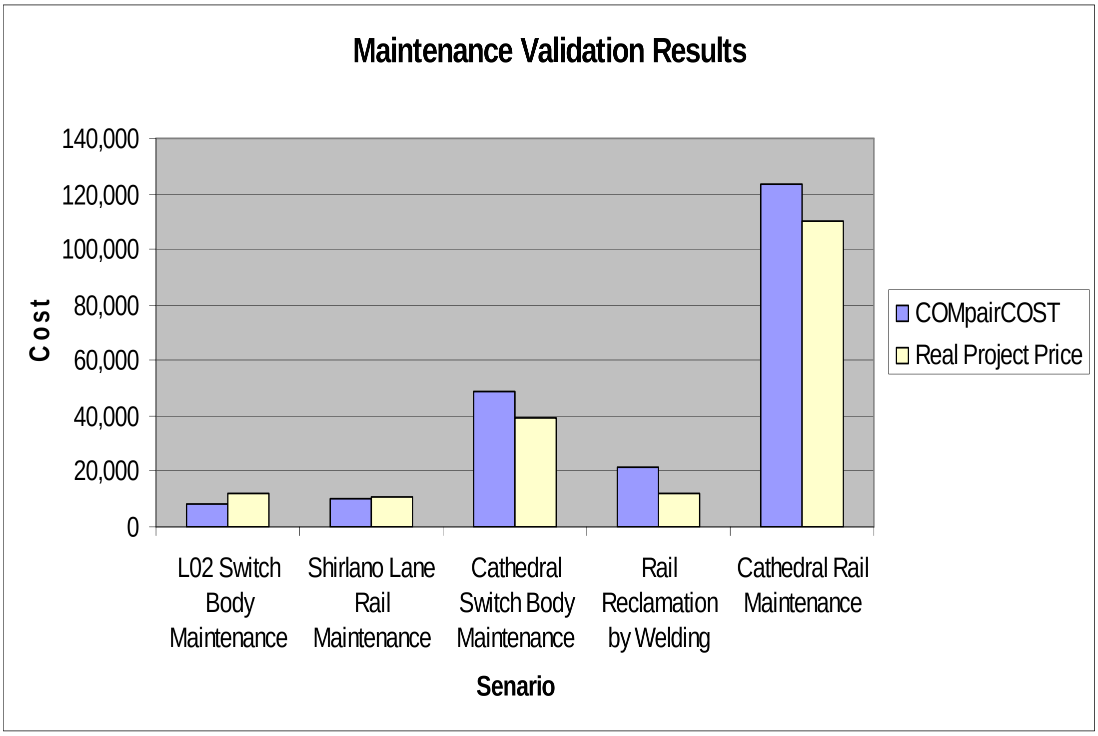


Figure 5-13 Maintenance Validation Results

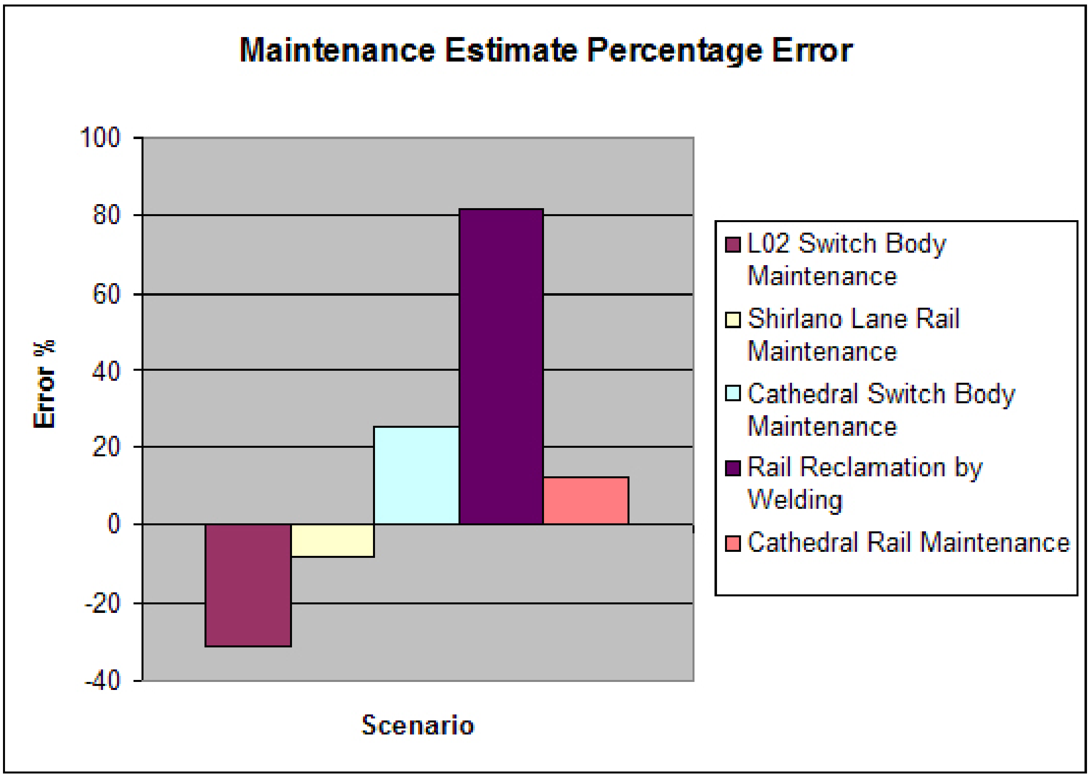


Figure 5-14 Maintenance Cost Estimate Percentage Error

Figure 5.14 presents the cost estimates produced by the methodology as a percentage error of the real project costs. The results suggest that three of the two scenarios were over estimated and two were underestimated. The largest level of error in the cost estimates was produced by the Rail Reclamation by Welding scenario with an error of 82%. Following analysis of the results presented in Table 5.8 and Table 5.9 the reason why there is such a large error in the estimate is difficult to conclude due to a lack of breakdown of costs into criteria allowing a comparative analysis to be performed between the real project costs and the cost estimates produced using the methodology. However factors that contribute to the error may be due to the expert produced biased ratio scores or not recalling by memory the similar project to reference. This may be due to the selection of a project that in reality was not similar. Similarly, it is difficult to conclude why there was an error of 31% in the LO2 switch body maintenance scenario other then again to suggest that the ratio scales may have been biased by the lack of experience of similar projects. The most accurate estimate was produced by the Shirlano Lane scenario with an error of -8%.

5.4 Exploration of Cost Model during Later Stages in the Project Life Cycle.

During a two hour focus group, the author explored the ability of the model to estimate costs during the later stages in the project life cycle, in particular Stages Four and Five as illustrated in Figure 4.6. The focus group sample is presented in Table 5.12.

Table 5-12 Stage Four and Five Estimating Focus Group Sample

Respondent	Position	Cost Engineering (CE) Experience	Purpose of Data Collection	Type of interview used
Respondent Q	Development Manager	7 years	Application of model at Stages 4&5	Focus Group, unstructured interview
Respondent R	Senior Commercial Manager	18	Application of model at Stages 4&5	Focus Group, unstructured interview
Respondent S	Project Manager	10	Application of model at Stages 4&5	Focus Group, unstructured interview

The author gave a short presentation over 15mins and outlined the cost estimating methodology to the attendees of the focus group. The attendees were then give 30mins to use the tool and were given opportunities to clarify any issues they had.

As discussed in Chapter 4, Stages Four and Five of the industrial case cost estimating process are concerned with producing a detailed feasibility estimate and a definitive estimate. Therefore, once the attendees has shown that they understood the methodology the following question was posed and the remaining 1.15min was used to discuss the models applicability.

"Would the model be of benefit if applied at Stages four and five of the cost estimating process?"

The key findings from the focus group are presented.

- It was felt that the use of ratio scales was not of benefit because the estimate could not be reused by another estimator unless all the assumptions were collected.
- The use of ratio scales could not be communicated and understood buy different estimators or individuals from different departments. The subjective nature of

the input data and the use of the verbal ratio scale e.g. bigger, much bigger, when discussing the costs would not provide confidence to individual that the estimates were accurate.

- When an estimate is produced at the later stages, the estimator does not think in terms of cost. They think in terms of time, for example labour or how many men are required to do the job etc. This is because the time or number of men to do the job never changes, although the value of money or cost is changing all the time. To do the job today still takes the same time but costs more. Therefore there experience is based on these areas rather then cost as a value.
- In order for the estimator to produce the ratio scales the estimator would first think in terms of time etc and then convert this to the fit the ratio scale. It was suggested that the calculation of the ratio scale would become very complex and also why produce one estimate to then convert into another estimate to estimate the same job.
- Finally, the estimators do not have historical data in a sufficient format to populate the 'item of know cost'.

5.5 Comparison of Proposed Approach with a Bottom-Up Approach

A bottom up cost estimating approach is concerned with identifying and estimating all individual items. R. Roy (2003) suggests that these types of estimates can take substantial time to develop and are therefore not usable within the early stages of the estimating life cycle. Furthermore, historical cost data is required for each item and this data can be hard to come by. The proposed cost estimating approach discussed in this thesis is better then a bottom up approach on two counts, these can be seen in the table below. However the bottom up approach is likely to produce a higher level of accuracy.

Bottom up	Proposed Approach
Take substantial time to develop R.Roy (2003)	**Quicker to produce (Depending on level of detail specified in comparison matrix)**
Require historical data for each item R.Roy (2003)	**Requires very limited historical cost data.**
Can produce a low level of error	Possible higher degree of error due the use of a cost estimator's experience.

Depending on the level of detail defined in the comparison matrixes (Section 5.2.6) will impact on the time that is required to estimate a project. The level of detail will however be less then that required by a bottom up approach therefore suggesting it is likely that the cost estimating approach proposed in this research will produce estimates more quickly. However, no comparative testing has been performed to validate this statement. Additionally, the proposed cost estimating approach's main attribute is its ability to deal with the issue of a lack of historical data which is common place at the early stages of the project lifecycle. Whereas, the bottom up approach requires substantial historical data therefore suggesting that this approach is better then a bottom up approach during the early stages of the project life cycle.

5.6 Summary and Key Observations

In summary this chapter has presented the development of a structured renewal cost estimating model and a maintenance cost estimating model for use at the early project life cycle stage when there is limited quantitative cost data available. Sensitivity and Monty Carlo analysis results are also presented. The validation results from both case studies are also presented. Finally an investigation into the proposed methodologies use at the later stages in the project life cycle is discussed.

This chapter has shown that the cost estimates produced by the renewal model were all under a 50% level of error and that three of the five estimates had under a 10% level of error. The results from the empirical validation also show that on most occasions COMpairCOST did outperform the manual estimating process performed by a consultant.

Through Monty Carlo analysis this chapter has investigated the uncertainty in the cost estimates. Results from the sensitivity analysis have shown the highly sensitive comparisons. In addition, these comparisons are the most important and should therefore be considered very carefully when scored.

This chapter has shown that four of the five cost estimates produced by the maintenance model were under a 50% level of error with only one under 10%. The chapter has also shown that the proposed methodology is not a valid approach to estimate renewal and maintenance costs at the later stages in the project life cycle. In the following chapter a step by step guide to the prototype software system will be presented. Also this chapter will discuss the validation result from an additional case study.

CHAPTER 6. DEVELOPMENT OF A PROTOTYPE SYSTEM AND ADDITIONAL CASE STUDY

The previous chapter discussed the development and validation of a renewal and maintenance cost model using switch and crossing case studies. The chapter also explored the models applicability to the later stages in the project life cycle.

This chapter discusses the development of a software prototype system based on the methodology discussed in Chapter 5. This chapter also presents the methodology applied to a different asset other then switch and crossing.

6.1 Chapter Aim

"To present a step by step guide to the developed prototype software system and present the validation results from an additional case study."

In section 6.2 the prototype software system 'COMpairCOST' is presented. Section 6.2.1 discusses how the matrixes were developed. A description of how the Excel formulas were developed follows this. Section 6.2.3 describes the use of Visual Basic Application. Whereas section 6.2.4 discusses the use of test data to identified errors in the model. Section 6.2.5 presents the results from a qualitative evaluation of the software system. Section 6.3 discusses the validation using a third case study. The chapter then concludes with a discussion of the result from all three case studies and summary and the key observations.

6.2 Overall Structure of Prototype Software System – COMpairCost

Based on the discussed methodology presented in Chapter 5 a prototype software system was developed. The structure of the proposed system consists of six main stages as shown in Figure 6.1. Following analysis of the cost estimate results and observation of the experts populating the matrixes with ratio scores it was observed that the experts reused some of the ratio score values across the project scenarios. The prototype system therefore has a standard base project predefined within it. This then allows the estimating process of comparing the alternative to be greatly increased in speed due to the ability to reuse some of the ratio scores should they be appropriate for the project being estimated. This predefined project (Stage 1) is then compared with remit data

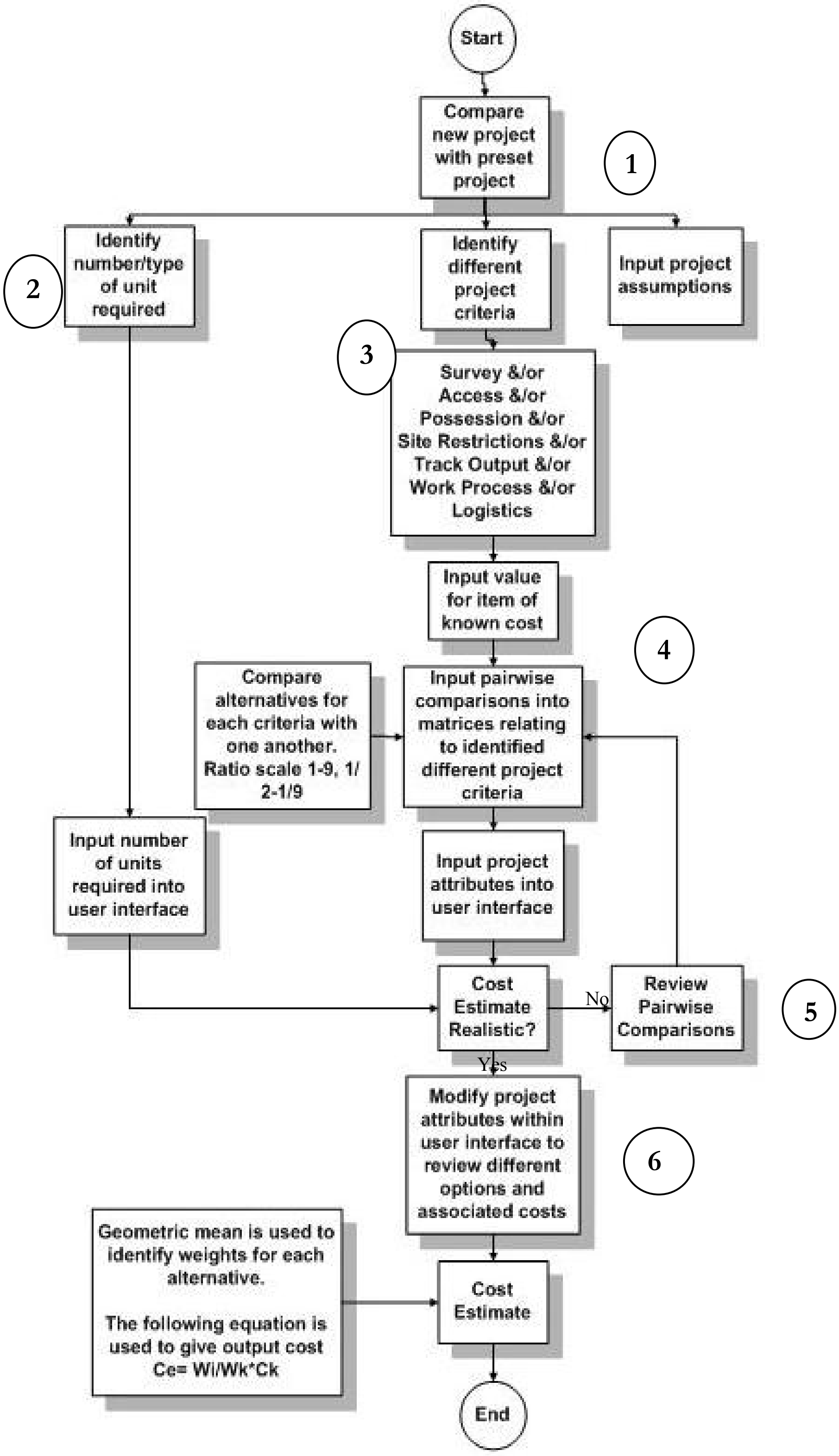


Figure 6-1 Overall Structure of Developed System

containing the new project to be estimated. The remit data is information concerning the new project to be estimated and includes the project background, business objectives, and requirements and products. The number of units (Stage 2), any assumptions and any differences in the criteria between the base project and the new project (Stage 3) are then identified. An alternative of 'known cost' (Stage 4) from the new project to be estimated is also required.

Once the pairwise comparisons scores have been updated accordingly the main interface is updated to represent the new project to be estimated. This involved changing the alternatives to represent the new project and the number of units are also entered. The resulting three-point estimate is then reviewed. Should the cost estimate look realistic (Stage 5) the estimate can be accepted. However, if the cost estimate looks wildly wrong the pairwise comparison scores need to be reviewed for inconsistencies and inaccuracies. Once the estimate is accepted a 'what if' analysis can be performed on the project (Stage 6). The system is named "COMpairCOST" and was used to aid empirical validation with industrial data. For each criterion within a switch and crossing renewal project the system provides a worksheet. For example, the Access criteria worksheet (from case study one) is shown in Figure 6.2.Within each worksheet, the domain experts populate the matrix with relative values from the ratio scale.

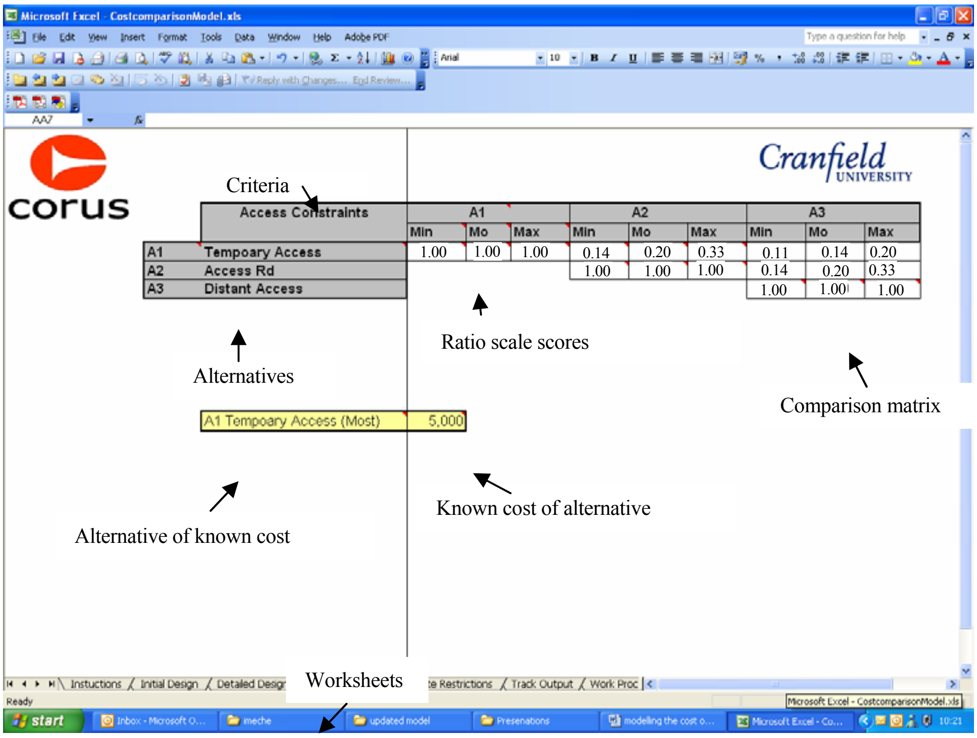


Figure 6-2 The systems 'Access' Criteria Worksheet

Additionally, the worksheet requires the input of the alternative of "known cost" and the corresponding cost. COMpairCOST provides a worksheet, as shown in Figure 6.3, which represents the main interface of the system. The interface worksheet presents the resulting estimates as a breakdown of criteria and a total three-point project cost. The data presented in Figure 6.2 is taken from case study one.

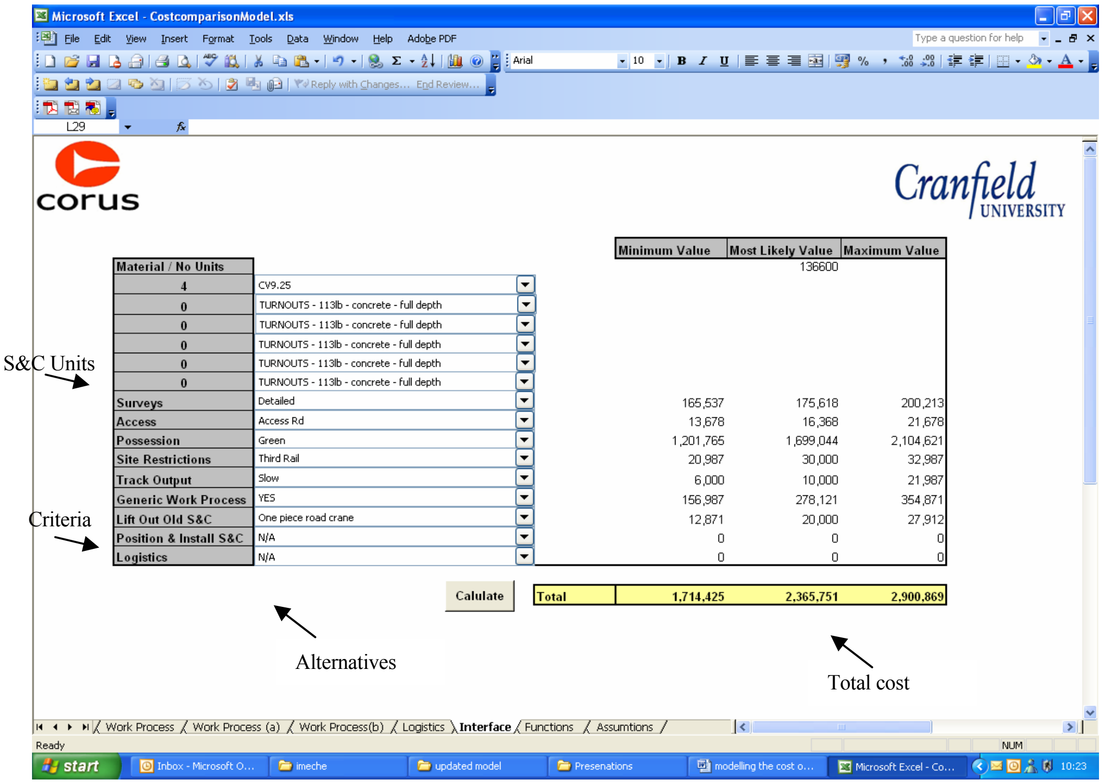


Figure 6-3 The Systems User Interface Worksheet

As comparisons have been made for all possible alternatives within the criteria additional decision support capabilities are present. A "What If" analysis can be performed. Alternative scenarios can be investigated and the corresponding costs can be identified. Consider the criteria from case study one; a project with a track output of 0-50 mph line speed. The estimator could change the track output to a different alternative and the tool will update the cost accordingly.

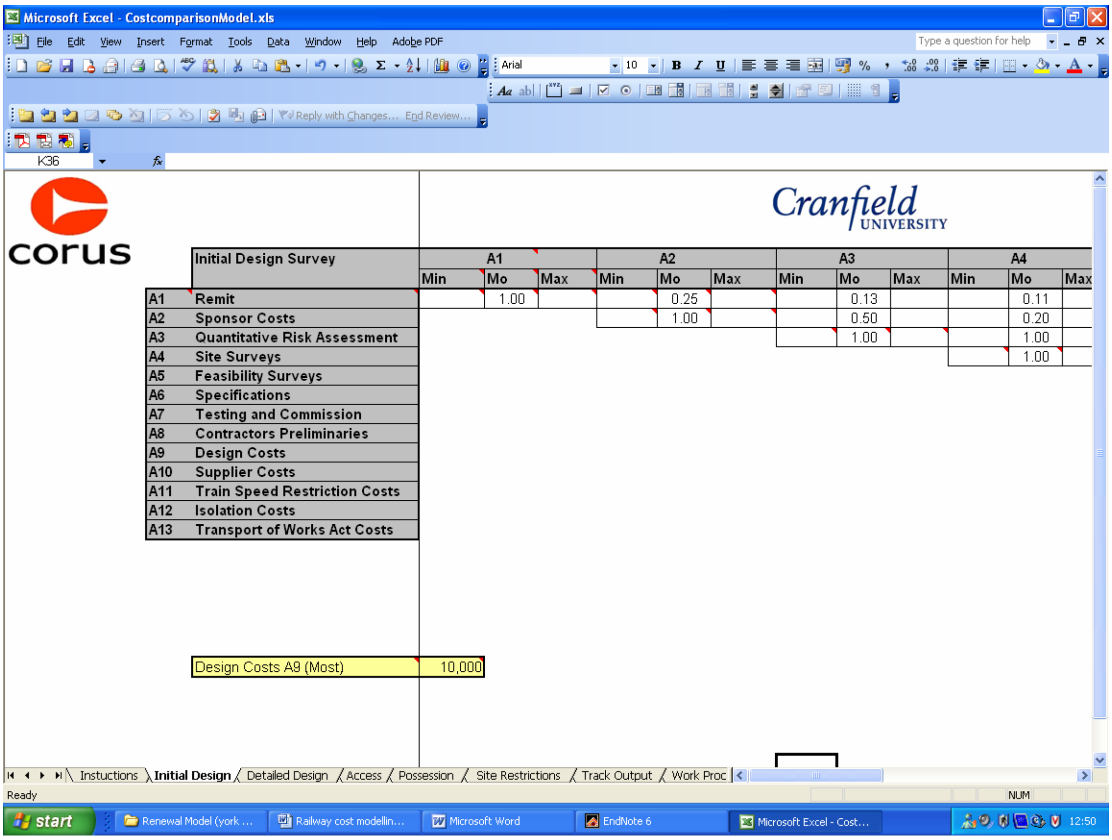
The system was developed using Microsoft Excel. Functionality was limited within Excel therefore the author wrote Visual Basic Application to allow Excel to provide the required functionality. The prototype system was developed following seven stages:

1. Matrices production,
2. Formula construct,
3. Visual Basic Application,
4. Validation of model with test data,
5. Questionnaire investigating systems usability. Improvements based on questionnaire results,
6. Matrices populated using ‘real’ data.

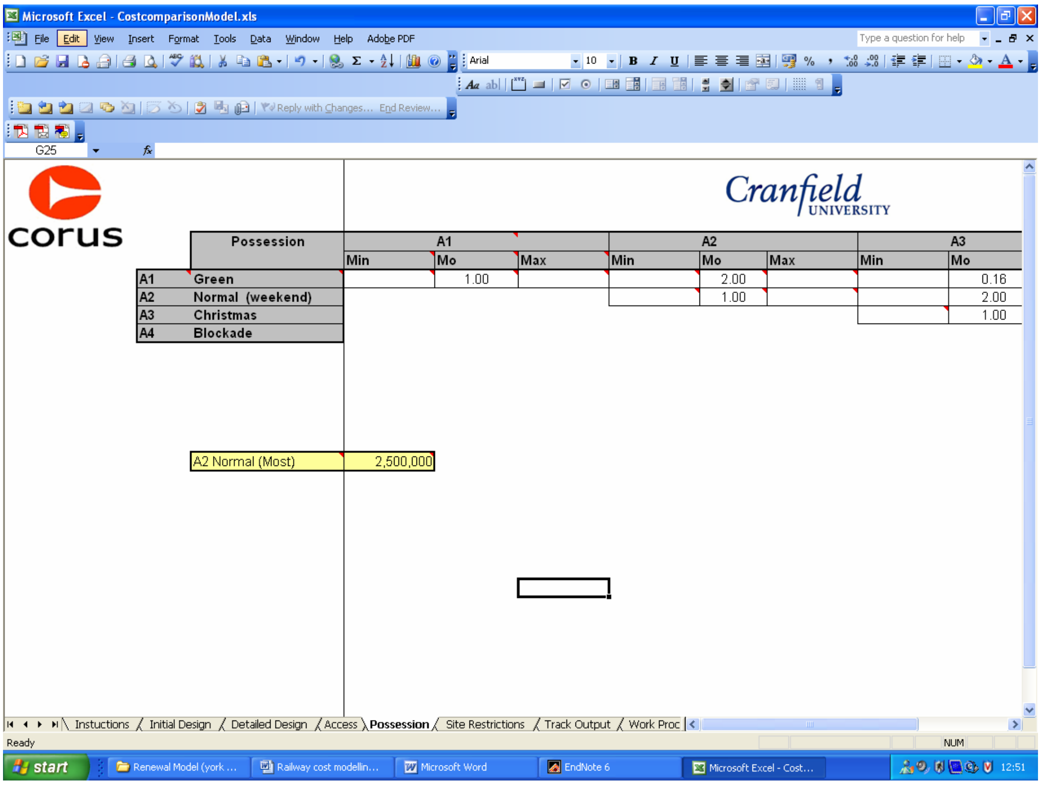
The following sections will describe each stage in more detail.

6.2.1 Matrix Development

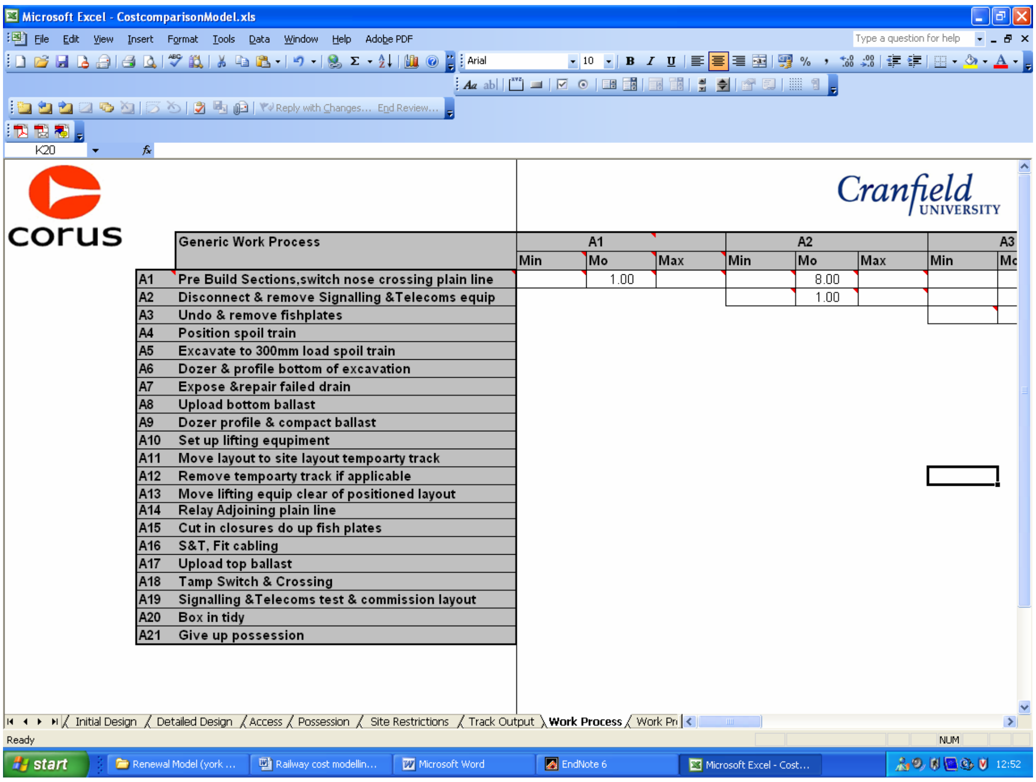
A matrix is produced for each of the project ‘criteria’ contained in the project structure. Each matrix is produced within an individual Excel worksheet. Figure 6.4 (a)-(c) illustrates the matrixes produced for ‘Initial Design’, ‘Possession’, and ‘Generic Work Process’ criteria from case study one. The remanding matrix screenshots can be seen in Appendix 6. These also contain the data from case study one.



(a)



(b)



(c)

Figure 6-4. (a) Initial design, (b) Possession, (c) Generic Work Process Matrix

6.2.2 Formula Construct

This stage involves the creation of Excel mathematical formulas needed to perform the calculations discussed in Section 5.3.7. Figure 6.5 illustrates the 'initial design' matrix, from case study one, and presents a calculation table which illustrates the row vector, geometric mean, and normalised geometric mean calculations for the alternatives being compared. The minimum values, the most likely values and the maximum values which are represented as minimum (min), most likely (mo), and maximum (min) are also presented. The most likely values have only been populated due to time restrains with the expert. Furthermore, the resulting cost estimates for each alternative are also illustrated.

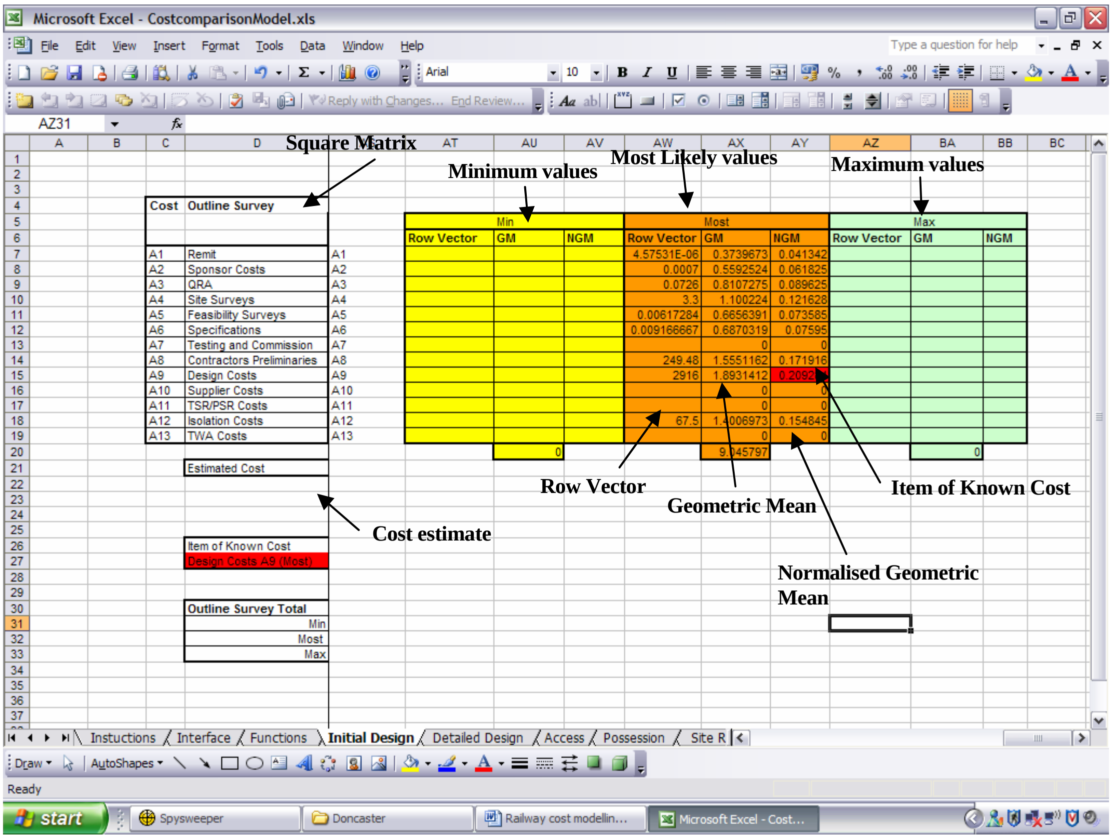


Figure 6-5 Initial Design Calculation Table

6.2.3 Visual Basic Application

During the development of the system it was observed that Excel had some limitations including, displaying error values when a cell was left blank within the matrix. The criteria and alternatives listed within the system represent all project possibilities. It is common that not all alternatives and criteria will total a project requiring estimating and will therefore not be included in the comparison analysis. Alternatives not included in the analysis are left as blank cells. Additionally due to the size of the matrices within the system, over one thousand individual formulas are required. To overcome these challenges the author wrote Visual Basic Application (VBA) algorithm. Table 6.1 presents the VBA algorithm used within the system, algorithm one addresses the blank cell issue were as algorithm two addresses the issue of placing a corresponding value into the matrix based on the value entered by the expert. The second algorithm reduces the amount of comparisons the experts has to complete by half. When comparisons are made within a square matrix the same items are compared twice. For example if A is compared with B and A is given a verbal scale of slightly bigger (ratio score 3) from Table 5.3 it can be calculated that the corresponding size of B when compared with A is slightly smaller (ratio scale of .33). The second algorithm calculates automatically and populates the matrix accordingly.

Table 6-1 Visual Basic Application Algorithm 1&2

<table>
<tr><th>Visual Basic Application Algorithm 1</th><th>Visual Basic Application Algorithm 2</th></tr>
<tr><td>Sub parti(n, ref, target)
Dim count
'MsgBox " Criteria -- " & target
ref1 = ref
Dim result As Double
'result = 1
resp = 1
col = 0
For count = 1 To n
'MsgBox "Test 2--" & result
'add 3 more cells to cell
ref = Sheets("Detailed Design").Range(ref1).Offset(0, col)
col = col + 3
'MsgBox "Test 3--" & ref
If ref = "" Then
'MsgBox "the value is Blank" ' Next count
Else
resp = resp * ref
result = resp
End If
'MsgBox "Test 4--" & result
Next count
'write result to destination
If result > 0 Then
Sheets("Detailed Design").Range(target) = result
Else
Sheets("Detailed Design").Range(target) = ""
End If</td><td>If Sheets("Logistics").Range("L8").Value = "" Then Sheets("Logistics").Range("I9").Value = ""
Else
If Sheets("Logistics").Range("L8").Value <= 10 Then
Sheets("Logistics").Range("I9").Value = 1/ Sheets("Logistics").Range("L8").Value
End If</td></tr>
</table>

6.2.4 Test Data

Formulas and functionality of the prototype system need to be validated and checked for inconsistencies. Therefore the author used some test data to check this. The author populated the matrices with random ratio scales and checked for errors in both the formulas and observed the outputs from the VBA code. Any observed errors were then investigated and corrected.

6.2.5 Qualitative Evaluation of the Software Prototype System

A semi-structured questionnaire was produced with the aim of assessing the usability of the prototype software system and can be seen in Appendix 7. A workshop was organised during case study one, during case study two and during case study three, where cost estimation expert(s) evaluated and populated the prototype system using project scenario data. The author gave a short presentation to the attendees, outlined the aims of the workshop and described and demonstrated the cost estimating methodology. The experts were then given one hour thirty minutes to assess the prototype software system for usability. The experts were asked to complete a semi-structured questionnaire once the model had been populated. The questionnaire results were used to further improve the model.

In addition to the Industrial expert's evaluation, PhD researchers specialising in cost estimation and cost related lecturers were asked to evaluate the model and complete the questionnaire. They were selected because the author believed they were a good input to the validation process due to their expertise in the area of cost and due to the author having access to them. The sample interviewed over the three case studies can be seen in Table 6.2. However, full understanding of the model by the researchers and lectures proved difficult because the attendees did not have experience of Switch and crossing renewal projects and therefore could not fully use the methodology. In hindsight a generic example/project should have been developed and the researchers and lectures populate the model based on this example.

Table 6-2 Interview Sample

Respondent	Position	Cost Engineering (CE) Experience	Purpose of Data Collection	Type of interview used
Respondent B	Switch and Crossing Cost Estimating Manager	Between 10-15 years	Usability Validation	Structured Interviews
Respondent C	Switch and Crossing Cost Estimating Manager	More then 15 years	Usability Validation	Semi-Structured Interviews
Respondent F	Cost Engineering Lecturer	N/A	Usability Validation	Semi-Structured Interviews
Respondent G	Cost Engineering Lecturer	N/A	Usability Validation	Semi-Structured Interviews
Respondent P	Maintenance Manager	5-10 years	Usability Validation	Semi-Structured Interviews
Respondent T	Senior Estimator	More the 15 years	Usability Validation	Semi-Structured Interviews
Respondent H	PhD Researcher	N/A	Usability Validation	Semi-Structured Interviews
Respondent I	PhD Researcher	N/A	Usability Validation	Semi-Structured Interviews
Respondent J	PhD Researcher	N/A	Usability Validation	Semi-Structured Interviews
Respondent K	PhD Researcher	N/A	Usability Validation	Semi-Structured Interviews
Respondent L	PhD Researcher	N/A	Usability Validation	Semi-Structured Interviews
Respondent M	PhD Researcher	N/A	Usability Validation	Semi-Structured Interviews
Respondent N	PhD Researcher	N/A	Usability Validation	Semi-Structured Interviews
Respondent O	PhD Researcher	N/A	Usability Validation	Semi-Structured Interviews

The aim of the questionnaire was to identify any weakness in the prototype system and to understand what improvements were needed. Results from the questionnaire can be seen in Figure 6.6. Figure 6.7 illustrates a screenshot of the prototype system's interface before the questionnaire using data from case study one. Based on the results from the questionnaire modifications were made as shown in Figure 6.8.

Some quotes from the questionnaire are included;

- "The interface session is good but needs some improvements"
- "User interface easy to navigate and input data"
- "The layout and the logic behind the operations is very good"
- "It would improve with help facilities on necessary cells"

- "It would be nice if all cells are cleared when a new user starts estimating"
- "It provides a structured approach to capturing knowledge/express knowledge about a new project"
- "Could it be made in a wizard based manner?"
- "Need to explain each field and have it as a comment for each item."

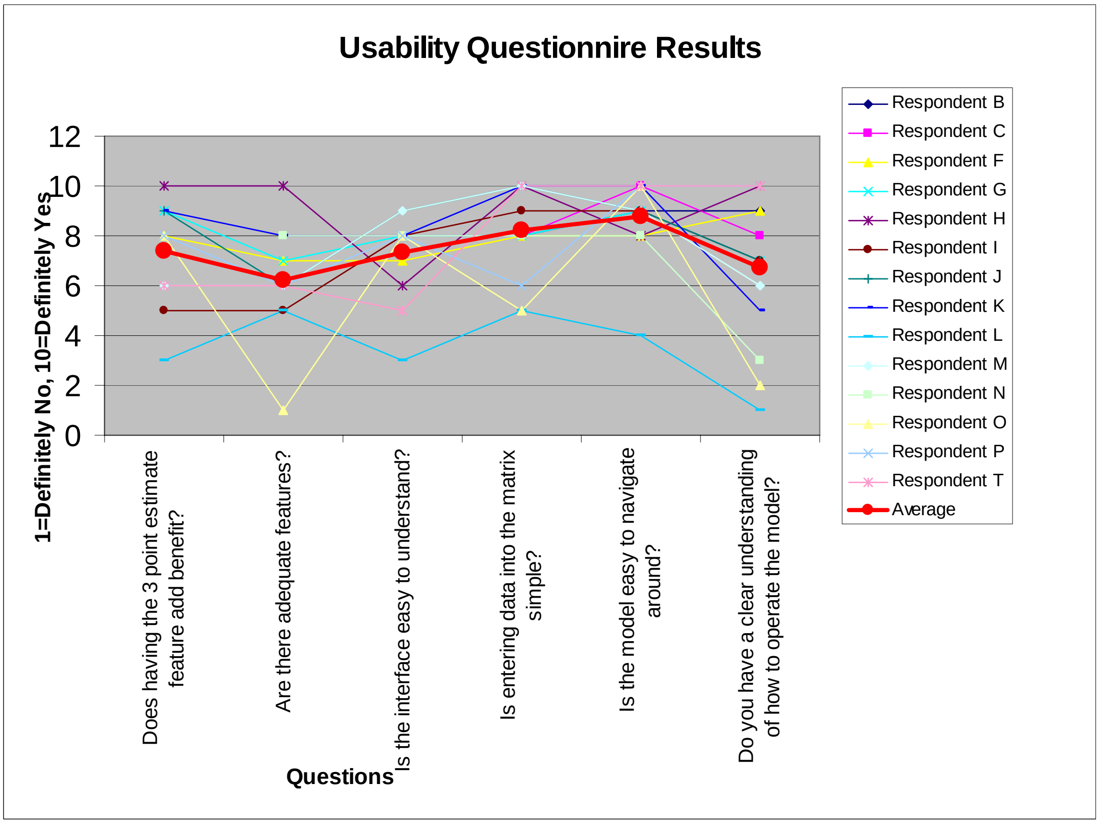


Figure 6-6 Usability Questionnaire Results

The questionnaire provided valuable data needed to further improve the model. Considering all the questionnaire results, the author identified key themes for further improvement. They included revaluation and redesigning the interfaces to provide the user with less information, thereby making the model more understandable and easier to use. Another theme from the results indicated that the help feature and user instructions needed improvement.

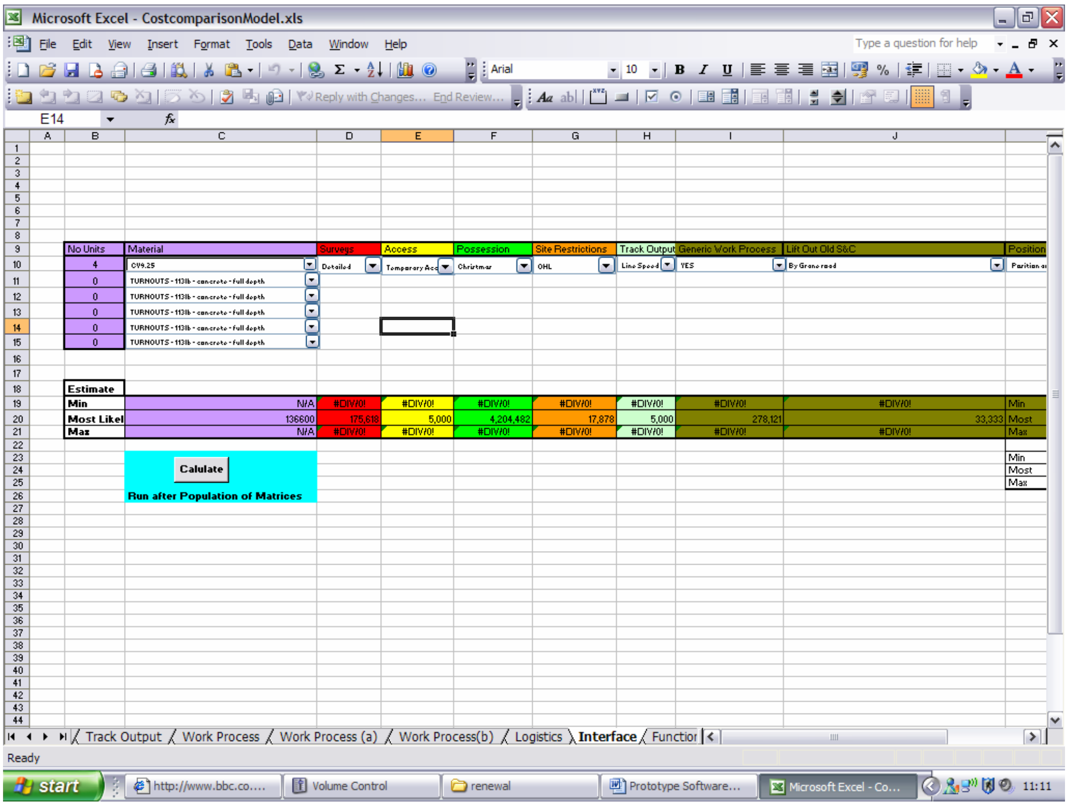


Figure 6-7 Prototype Interface before Improvements

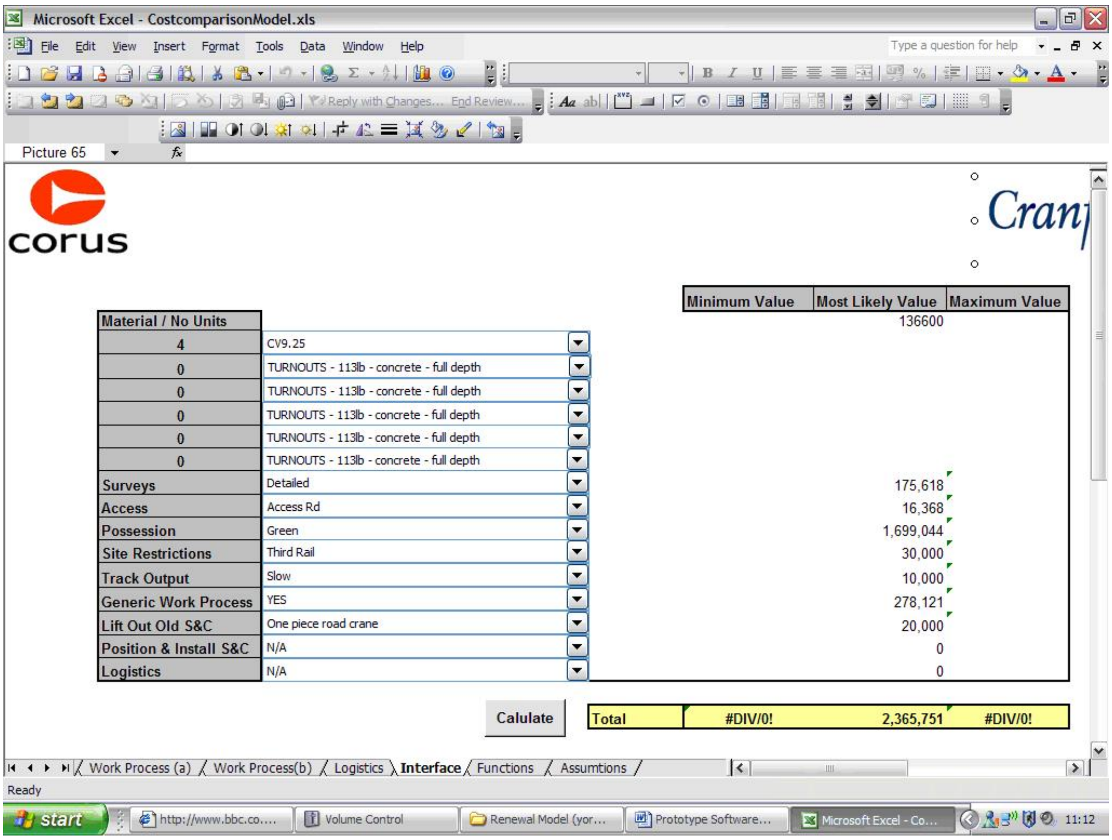


Figure 6-8 Prototype Interface after Improvements

Figure 6.8 illustrates the prototypes interface following the recommended changes collected by the usability questionnaire. The Figure illustrates the estimated most likely costs and are broken down into the units costs, a detailed survey cost, the cost to construct an access road, the cost of using a green possession, the cost of have a third rail as a site restriction, the cost of track output slow and the cost of lifting and replacing the unit in one piece using a road crane.

6.2.6 Maintainability / Expandability

Microsoft Excel was chosen as the software platform to develop the prototype system. This was because MS Excel allows rapid prototyping of the models relationships and provides flexibility to modify data and formulae as needs arise.

Any expandable requirements of the model can be easily achieved and undated using the Excel environment as it is an open software environment.

6.3 Track, Sidings and Insulated Rail Joint Cost Model Construct – Case Study Three

This section will discuss the additional model construct and validation of the proposed cost estimating methodology discussed in Chapter 5. Five renewal and maintenance projects of assets including Track, Sidings, and Insulated rail joint/insulated block joint (IBJ) are used.

6.3.1 Research Methodology

This section will discuss the research methodology used for the data collection and validation. One four hour meeting and one four hour interview was conducted over two days with a Railway renewal and maintenance expert. During the first day the author presented and explained the prototype software framework. Also during the meeting the author collected five historical project scenarios from document analysis of internal company documents and identified the cost drivers through discussion with the expert. During the four hour interview on the second day the expert populated and assessed the prototype software system based on the five historical project scenarios collected during the previous day. The real project scenario cost and the cost estimates produced by the methodology were then compared. Table 6.3 presents the primary sources of data collection.

Table 6-3 Primary Data Collection

Respondent	Position	Cost Engineering (CE) Experience	Purpose of Data Collection	Type of Interview used
Respondent T	Senior Estimator	More then 15 years	Model Construct & Model Population	Semi-Structured Interview
			Usability Questionnaire	Semi- Structured Questionnaire

6.3.2 Track

Railway track as shown in Figure 6.9 consist of Sleepers, Rails, and Fastenings. The main purpose of track is to transport passenger and fright trains. A sleeper is used as a base for the track which lay on top of ballast. The rail interfaces with the train's wheel. And the fastenings hold the components in place.

Figure 6-9 Track

6.3.3 Sidings

Sidings as shown in Figure 6.10 refers to a section of rail which are used to temporality store stationary rolling stock while loading, unloading or a section of rail which provides access to mines, factories, quarries etc. Marshalling yard or rail yards refers to group of sidings. Sidings connected at both ends are called loops loop.

Figure 6-10 Sidings at Cambridge Station

6.3.4 Insulated Rail Joint/Insulated Block Joint IBJ

Insulated rail joint/insulated block joint are rail joints which incorporate insulation to isolate individual track circuits. It is rail joint designed to stop the flow of the electric current from rail to rail by means of insulations. They separate the rail ends and other metal parts connecting them. Figure 6.11 illustrates an Insulated Block Joint.

Figure 6-11 Insulated Block Joint

6.3.5 Model Construct

In order to validate the proposed cost estimating methodology the identification of the cost drivers is required. The project structure discussed in Section 5.3.5 is then populated with the cost drivers. Similarly to the approach taken in case study two, the prototype system developed during case study one was used to aid validation. The project structure from case study three replaced the structure from case study one and square matrixes were developed based on the new project structure.

Figure 6.12 presents the project structures for the three types of assets involved in case this case study they include, Sidings, Track and Insulated Rail Joint assets. The cost drivers contained in this structure has been taken from the analysis of five historical project scenarios and is grouped around the main renewal project criteria as discussed in the project structure construct section in Chapter 5. These historical projects were obtained from internal company records. Unlike the project structure in case study one

a generic project structure was not developed for each asset, rather the structure only contains the cost drivers relating to the identified historical projects. Related documented data containing the cost drivers for these assets was limited and therefore data would have had to have been elicited from experts during workshops in order to develop a generic project structure. This would have been unrealistic due to time restraints and access to the relevant experts. Similarly to case study two, this model therefore can not provide any "what if analysis" and comparisons can not be reused. Using the approach discussed in Sections 5.6.3 – 5.6.5 the alternatives are compared and the matrixes are populated by an expert using ratio scales and cost estimates are produced. The square matrix populated with ratio scores for the Purley scenario is presented in Table 6.5. The fully populated matrixes for each project scenario during this case study can be seen in Appendix 8. Because the project scenarios were broken down into 'alternative' level costs an alternative was used as the 'known cost'

6.3.6 Empirical Validation of the Developed Maintenance Model

The validation process involved one four hour interview were an expert with renewal and maintenance cost estimating experience populated the model with pairwise comparisons based on the context of the five scenarios presented in Table 6.4. The cost estimates produced by the model are compared with the project costs identified from the historical projects. The results can be seen in Table 6.6 and Figure 6.13. Figure 6.14 presents the cost estimate error as a percentage from the real project cost.

Figure 6.11 presents the level of error in the cost estimates produced by COMpairCOST when compared with the real project price. The results indicate that the Bristol Scenario performed the worst with a level of error of 185% The next worst performing cost estimate was produced using the Toten New Bank scenario with a level of error of 75%. The cost estimate error produced using the Westbrook scenario was 50%. During the Purley scenario the estimate had an error of 29% and the best performing estimate was achieved using the London scenario with an error level of 23%. Four of the estimates produced by COMpairCOST were underestimated and one was over estimated. The cost data gathered from the project scenarios was broken down into costs for each alternative.

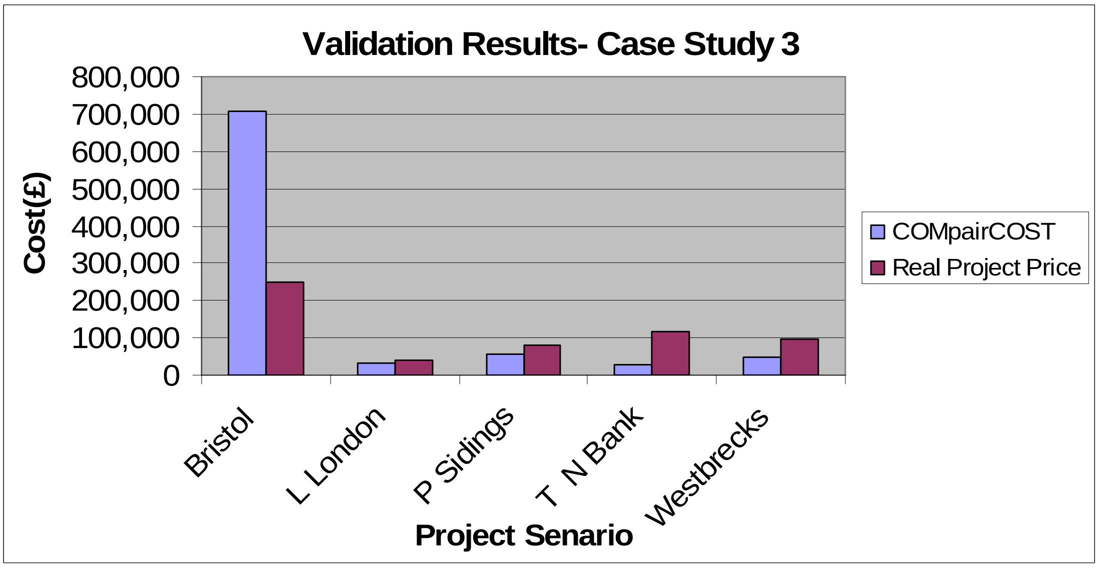


Figure 6-12 Additional Asset Validation Results

, This allowed the author to identify through the use of a comparative analysis between the cost estimates with the real project costs which alternatives were difficult to complete.

Following analysis of the Bristol scenario results presented in Table 6.6, it is observed that the high level of error is due to the over estimation of all the compared alternatives apart from two including (1) Preparatory Works, Make up ballast levels, supply and lay in new sidings with serviceable rail on Inc serviceable concrete sleepers(F23) and all associated fittings. Siding 3 and (2) the Preparatory Works, Make up ballast levels, sleepers(F23) and all associated fittings.

It was also observed that during the Toten New Bank scenario, site prelims, road install approx 128.3m and 230mm of plain line, excavate and prepare formation sub grade, handle and lay bottom ballast, handle and load all accumulative spoil into road vehicles were all considerably underestimated and explains why the total cost estimate had a large level of error.

The result obtained from the Westbrook scenario suggest that Thermit welding of rail joints, IBJ Recovery Works Remove existing redundant BS113a FB rail IBJ in CWR track and install new closurer ail, Thermit wielding of Rail joints(32) and Installation Works IBJ Installation BS113A FB rail (16) comparisons were considerable underestimated and again explains why there was an error of 50%.

The percentage error of 29% observed during the Purley Project scenario results can be explained by a considerable underestimating during the comparison of, Make up ballast levels & supply and lay in new sidings with serviceable rail on &inc serv F23 concrete and all associated fittings, Supply and install by 8 contra Flexture turnout and inc rail bearers & and all associated fittings and prelims.

The best performing estimate was produced during the London scenario however, this still has a high degree of error at 23%. The error can be explained by the underestimation of the IBJ recovery Works - Remove existing redundant BS113A FB rail IBJs in CWR track in installing new closure rail and the Management - Project Management comparison by the expert.

A deep understanding of the experts rational when populating the square matrixes is not understood. Should this be understood it may provide more insight into the reasons to why some of the estimates had a large degree of error and why some were more accurate then others. However, some factors that may contribute to the inaccuracy may include manual error, the particular alternatives were difficult to compare or the expert scenario recalled by the expert was not very similar.

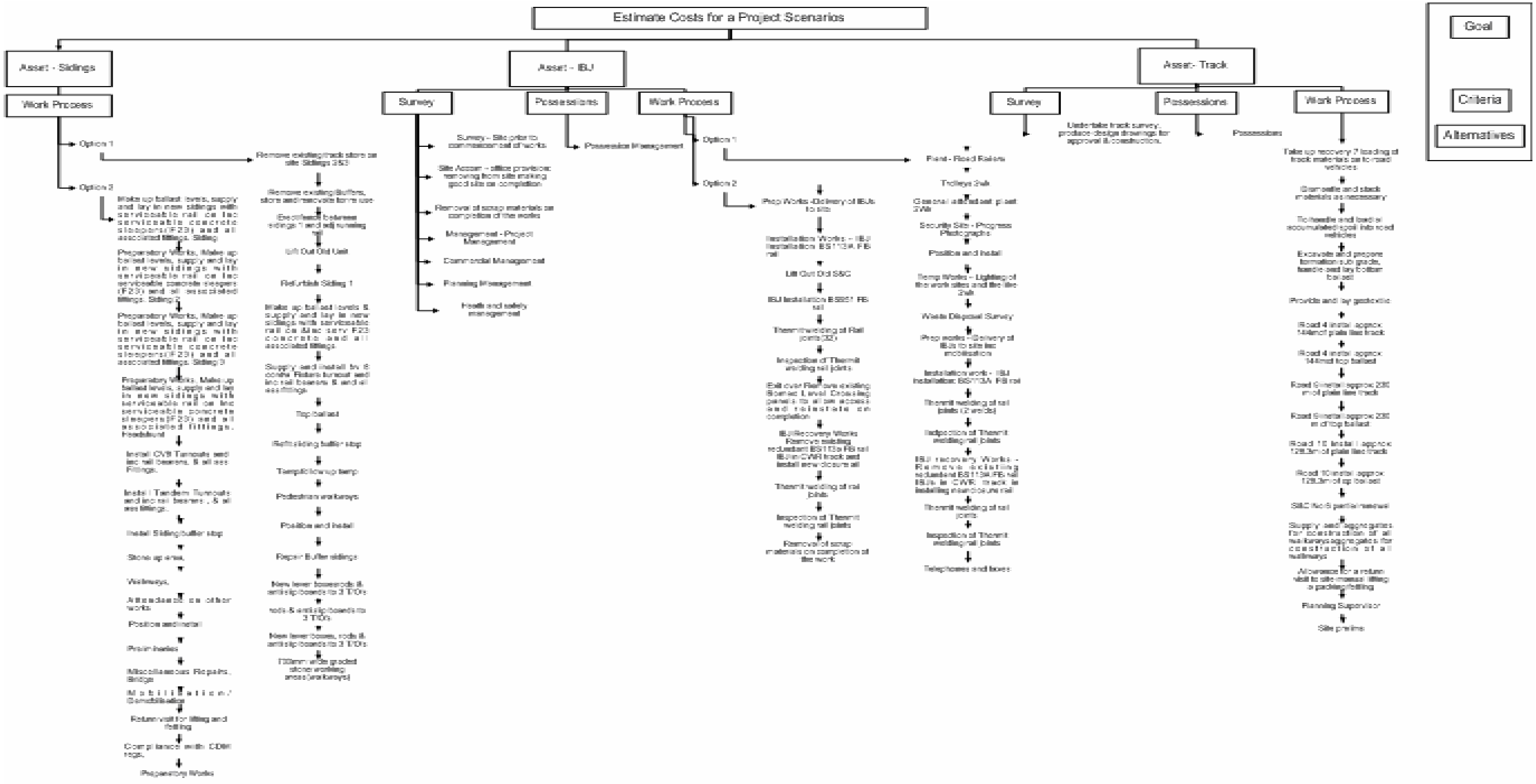


Figure 6-13 Project Structure Populated with Five Project Scenario Cost Drivers

Table 6-4 Track, Sidings, Insulated Rail Joint Project Scenarios

Bristol	London	P way works for Purley Sidingss	Toten New Bank	Westbrooks
Removal of Old sidings, Site Clearance, Relaying of new sidings and stoning of Depots	Site Accomidation - office provision: removing from site making good site on completion Q1	Remove existing track store on site Sidings 2&3 Q310	Undertake track survey, produce design design drawings for approval & constrauction.	Survey Site prior to commencement of works
Make up ballast levels, supply and lay in new sidings with servicable rail on Inc serviceable concrete sleepers(F23) and all associated fittings. Siding 1 Q324	Removal of scrap materials on completion of the works	Remove existing Buffers, store and renovate for re use Q2	Take up recovery 7 loading of track materialson to road vechcles	Prep WorksDelivery of IBJs to site
Prepartory Works, Make up ballast levels, supply and lay in new sidings with servicable rail on Inc serviceable concrete sleepers(F23) and all associated fittings. Siding 2 Q332	Management - Project Management Q1	Erect fence between sidings 1 and adj running rail Q200	Dismantle and stack materials as necessary	Installation Works IBJ Installation BS113A FB rail (16)
Prepartory Works, Make up ballast levels, supply and lay in new sidings with servicable rail on Inc serviceable concrete sleepers(F23) and all associated fittings. Siding 3, Q360	Commercial Management Q1	Lift Out Old S&C	To handle and load all accumulated spoil into road vechiles	Lift Out Old S&C
Prepartory Works, Make up ballast levels, supply and lay in new sidings with servicable rail on Inc serviceable concrete sleepers(F23) and all associated fittings. Headshunt, Q45	Planning Management Q1	Refurbish Siding 1 Q1	Excavate and prepare formation sub grade, handle and lay bottom ballast	IBJ Installation BS951 FB rail (4)
Install CV8 Turnouts and inc rail bearers, & all ass Fitiings. Q2	Heath and saftly management Q1	Make up ballast levels & supply and lay in new sidings with servicable rail on &inc serv F23 concrete and all associated fittings Q345	Provide and lay geotextile	Thermit weilding of Rail joints(32)
Install Tandom Turnouts and inc rail bearers , & all ass fittings, Q1	Possession Management - attending meetings 1wk	Supply and install bv 8 contra Flexture turnout and inc rail bearers & and all ass fittings Q1	Road 4 intall approx 144mof plain line track	Inspection of Thermit welding rail joints
Install Sliding buffer stop Q2	Plant - Road Railers Q1	Top ballast Q75	Road 4 intall approx 144mof top ballast	Exit over Remove existing Bomac Level Crossing panals to allow access and reinstate on completion
Stone up area, Q1	Trolleys 2wk	Refit sliding buffer stop QQ2	Road 9 install approx 230 m of plain line track	IBJ Recovery Works Remove existing redundant BS113a FB rail IBJ in CWR track and install new closurer ail
Walkways, Q75	General attendant plant 2Wk	Tamp/follow up tamp Q375	Road 9 install approx 230 m of top ballast	Thermit welding of rail joints
Attendance on other works, Q1	Security Site - Progress Photographs Q1	Pedestrain walkways Q2	Road 10 install approx 128.3m of plain line track	Inspection of Thermit welding rail joints
Position and install	Position and install	Position and install Q1	Road 10 install approx 128.3m of op ballast	Removal of scrap materials on completion of the work
Preliminaries, Q1	Temp Works - Lighting of the work sites and the like 2wk	Repair Buffer sidings 1 Q1	S&C No 6 partial renewal	
Miscellaneous Repairs, Bridge, Q1	Waste Disposal Survey Q1	New lever boxes, rods & anti slip boards to 3 T/O's Q1	Supply and aggregates for construction of all walkways	
Mobilisation/Demobilisation, Q1	Prep works - Delivery of IBJs to site inc mobilisation Q1	700mm wide graded stone working areas(walkways) Q1	Allowance for a return visit to siteie manual lifting a packing fettling	
Return visit for lifting and fettling, Q1	Installation work - IBJ installation: BS113A FB rail Q1		Planning Supervsior	
Compiliance with CDM regs, Q1	Thermit welding of rail joints (2 welds) Q1		Possessions	
Prepartory Works Q1061	Indpection of Thermit welding rail joints Q1		Site prelims	
	IBJ recovery Works - Remove existing redundant BS113A FB rail IBJs in CWR track in installing new closure rail			
	Thermit welding of rail joints (Q1			
	Inspection of Thermit welding rail joints			
	Telephones and faxes			

Table 6-5 Ratio Score results for Purley Sidings Scenario

	Pway Works for Purley Sidings		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14
		Min	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo
A1	Remove existing track store on site Sidings 2&3 Q310		1.00	1.00	2.00	1.00	0.11	0.11	1.00	2.00	0.11	1.00	1.00	2.00	1.00	1.00
A2	Remove existing Buffers, store and renovate for re use Q2		1.00	1.00	1.00	0.20	0.11	0.11	1.00	0.50	0.20	1.00	1.00	1.00	0.50	1.00
A3	Erect fence between sidings 1 and adj running rail Q200		0.50	1.00	1.00	0.11	0.11	0.11	0.20	0.30	0.11	0.20	0.11	0.50	0.15	0.20
A4	Refurbish Siding 1 Q1		1.00	5.00	9.00	1.00	0.11	0.11	1.00	0.50	0.50	2.00	1.00	1.00	1.00	1.00
A5	Make up ballast levels & supply and lay in new sidings with servicable rail on &inc serv F23 concrete and all associated fittings Q345		9.00	9.00	9.00	9.00	1.00	2.00	0.11	9.00	9.00	9.00	9.00	9.00	9.00	9.00
A6	Supply and install bv 8 contra Flexture turnout and inc rail bearers & and all ass fittings Q1		9.00	9.00	9.00	9.00	0.50	1.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00
A7	Top ballast Q75		1.00	1.00	5.00	1.00	9.00	0.11	1.00	1.00	0.20	1.00	0.50	1.00	0.50	1.00
A8	Refit sliding buffer stop QQ2		0.50	2.00	3.00	2.00	0.11	0.11	1.00	1.00	0.11	0.50	0.11	1.00	0.11	1.00
A9	Tamp/follow up tamp Q375		9.00	5.00	9.00	2.00	0.11	0.11	5.00	9.00	1.00	4.00	1.00	8.00	2.00	8.00
A10	Pedestrain walkways Q2		1.00	1.00	5.00	0.50	0.11	0.11	1.00	2.00	0.25	1.00	1.00	1.00	0.50	1.00
A11	Position and install Q1		1.00	1.00	9.00	1.00	0.11	0.11	2.00	9.00	1.00	1.00	1.00	2.00	1.00	2.00
A12	Repair Buffer sidings 1 Q1		0.50	1.00	2.00	1.00	0.11	0.11	1.00	1.00	0.13	1.00	0.50	1.00	4.00	0.50
A13	New lever boxes, rods & anti slip boards to 3 T/O's Q1		1.00	2.00	7.00	1.00	0.11	0.11	2.00	9.00	0.50	2.00		0.25	1.00	2.00
A14	700mm wide graded stone working areas(walkways) Q1		1.00	1.00	5.00	1.00	0.11	0.11	1.00	1.00	0.13	1.00	0.50	2.00	0.50	1.00

Table 6-6 Cost Estimate Results produced by COMpairCost Compared with Real Project Price

Scenario	Item	COMpairCOST	Real Project Price
	Make up ballast levels, supply and lay in new sidings with servicable rail on Inc serviceable concrete sleepers(F23) and all associated fittings. Siding 1	28,249	28,250
	Prepartory Works, Make up ballast levels, supply and lay in new sidings with servicable rail on Inc serviceable concrete sleepers(F23) and all associated fittings. Siding 2	23,671	28,947
	Prepartory Works, Make up ballast levels, supply and lay in new sidings with servicable rail on Inc serviceable concrete sleepers(F23) and all associated fittings. Siding 3,	30,852	31,388
Senario 1 Location - Bristol Asset - Sidings	Prepartory Works, Make up ballast levels, supply and lay in new sidings with servicable rail on Inc serviceable concrete sleepers(F23) and all associated fittings. Headshunt,	20,428	3,924
	Install CV8 Turnouts and inc rail bearers, & all ass Fitiings.	39,197	7,737
	Install Tandom Turnouts and inc rail bearers , & all ass fittings,	98,114	5,961
	Install Sliding buffer stop	34,861	1,016
	Stone up area,	131,823	92,710
	Walkways,	21,498	428
	Attendance on other works,	51,409	16,077
	Position and install	50,609	N/A
	Preliminaries,	30,325	17,708
	Miscellaneous Repairs, Bridge,	20,238	4,010
	Mobilisation/Demobilisation,	30,484	1,016
	Return visit for lifting and fettling,	75,173	4,571
	Compiliance with CDM regs,	9,176	2,395
	Prepartory Works	10,824	1,655
	Total	**706,931**	**247,792**
	Remove existing track store on site Sidings 2&3	2,130	1,801
	Remove existing Buffers, store and renovate for re use	2,671	845
	Erect fence between sidings 1 and adj running rail	2,238	296
	Lift Out Old S&C	2,783	
	Refurbish Siding 1	1,932	3,085
	Make up ballast levels & supply and lay in new sidings with servicable rail on &inc serv F23 concrete and all associated fittings	3,536	32,734
Project Scenario 2 Location - Purley Sidingss Asset -Sidings	Supply and install bv 8 contra Flexture turnout and inc rail bearers & and all ass fittings	10,377	17,563
	Top ballast	3,297	3,300
	Refit sliding buffer stop	8,190	845
	Tamp/follow up tamp	2,033	6,236
	Pedestrain walkways	4,719	296
	Prelims	4,410	9,396
	Repair Buffer sidings 1	4,565	229
	New lever boxes, rods & anti slip boards to 3 T/O's	2,735	3,236
	700mm wide graded stone working areas(walkways)	1,881	1,069
	Total	**57,497**	**80,929**
	Survey Site prior to commencement of works	1,345	638
	Prep WorksDelivery of IBJs to site	2,671	2,671
	Installation Works IBJ Installation BS113A FB rail (16)	8,339	35,079
	Lift Out Old S&C	3,946	N/A
	IBJ Installation BS951 FB rail (4)	5,743	6,019
	Thermit weilding of Rail joints(32)	2,607	16,478
Project Scenario 3 Location - Westbrooks Asset -IBJ	Inspection of Thermit welding rail joints	5,234	1,726
	Exit over Remove existing Bomac Level Crossing panals to allow access and reinstate on completion	5,515	0
	IBJ Recovery Works Remove existing redundant BS113a FB rail IBJ in CWR track and install new closurer ail	5,648	21,137
	Thermit welding of rail joints	2,015	10,299
	Inspection of Thermit welding rail joints	4,065	1,079
	Removal of scrap materials on completion of the work	1,256	1,684
	Total	**48,384**	**96,810**
	Site Accomidation - office provision: removing from site making good site on completion	500	385
	Removal of scrap materials on completion of the works	1,000	1,451
	Management - Project Management	838	2,084
	Commercial Management	842	288
	Planning Management	723	127
	Heath and saftly management	1,324	265
	Possession Management - attending meetings 1wk	3,884	170
	Plant - Road Railers	934	1,380
	Trolleys 2wk	3,863	46
Project Scenario 4 Location- L London Asset - IBJ	General attendant plant 2Wk	761	886
	Security Site - Progress Photographs	1,766	58
	Position and install	1,651	N/A
	Temp Works - Lighting of the work sites and the like 2wk	1,557	122
	Waste Disposal Survey	1,024	276
	Prep works - Delivery of IBJs to site inc mobilisation	704	1,451
	Installation work - IBJ installation: BS113A FB rail	1,060	2,844
	Thermit welding of rail joints (2 welds)	2,615	1,679
	Indpection of Thermit welding rail joints	2,253	831
	IBJ recovery Works - Remove existing redundant BS113A FB rail IBJs in CWR track in installing new closure rail	714	3,414
	Thermit welding of rail joints	1,259	1,679
	Inspection of Thermit welding rail joints	1,376	830
	Telephones and faxes	152	17
	Total	**30,800**	**40,013**
	Undertake track survey, produce design design drawings for approval & constrauction.	1,023	1,094
	Take up recovery 7 loading of track materialson to road vechcles	1,094	4,132
	Dismantle and stack materials as necessary	917	0
	To handle and load all accumulated spoil into road vechiles	1,140	11,115
	Excavate and prepare formation sub grade, handle and lay bottom ballast	791	11,599
	Provide and lay geotextile	1,448	1,201
	Road 4 intall approx 144mof plain line track	4,251	13,999
Project Scenario 5 Location- Toten New Bank Asset - Track	Road 4 intall approx 144mof top ballast	1,351	4,291
	Road 9 install approx 230 m of plain line track	4,228	22,369
	Road 9 install approx 230 m of top ballast	833	6,840
	Road 10 install approx 128.3m of plain line track	1,933	12,319
	Road 10 install approx 128.3m of op ballast	1,870	3,819
	S&C No 6 partial renewal	1,121	3,803
	Supply and aggregates for construction of all walkways	770	2,081
	Allowance for a return visit to siteie manual lifting a packing fettling	1,161	1,433
	Planning Supervsior	2,862	1,687
	Possessions	2,466	0
	Site prelims	782	16,369
	Total	**30,041**	**118,151**

supply and lay in new sidings with serviceable rail on Inc serviceable concrete

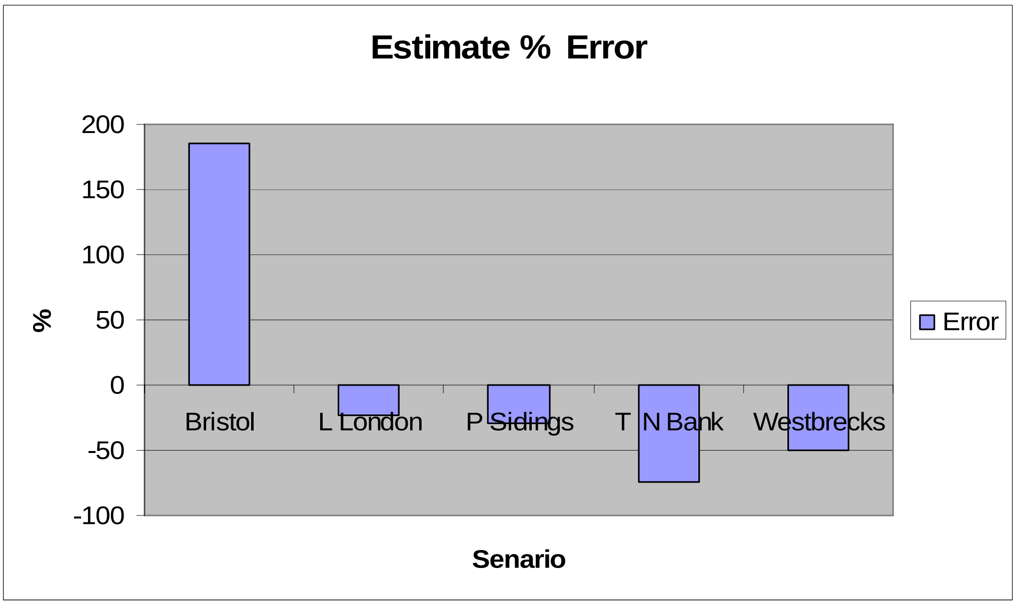


Figure 6-14 Additional Asset Cost Estimate Percentage Error

6.4 Results from 'COMpairCost' across Three Case Studies

This section of the chapter will present all the cost estimate results produced by the proposed methodology. Figure 6.15 presents the validation results from the three case studies, whereas Figure 6.16 illustrates the percentage error results from the three case studies.

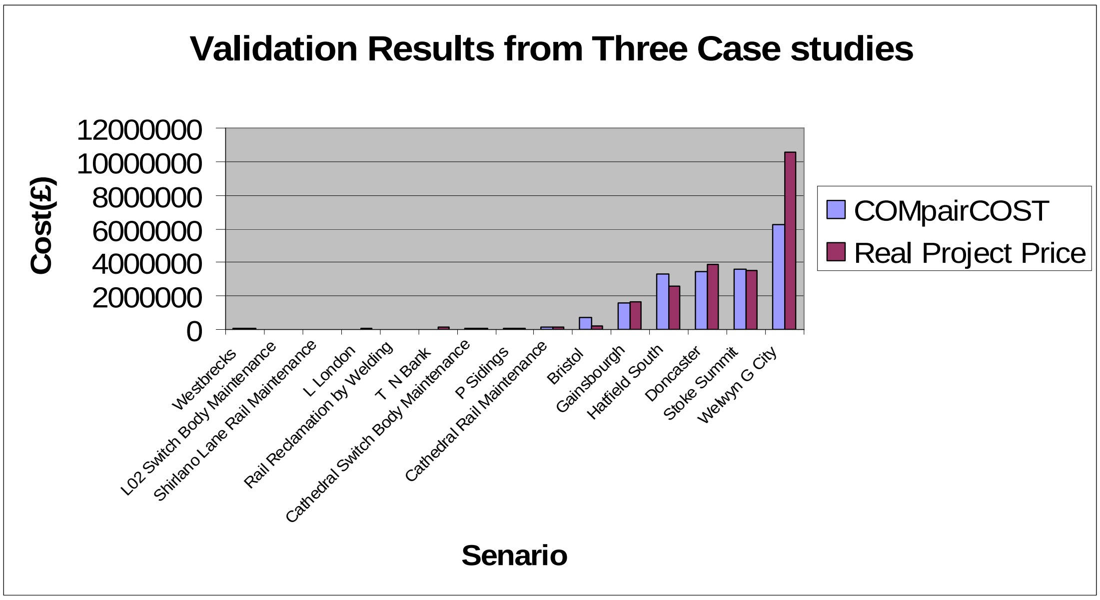


Figure 6-15 Validation Results from Three Case Studies

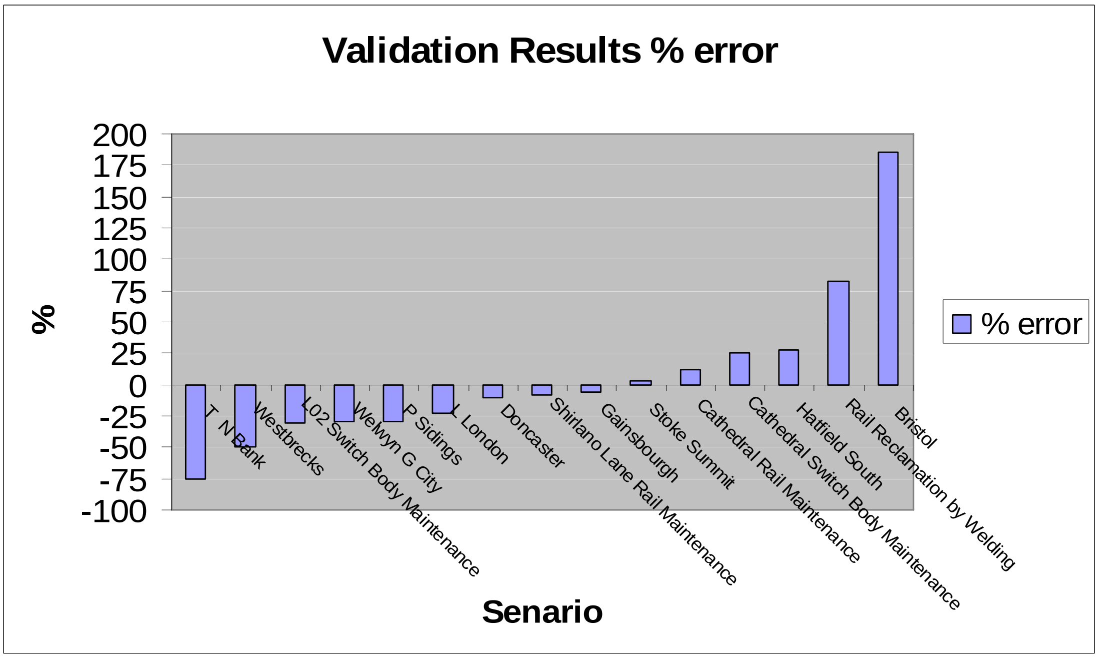


Figure 6-16 Validation Results – Cost Estimate Percentage Error

The results indicate that from the 15 project scenarios three estimates produced by the methodology had an error of +- 10% from the real price, five estimates had an error of +- 20%, nine projects had an error +-30%, eleven projects had an error of +- 40% and, eleven of the twelve project scenarios had an error of +- 50 %.

During case study one, two of the cost estimates had an error of less than 10%, three of the cost estimates had an error of 20%, four had an error of 30% and all five had an error of less the 50%. Case study twos results indicated that one of the estimates has an error of less then 10%, two estimates had an error of less then 20%, three less then 30% and four estimates were less then 40 %. The results from case study three indicated that two of the cost estimates had an error of less then 30% and three had an error less then 40%.

6.5 Suggested Sources of Bias Associated with the Proposed Methodology

The author investigated why there was error and possible bias within the results presented in Section 6.4. The following sections will discuss some of the possible causes.

The results presented in Figure 6.16 indicate that nine of the estimates were underestimated. The literature review has suggested that the main cause of underestimation is strategic misrepresentation (Flyvbjerg, *et al* (2002) and therefore this may explain why many of the project scenarios were underestimated. Understanding the rational of the estimator, when estimating the project scenarios, may provide further understanding of the cause of the error. However, this is not feasible due to access to the estimators. If the estimates produced by the proposed methodology were in fact underestimated by strategic misrepresentation it is very difficult to introduce a mechanism that would remove this when using the proposed methodology. The business culture is always driving to reduce costs. Many bids are won by providing the same quality but at a cheaper price. Therefore culturally estimators are valued for producing the cheapest costs in order to ‘win the job’ or get the projects approved hence the under estimation. The introduction of a 3 point estimate to the proposed methodology will reduced this type of bias because the worst and best cases have to be considered. However, this is not conclusive as the 3 point estimate was not validated due to time constraints with the estimators during the case studies.

‘Lack of experience’ may be a main contributor to the error present in the results. To address this type of bias a cross section of estimators should use the proposed methodology and their results compared, an average could be taken and used as the final estimate, this would have made the results more representative. However, due to access constraints with estimators during the case studies this approach could not be adopted. Or, a cross section of similar projects could have be recalled from memory by one estimator and used to estimate the project. (Whether the estimator had employed this technique was not identified during the case studies). Furthermore the costs should be estimated by individuals who are familiar with the work (project) at hand not somebody who is familiar with estimating techniques. A method or tool for assessing an estimator's reasoning / rational for identifying a similar project would also aid in reducing this type of bias.

The proposed methodology discussed in this research requires an 'item of know cost'. This 'item of know cost' is taken from a historical project and provides the bases to estimate all other items costs using the pair wise comparisons made by the estimator. The 'item of know cost' may be taken from a historical project which was perceived to have summaries but in fact did not. 'Unknown costs' of items could be included in the 'item of known cost' which is not applicable to the new project being estimated and therefore introduces error into the estimate. These 'unknown costs' can be hard to identify because no historical data or assumptions have been collected. This type of bias is present in these research results because the historical project data used for the item of known cost did not have a detailed break down of costs associated to it. Using more then one sources of data as the item of know cost many have made it more representative and reduced the bias.

Both 'Optimism bias' and 'Rosy Retrospection' are discussed in the literature review as a possible cause of error in the results. 3 point estimating is proposed as a strategy to reduce these biases because a worst case estimate has to be considered when producing the 3 point estimate.

The 'Subadditivity Effect' is also discussed in the literature and is a form of bias were the estimator may underestimate items in the project structure which are at a higher level of granularity and over estimate items which are at a detailed level of granularity. To address this bias the estimator should estimate project level items that are at a middle level of granularity. Finally 'Memory Bias' is suggested as a cause of error in the results. This could be addressed by using more then one estimator. However this was not possible in this research as access to estimators was limited.

The table below presents the suggested biases present in this research results, there reduction strategy and whether this strategy was implemented in this research.

Table 6-7 Bias and Reduction Strategies

Bias	Bias Reduction Strategy	Comments
Underestimation	Produce a 3 point estimate. Use more then one estimator.	3 point estimates are incorporated in the proposed methodology Only one estimator was available.
Lack of Experience	Use more then one estimator. Use more then one 'similar' recalled project from memory. Discuss the results as a team.	Due to access restrictions only one estimator was available and the capture of the estimator rational when recalling projects was not captured.
Item of Know Cost	Use different sources if possible.	Due to limitations in data low level 'items of known cost' were not available.
Optimism Bias	Produce a 3 point estimate	3 point estimates are incorporated in the proposed methodology.
Rosy Retrospection	Produce a 3 point estimate	3 point estimates are incorporated in the proposed methodology.
Subadditivity Effect	Estimate costs of items at a middle level of the granularity were possible.	This bias was not addressed in this research.
Memory Bias	Use more then one estimator.	Due to access restrictions only one estimator was available.

6.5.1 Correlations between size of project, number of cost elements and the estimators experience

The author investigated the possibility of correlations between certain factors and the error level in the estimate. With this aim a set of questions were developed including:

1. Does the size of the project in terms of cost affect the level of error in the estimate?

2. Does the number of cost elements, compared during the production of an estimate, affect the level of error in the output cost estimate?
3. Does the estimators cost estimating experience in years, affect the level of error in the estimate?

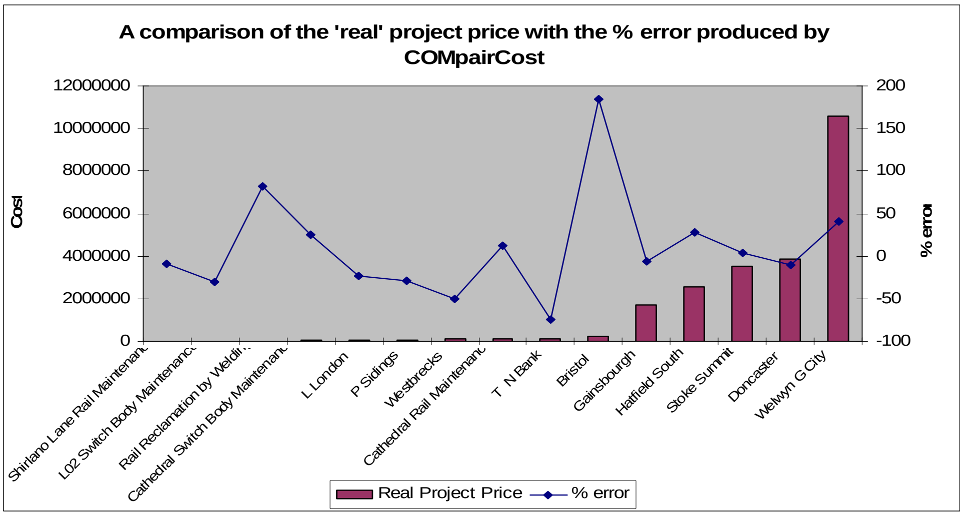


Figure 6.17 Comparison of ‘Real’ Project Price with Estimate Percentage Error

Figure 6.17 illustrates a comparison of the ‘real’ project price with the cost estimate percentage error produced by COMpairCost. The ‘Welwyn G City scenario is the largest in terms of price at £1056991 and the cost estimate produced by COMpairCost had a 41% error. Whereas, the Bristol scenario had a real project cost of £24779 and the highest level of error at 185%. Therefore, suggesting that there is no correlation between the size of project in terms of cost and the percentage error in the estimates produced.

Analyses of the number of cost alternatives compared, during the scenarios, compared with the percentage error are investigated and the results are shown in Figure 6.18. The results from all three case studies are shown. Similarly to the results presented in Figure 6.17 the cost estimate percentage error is random when compared against the number of cost alternatives compared during the population of the methodology with ratio scales. However, the results from the first case study including project scenarios; Gainsbourgh Hatfield South, Stoke Summit, Doncaster and Welwyn G City are consistently nearer the real project cost and also the cost estimate error is produced by an over estimate, unlike case studies two and three were the costs are nearly equally over and under estimated.

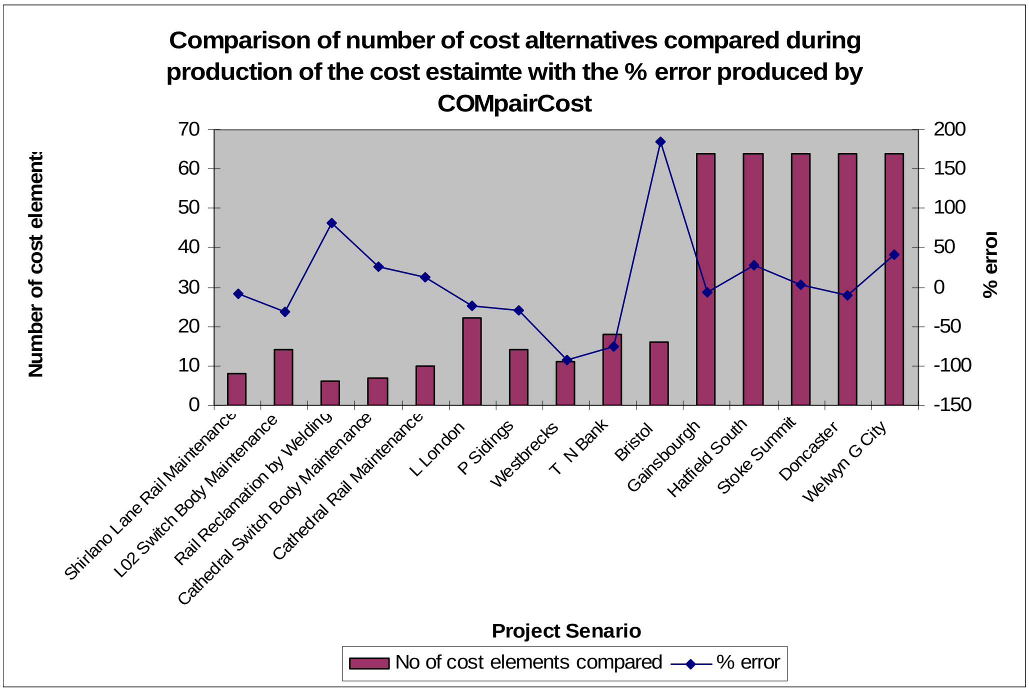


Figure 6.18 Comparison of Number of Cost Alternatives Compared with Estimate Percentage Error

Additionally, the max number of cost alternatives compared during the first case study is substantially greater at sixty four comparisons, whereas the max number of comparisons from the other two case studies is twenty two. Furthermore, a consistent sixty four cost alternatives were compared for each of the project scenarios during the first case study, unlike the number of cost elements compared during case study two and three falling within a range of six and twenty.

The estimator's years of experiences in cost estimating is compared with the cost estimate percentage error. The results are shown in Figure 6.19. During case study one the estimator's years of experience were ten, in case study two the number of years were five and in case study three the number of years were fifteen. The results from this analysis also suggest that the error is also random when compared against the experts number of years experience in estimating projects.

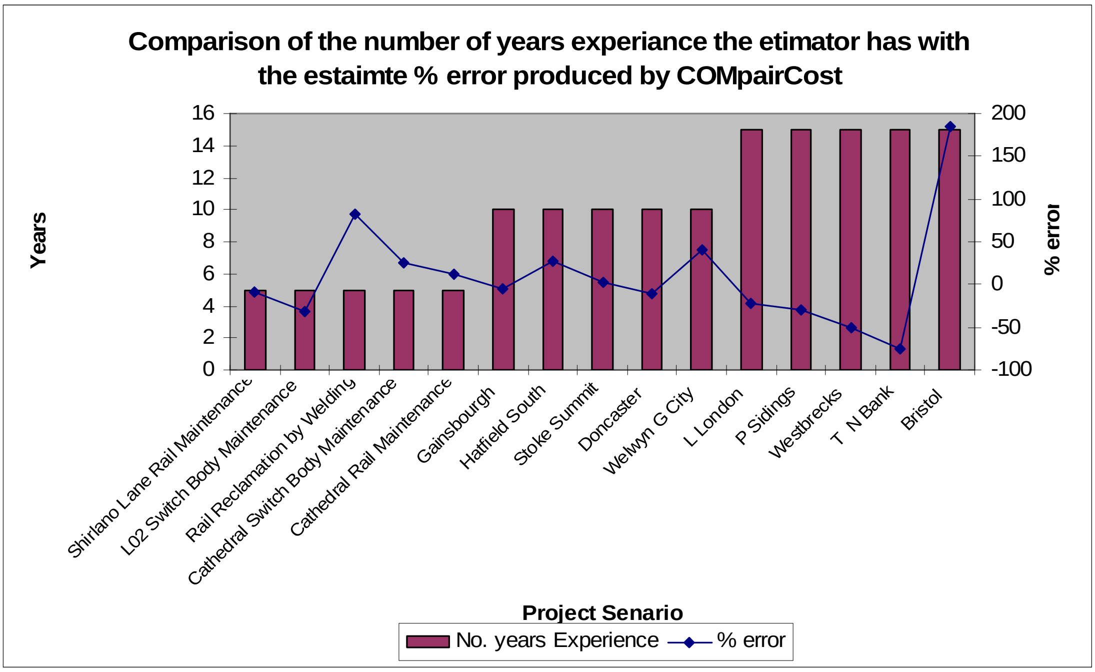


Figure 6.19 Comparison of the Number of Years Experience with Estimate Percentage Error

6.5.2 Subjective Analysis

Further analysis was conducted on the results presented in Section 6.4. Table 6.7 summaries the authors suggested reasons why the methodology may have produced high levels of error using subjective analysis. The selected scenarios under analysis have been chosen because they gave the worst performing cost estimates.

Table 6.7 Suggested Reasons Why Methodology Produced High Cost Estimate Errors

Project scenario	level of error %	Suggested reason why error occurred
Welwyn garden city	41	The cost estimate produced for the 'work process criteria' does not appear to be related to the number of units renewed. The cost estimate should be multiplied by the number of units (13)
Hatfield South	28	Possession cost for this scenario may be too high. A comparison of the Hatfield South and Stoke Summit scenario indicate that the possession costs are the same however, the number of units renewed in the projects are very different.
Rail reclamation by welding	82	Difficult to conclude. However the expert may have biased the ratio scores by understanding the project to be twice as large as is was in reality.
LO2 switch body maintenance	31	Difficult to conclude suggest that the ratio scales may have been biased by the lack of experience of similar projects
Bristol Scenario	185	Due to the over estimation of all the compared alternatives apart from two including (1) Preparatory Works, Make up ballast levels, supply and lay in new sidings with serviceable rail on Inc serviceable concrete sleepers(F23) and all associated fittings. Siding 3 and (2) the Preparatory Works, Make up ballast levels, supply and lay in new sidings with serviceable rail on Inc serviceable concrete sleepers(F23) and all associated fittings.
Toten New Bank	75	Under estaimtion of site prelims, road install approx 128.3m and 230mm of plain line, excavate and prepare formation sub grade, handle and lay bottom ballast, handle and load all accumulative spoil into road vehicles alternatives.
Westbrook	50	Thermit welding of rail joints, IBJ Recovery Works Remove existing redundant BS113a FB rail IBJ in CWR track and install new closurer ail, Thermit wielding of Rail joints(32) and Installation Works IBJ Installation BS113A FB rail (16) comparisons were considerable underestimated
Purley	29	Considerable underestimating during the comparison of, Make up ballast levels & supply and lay in new sidings with serviceable rail on &inc serv F23 concrete and all associated fittings, Supply and install by 8 contra Flexture turnout and inc rail bearers & and all associated fittings and prelims alternatives
London	23	Underestimation of the IBJ recovery Works - Remove existing redundant BS113A FB rail IBJs in CWR track in installing new closure rail and the Management - Project Management comparisons by the expert.

The results presented in Table 6.7 do not suggest any common themes to why the methodology produced high degrees of error across all the case studies and across the individual case studies. However, the results may indicate that these particular drivers are difficult to estimate and that the estimator may have introduced cognitive bias when estimating.

6.6 Reuse of Captured Data

The proposed methodology in this research provides four main types of data which are available for reuse. These include the pair-wise comparisons made by a domain expert, assumptions, the 'item of know cost' and the final cost estimates produced by the methodology.

The main area of reuse surrounds the pair wise comparison data. Pair-wise comparison data is contained within matrices specific to items within the project being estimated. A library of these matrices could be developed. An estimator would build up the estimate by selecting matrixes which are most appropriate to the new project items being estimated. This reuse of matrices would be particularly beneficial to novice estimators who do not have the experience to populate the matrices using the pair wise comparisons but could simply select the matrices which match the remit information. This reuse of matrices would also be beneficial to experienced estimators who would similarly select the appropriate matrix but could modify the comparisons if required. The approach of using a library of matrices greatly speeds up the estimate creation process.

The pair wise comparison data suggests how much bigger or smaller items are when compared with one another in terms of costs. Using this information, resource allocation could be performed assuming that there is a similar correlation in terms of size. i.e 'stone blowing' is 4 times bigger in terms of cost when compared with 'tamping' and would therefore require 4 times the resources.

Any assumptions captured during the estimate would indicate the reasoning behind the decisions made by the estimator. This information would become available for others to critique and learn lessons from.

The 'item of cost' could be reused in different estimates assuming it represented those items cost realistically.

When an estimator produces the estimates using pair wise comparisons, this data is domain specific i.e Railway renewal and maintenance switch and crossing projects. It is therefore difficult to apply these details to other sectors. Furthermore, the details could be difficult to reuse at the later stages in the cost estimating process because of the subjective nature of the input data and the use of verbal scales when discussing the costs. The results from a study investigating the use of the methodology at later stages in the cost estimating process are discussed in section 5.4.

6.7 Reuse of Matrixes for Additional Assets.

A major benefit of the methodology proposed in this thesis is the matrixes used to estimate renewal and maintenance costs can be can be applied to any other asset. During the validation exercise described in this thesis four different assets were used these include S&C, Track, Sidings and Insulated Rail Joints.

To reuse the matrixes the steps required include creating a new project structure which would involve identifying all cost drivers for the new asset as discussed in Section 5.2.5 and populating a blank matrix based on a new project structure, (please see Section 5.2.5). Pair wise comparison data would then be collected from the experts and populated in the matrix against the corresponding drivers.

6.8 Summary and Key Observations

In summary this chapter has presented a step by step guide to the prototype software system development. Additionally, a qualitative assessment of the usability of the prototype software system is discussed. An additional validation case study including Track, Sidings and Insulated rail joints are also discussed. Also presented are the results from all three case studies. Furthermore an investigation into correlations between factors is presented and the cost estimate level of error is presented

Thought the usability questionnaire areas concerning the software prototype software system which requiring further development were identified. These results also showed that in many areas the prototype system scored well for usability

This chapter has shown that two of the five cost estimates produced by the model during case study three were within a 50% level of error. With the cost estimate produced for the Bristol scenario having a 185% level of error.

This chapter has shown that estimating experience, number of cost elements and size of project in terms of cost did not affect the error in the produced estimate. The following chapter will present a discussion the limitations, future work and will conclude this thesis.

CHAPTER 7. DISCUSSION AND CONCLUSIONS

7.1 Introduction

This chapter discusses and concludes the findings from the research project. The chapter discusses how well the research aims and objectives have been met, the limitations of the findings and future work. Also discussed are the contributions this research has made to knowledge in renewal and maintenance costs estimating and cost estimating in general. This chapter also concludes the research hypothesis.

7.2 Chapter Aim

To discuss and conclude the findings from this thesis

In section 7.3 the author discusses the research aims objectives. Section 7.6 presents the research contributions whereas section 7.7 presents the research limitations. Section 7.8 discusses further work and finally section 7.9 concludes the research.

7.3 Discussion of Research Aim and Objectives

The initial main two aims of this research were to:

1. Identify and understand renewal and maintenance cost estimating issues.
2. Understand the current renewal and maintenance cost estimating practice within the Rail industry.

Completing these two objectives led to the development of the research gap which then led to the development of the following research aim.

'To develop a structured framework that estimates Railway Infrastructure renewal and maintenance costs when there is a lack of quantitative cost data at the early stages of the project life cycle.'

Considering the research aim and further review of the literature the following research hypothesis was generated.

"A Pair wise comparison technique can be applied to the early project life cycle stages of Railway Infrastructure renewal and maintenance projects and produce cost estimates that fall within an error range dictated by industry"

In order to address the research aim and to investigate the hypothesis the following objectives were developed.

3. Develop a Railway renewal and maintenance cost estimating methodology which is suitable for the initial stage of a project life cycle when there is a lack of data.
4. Develop a prototype software system based on the proposed methodology.
5. Validate the proposed methodology using three industrial case studies

The following section of this chapter will discuss how the research aim and objectives have been addressed.

7.3.1 Objective 1

Objective 1 was to identify and understand renewal and maintenance cost estimating knowledge and the cost estimating issues. This objective was achieved by conducting an extensive literature review.

7.3.1.1 Key Observations from the Literature Review

In order to achieve Objective 1 six research questions were developed as shown in Figure 9. The following section will discuss the results from these research questions.

1. *What approaches and techniques are currently used to estimate renewal and maintenance project costs?*

Evidence was presented showing that there are many different approaches to estimate renewal and maintenance costs. These techniques have included the use of equations (Muiga *et al.* (1979) and (Clark *et al.* (2002), bottom up estimation (Myers *et al.* (1778), regression analysis (Wahby *et al.* (2001), analogy based estimation (Rush (2003), parametric based estimation Al-Suhaibani *et al.* (1999) and Life Cycle Cost

Analysis (Zoeteman, A. *et al.* (1999). These results have been achieved by conducting content analysis on relating literature. The literature review results have shown that two studies have used bottom up estimating technique, four studies have used a parametric approach, one study used analogy, one study used regression analysis, lifecycle cost analysis was adopted in twelve studies and the use of equations was also adopted in twelve studies.

It was also observed that renewal and maintenance cost estimating involves the consideration of CAPEX and OPEX costs. CAPEX is concerned with capital expenditure whereas OPEX is concerned with the operational costs. This can be seen to be a major difference when compared to new product development cost estimation which does not involve the consideration of operational costs.

2. *What are the cost estimating themes and trends observed across domains?*

Evidence was presented showing that the use of life cycle cost analysis techniques are a common theme within the Railway renewal and maintenance literature. There is no other observed application of a cost estimating technique to estimate Railway renewal and maintenance costs. This is due to life cycle cost analysis techniques providing optimal renewal and maintenance cost estimates over a given life, which is a requirement of the infrastructure manager, whose goal is to develop optional renewal and maintenance strategies.

Excluding the Railway literature, the use of renewal and maintenance cost estimating equations and CER is also a very common theme. The use of this technique is applied across many domains and alongside life cycle costs analysis is the most widely used technique.

Furthermore, an argument is presented suggesting there is a lack of Railway renewal and maintenance cost estimating research when compared to other domains and paradigms.

3. *What are the main issues when estimating renewal and maintenance costs?*

Most renewal and maintenance studies discuss the use of historical quantitative data to produce estimates. However, evidence is presented suggesting that quantitative data can be fragmented, improperly referenced, might not be in a digital format, might not be self explanatory or may not be available at all.

Many of the models discussed in the literature are only specific to the situation that they were developed for. This therefore means that they are not generic to other problem areas. This may be explained by the many differences in the cost estimating problem environments and hence why many different models are developed.

4. *What are the gaps in the research literature that require further investigation?*

As the estimate move through the stages in the project life cycle more quantitative data becomes available for estimating purposes. However, during the early stages in the project life cycle there is lack of project definition and detail which results in lack of understanding of what data is required.

Data may also not be available at latter stages in the project life cycle. Evidence is presented suggesting literature falls to address the lack of methodologies which can produce cost estimates when quantitative cost data is limited or not available.

5. *How can the work of others help this research?*

It is observed that the renewal and maintenance cost estimating domain faces similar problems to software effort estimation problems including a lack of available quantitative data. Therefore, a proposed methodology by Sheppard *et al.* (2001) was modified and applied to the renewal and maintenance cost estimating problem.

7.3.2 Objective 2

Objective 2 was to understand how renewal and maintenance cost estimating is currently done within the Rail industry. This objective was achieved by eliciting cost estimating process knowledge through workshops and interviews with key industrial experts using a case study approach.

7.3.2.1 Key Observations from Renewal and Maintenance Cost Estimating: Current Practice

In order to achieve Objective 2 four research questions were developed as shown in Figure 9. The following section will discuss the results from these research questions.

6. *What is the most appropriate approach to model and analysis the industrial case study?*

A mechanism was needed to provide a means to understand and analyse the renewal and maintenance cost estimating processes within the industrial case. In order to collect data concerning process knowledge an approach was needed. Expert Process Knowledge Analysis Tool was chosen as the most suitable approach (XPat). The author was able to capture the tacit knowledge (knowledge in people's heads) and produce the information requirements for the development of IDEF0 process models. The data collection results were captured during industry attended workshops.

IDEF0 was chosen as the most appropriate approach to model the AS:IS state of the complex renewal and maintenance cost estimating processes. IDEF0 was chosen because it is a function modelling method which is designed to model the actions, and activities of an organisation or system. Also because the author had had previous training, because of it its availability and support. Once the processes were documented using IDEF0 it provided a means to identify weaknesses within the processes. The process models were validated using member checking and threats to data validity were considered.

7. *What approaches and techniques are currently used to estimate renewal and maintenance project costs within the industrial case study?*

Though the use of XPat and IDEF0 the cost estimating techniques and processes used within the industrial case study were identified. These cost estimating process included a five stage approach incorporating the production of an 'Order of Magnitude Estimate', a 'Budget Estimate', a 'Feasibility Estimate' and a 'Definitive Estimate'. The organisation was at the early stages of implementing this five stage approach using a bottom up cost estimating technique. The database containing the costs needed to produce the bottom up estimates was very underdeveloped and did not currently produce any estimates. Furthermore, because the database was underdeveloped estimates were produced by unstructured best guess.

8. *What are the main issues and challenges when estimating renewal and maintenance project costs?*

Though the use of XPat and IDEF0 the renewal and maintenance cost estimating issues were identified. In order to effectively implement a bottom up estimating approach much quantitative data is required. However, analysis has shown that cost data was fragmented, poorly referenced or not available. A cost structure which would be populated with historical cost data was needed.

Validation of the cost estimates was a manual process and done by an expert estimator. Furthermore, novice estimators had a large learning curve when understanding the complexities of the required quantities, suggesting a need for process which could automate the validation of the estimates and automate some of the estimating process.

Unstructured 'best guess' estimating was applied at the early stage of the project life cycle. Additionally, risk was not considered and therefore a 3 point estimating approach was needed.

The use of XPat and IDEF0 also provided the author and participating organisation with the data requirements, users of the data and activities that were involved in the estimate production process. IDEF0 has also helped define areas for further analysis and focus the direction of this research.

With an understanding of the current cost estimating processes within the organisation analysis of the most appropriate cost techniques for each stage in the process considering the current issues was undertaken. Due to lack of available data analogy based estimation is suggested as an appropriate approach to use at the early stages of the project life cycle.

9. *Do observations from the industrial case study validate the findings from literature?*

Evidence is presented suggesting that the results from the industrial case study do validate the finding from the literature review. Considering the findings from the industrial case study support the clams from the literature, they therefore further increase the justification for this research.

7.3.3 Objective 3

Considering the hypothesis generated after the literature review 'Objective 3' was to develop Railway renewal and maintenance cost estimating methodology which is suitable for the initial stage of a project life cycle when there is a lack of data. This objective was completed using three case studies which provided data to construct and validate the proposed models.

7.3.3.1 Key Observations from the Model Construct

In order to achieve Objective 3, two research questions were developed as shown in Figure 9. The following section will discuss the results from these research questions. One case study was used to construct and validate an S&C renewal cost model. A second case study was used to construct and validate the S&C maintenance cost model. Finally a third case study were assets including Track, Sidings and Insulated rail Joints were used to construct the project structure and validate the estimates produced by the methodology.

10. *What are the renewal and maintenance processes and 'cost drivers' relating to Railway renewal and maintenance projects?*

Since a main objective of this research was to develop a renewal and maintenance cost estimating methodology using pair wise comparisons data collection was required. To develop the 'project structure' stage in the proposed methodology (Section 5.5.4.1) switch and crossing renewal and maintenance processes, and the 'cost drivers' were captured during case study one and two. Whereas cost drivers were identified for Track, Sidings and Insulated Rail Joints projects during case study three. A main challenge in the development of the project structures during case study one was the availability of quantitative data. Therefore, during the case study activity, workshops and semi-structured interviews with related switch and crossing renewal experts were used to capture and document the process and cost drivers. A generic project structure could not be developed for case studies two and three due to a lack of available quantitative data. A knowledge elicitation workshop similar to the approach used in case study one could have provided the data required to produce a generic project for both case studies. However, due to access limitations with the experts this was not possible.

Case study one provided the bulk of the data required to construct the structured renewal cost estimating methodology. To reduce bias and make the results generic for Switch and Crossing renewal projects triangulation was employed. Multiple experts were also interviewed. All interviews were audio taped and transcribed. Content analysis was also performed on relating literature including internal company documents.

During case study two a structured maintenance cost estimating methodology was developed. Workshops were not employed rather using only a semi-structured interview with an expert. This was due to the size of the available sample. A new project structure relating to switch and crossing maintenance was developed. This structure replaced the renewal structure developed during case study one.

During case study three, five project scenario captured from internal documents were used to construct the project structure. The drivers contained within these project scenarios were translated into the project structure.

From analysis of the results during case study one it was observed the units and possessions to be the main cost drivers in renewal projects. Analysis of the results during case study two provide problematic in identifying the main cost drivers this was because many of the cost estimates were similar in size. The main cost driver identified during the analysis of the results from case study three suggests that the work process is the main cost driver in the renewal project.

11. What are the pairwise comparison ratio scales between alternatives?

Following the development of the 'project structure' during case study one, pairwise comparison was made by an expert during an interview. Comparisons were made based on five historical project scenarios, per case study, as discussed in Section 5.5.5. The project scenarios ranged in complexity, location and price. Pair wise comparisons were then made by an expert based on historical maintenance project scenarios.

The amount of pairwise comparisons that the expert requires to complete is dependant on the amount of identified project alternatives contained within the project being estimated. The main challenges when making pairwise comparisons it the time required to populate the square matrixes. Furthermore, the pairwise comparison process is repetitive and may become tedious. To a new user of the methodology the process may seem confusing and the user may not fully understand the use of the ratio scales, therefore suggesting the methodology should have an extensive help section with a working example shown.

7.3.4 Objective 4

Objective 4 was to develop a prototype software system based on the proposed methodology. This objective was achieved by using Microsoft Excel.

7.3.4.1 Key Observations from COMpairCOST Development

In order to achieve Objective 4 a research question were developed as shown in Figure 9. The following section will discuss the results from this research question.

12. What is the most appropriate approach to aid software prototype development?

The implementation of the proposed methodology into a software tool was discussed in Chapter 6. The software tool named "COMpairCOST" was developed using widely known and used software called Microsoft Excel. This means that many other organisations can understand and use the tool relativity easily. Excel provides a means to input data and run mathematic calculations on this data which is a requirement of the proposed cost estimating methodology.

Functionality was limited within Excel so Visual Basic Application was used to provide the additional functionally required. Random comparisons were used as test data during the development of COMpairCOST. This enabled inconstancies in the models calculations be identified and modified accordingly.

7.3.5 Objective 5

Objective 5 was to validate the proposed methodology using three case studies. This objective was achieved by using a total of fifteen projects from a switch and crossing renewal case study, a switch and crossing maintenance case study and a Track, Sidings and Insulated Rail Joint case study.

7.3.5.1 Key Observations from the Validation

In order to achieve Objective 5 six research questions were developed as shown in Figure 9. This section will discuss the results from theses questions.

13. Across three case studies what are COMpairCOST's validation results?

The development of COMpairCOST provided a means to validate the proposed cost estimating methodology. To validate the methodology five historical projects were identified from each case study. Five cost models were constructed based around the 'project structures' developed from the three case studies including, S&C renewal, S&C maintenance and a mixture of Track, Sidings and Insulated Rail Joint renewal and maintenance.

During case study one the cost estimates produced by the methodology were compared with cost estimates produced by a consultant (percentage allowance) and the real project costs. Analysis of the results indicates that the consultants' estimates were underestimated and the methodologies were overestimated. This underestimation may be explained by technical, economic, physiological or political factors as suggested by Flyvbjerg, *et al* (2002). This may then suggest using the structured methodology presented in the research may remove some of these issues when estimating costs.

Two estimates produced by the methodology had a high level of error they include, the Welwyn garden City scenario and the Hatfield South scenario. The error in the Welwyn garden City scenario may be explained by the work process criteria not appearing to be related to the number of units renewed. The error in the Hatfield South scenario may be explained by the overestimated possession costs.

Following analysis of the results during case study two, the reason why there is such a large error in the Rail reclamation by welding scenario estimate and the is LO2 switch body maintenance scenario difficult to conclude however that the ratio scales may have been biased by the lack of experience of similar projects.

A comparison of the cost estimates produced by the methodology, broken down at 'alternative' level, with the real project costs suggested that some of the alternatives being compared were considerably over estimated or underestimated. Similarly to case study two the reason to why these occurred is difficult to conclude, other then to say the expert may have been biased in this experience of this type of project.

Suggestions to why the methodology produced errors across all three case studies were investigated for trends and are presented in Table 6.5. Through the use of subjective analysis reasons why there were high degrees of error include, manual error, the recall from memory of a similar project was biased due to when the expert was involved in the similar project. Comparisons of certain alternatives are difficult, how similar the project used as a reference to the new project estimated may affect the accuracy.

Analysis across the three case studies suggest that of the fifteen projects three estimates produced by the methodology had an error of +- 10% from the real price, five estimates had an error of +- 20%, nine projects had an error +-30%, eleven projects had an error of +- 40% and, twelve of the 15 project scenarios had an error of +- 50 %.

Additional analysis was conducted to investigate any possible correlations between factors including number of year's experience, size of the project in terms of cost and number of the cost elements compared with the level of error in the cost estimate produced by COMpairCOST. The results suggest that there are no correlations between these factors and the estimate level of error.

To test COMpairCOST for usability a structured questionnaire was developed which and fourteen respondents interviewed. In general the users found COMpairCOST to be easy to use. However, some respondents had expressed concerns over the help features and the presentation of the interface. Considered these issues COMpairCOST was modified accordingly.

A Monty Carlo and Sensitivity analysis was carried out on COMpairCOST using one of the historical project scenarios. The aim was to understand the uncertainty in the pairwise comparison scores and to identify the certainty of the cost estimate for each alternative falling within a range of costs. The aim of the results from the sensitivity analysis was to identify what were the important pairwise comparisons and how much they affected the resulting estimate. These results would then be used to either remove less sensitive comparisons as they has minimum affect on the cost estimate thus reducing the number of comparison the expert has to make. However, the results suggested that all comparison have nearly equal importance.

14. Do the results prove or disprove the hypothesis?

These results prove the hypothesis to be true most of the time with twelve of the fifteen estimates falling under the required level of error. Suggesting that the proposed structured methodology can be a beneficial approach to estimating renewal and maintenance cost at the early project life cycle stages when there is a lack of quantitative cost data available.

15. Do the results from the three case studies lead to any generalisations?

The validation was conducted over three case studies, one case study was based on switch and crossing renewal projects, one was based on switch and crossing maintenance projects and the third case study was based on additional renewal assets including Track, Sidings and Insulated Rail Joints. The results suggest that the methodology has been successful across these assets and it could therefore be generalised that it would be successful across all Railway assets.

However, the methodology may not suitable when comparing alternatives from projects that are greater in terms of cost then the verbal/ratio scale suggested by (Saaty (1990)). Should this situation occur it would be advisable to produce a square matrix with alternatives that are no greater the +- nine times each other. This would however change the aggregation of costs within the model.

16. Can the proposed methodology be applied to stages 4 and 5 in the project life cycle?

The main focus of this research has been the application of the proposed methodology to estimate costs at the early stages in the project life cycle. However, a study was conducted which investigated the applicability of the proposed methodology to stages four and five of the project life cycle. A sample of three experts was interviewed using an unstructured focus group approach. The main conclusion from the results suggests that the methodology would not be an appropriate approach to estimate costs at these stages because of issues with collection of assumptions.

7.4 Location of Research within the Taxonomy / Classification of other Cost-Estimating Approaches

R.Roy (2003) suggests that cost estimating approaches can be classified into the following groups. Traditional costing, Bottom up, Activity based costing, Feature based costing, Parametric cost estimating, and Analogy based costing. The research presented in this thesis locates itself within the 'Analogy' taxonomy / classification of cost estimating processes. Analogy is concerned with transferring information from a particular subject (the analogue or source) to another particular subject (the target). The proposed cost estimating approach suggested in this research draws on the past experience an estimator has of similar projects (analogue or source) to the current project (the target) which requires costs to be estimated.

Classification of Analogy based estimation covers three main groups these include Case Based Reasoning, the use of the Analytic Hierarchy Process and the third group is a more general group which covers approaches that can not be classified by the other two groups. The proposed approach discussed in this thesis uses some of the techniques suggested in the analytical hierarchic process and therefore it should be located in this classification. However, much of the use of Analytic Hierarchy Process research is based within the software effort estimation domain, whereas this research has been based within Railway renewal and maintenance cost estimating domain.

7.5 Transferability to Other Problems

Considering the case study results a generalisation has been drawn that the proposed methodology can be applied to the renewal and maintenance costs of other railways assets.

This research has taken from the software domain an approach that uses pair wise comparisons to estimate effort, and applied this to estimate renewal and maintenance costs in the Railway domain. The successful transfer of domains and problems suggests that pair wise comparisons and the methodology discussed in this thesis could be applied to estimate any problem that could be broken down into a 'project Structure'. However further validation using additional case studies describing different problems and domains need to be done before this is conclusive.

7.6 Business Impact Analysis

The impact of using the methodology in an organisation would mainly involves the project structure. The project structure would need to be developed based around the asset in question. This thesis has identified that data to build this structure can be limited and therefore knowledge elicitation techniques need to be used to elicit the data required for the structure, from experts. This exercise can prove time consuming and therefore expensive for an organisation.

The representation of the methodology was achieved by developing a prototype software system using Microsoft Excel. This was done because it provided an inexpensive means of testing the research. Furthermore, Microsoft Excel can easily, quickly and cheaply be implemented and integrated onto a Microsoft Windows workstation.

Maintenance issues will need to be considered. The project structure would need to be updated with new e.g. work processes, new techniques, new materials, should they be introduced into the organisations renewal and maintenance plans. Similarly the base project containing the predefined ratio scores would need to be updated should any new e.g. work process or materials technique be introduced.

The development of a handbook which describes the methodologies process with the use of examples may also need to be considered. The handbook would be similar to a 'help file' and would reduce the bias in the comparison due to the expert not fully understanding how to use the ratio scores or other aspects of the methodology.

7.7 Research Contributions

This research has made the following contributions to renewal and maintenance cost estimating knowledge.

The primary contribution of this research stems from the development of a structured renewal and maintenance cost estimating methodology that provides cost estimates at the early project life cycle stages when quantitative data is limited. The development of the methodology was achieved by modifying an effort estimation methodology from the Software domain (Sheppard and Cartwright (2001), and applying it to renewal and maintenance cost estimating problems in the Railway Domain.

Additionally, through the critical evaluation of the literature, the research has identified the main challenges in renewal and maintenance cost estimating.

This research has extended Railway renewal and maintenance knowledge by developed a generic Switch and Crossing project structure.

This research has captured tacit knowledge from experts using pair wise comparisons. This knowledge has included the relationships between Switch and Crossings, Track, Sidings and Insulated Rail Joints project drivers in terms of the comparative size of the costs. Furthermore, this research has also identified major cost drivers based on a series of case studies.

Considering the proposed methodology is located in the taxonomy of Analogy based cost estimating this research has extended this knowledge by combining pair wise comparison and 3 Point estimating.

Based on the results from the case studies the proposed methodology can be generalised and contribute to estimating renewal and maintenance costs of all assets within the Railway domain.

7.8 Limitations

This work has several limitations. The following section will discuss these limitations. A literature review was the main method to achieve Objective 1. An extensive review of the library catalogue and electronic e-journals provided by Cranfield University was undertaken. Analysis of the paper reference lists led to further data. However, the university does not provide an exhaustive list of e-journals nor can data unavailable from the library catalogue be collected through an interlibrary loan on all occasions due to resource issues.

Validation of the IDEF0 models and project structure in Case study two and three was done by experts. It would have been better to use another expert who was not involved during the development stages.

Three case studies were used to construct and validate the proposed methodology. Case study one developed a generic project structure through the use of different primary and secondary data collection techniques however, the main limitation for case study two was that only one expert was interviewed in order to construct and validate the project structure. In order to make the maintenance model generic (Case study 2) it would have been better to interview a number of maintenance experts and used triangulation. Similarly, during case study three a generic project structure was not developed.

Historical project scenario data needed to validate the model during case study one was limited; a structured questionnaire was therefore developed. Only one expert was interviewed using this questionnaire. This therefore could suggest that the scenario costs used to validate the methodology against could be prone to bias. It would have been better to have interviewed many experts and collectively used the results for each scenario. This however was not possible due to expert access constraints.

One of the fundamental limitations of the methodology is that the output cost estimates are dependant on the ratio score made by an expert. The comparisons made by an expert are based on his or her experience. Flyvbjerg, *et al* (2002) suggests that cost estimating based on experience can be prone to bias. Furthermore, the model can only be used by an individual who has experience of similar projects.

A focus group was used to understand the proposed methodologies application at stages 4 and 5 in the project life cycle. The data captured during this exercise was conducted by active listening and note taking. Validity might have been improved by recording the session using audio tape, however due to confidentially this was not permitted. Any use of audio tapes may have prevented the attendees from freely speaking there minds.

The usability of the model was investigated. The methodology was presented and time was allocated for the respondent to use the model. It was felt that not enough time was allocated to the use the model before the questionnaire was answered. This may have influenced the questionnaire results.

The model developed during case study two and three do not provide any 'what if' analysis and do not allow reuse of ratio scores.

7.9 Recommendations for Further Work

The research would benefit further by developing a generic switch and crossing maintenance project structure. This would require a more through evaluation of additional maintenance case studies within industry.

The methodology has been applied to five project scenarios which are not of a switch and crossing asset. To validate the models applicability to other assets further case studies of different assets would be of benefit.

Currently the model can only be used by an experienced estimator who populates the matrix with pairwise comparison score accordingly. Once these comparison score have been completed the model holds valuable data which could be reused. This reuse of comparison data could be explored with the aim of allowing a novice estimator to use the tool. As well as speeding up the whole estimate production process.

An in depth understanding of the experts experience / rational when populating the square matrixes with ratio scores is needed. This understanding could help towards answering why the methodology was producing accurate and inaccurate estimates. This thesis has made some attempt to try to understand this by investigating some correlation between factors including number of year's experience and the author has suggested some possible reasons however, further work needs to be done.

Furthermore, an understanding of the rational may provide an understanding of the experience requirements, an estimator would need, in order to use the methodology effectively. This may be in the form of a check list type tool.

Knowledge management is also a key area of further work. The knowledge captured using the proposed methodology could be classifying and categorising according to ontology for sharing and reuse within an organisation.

7.10 Conclusions

The research has achieved all the objectives set in Chapter 3. The key conclusions from the research are:

- Renewal and Maintenance cost estimating is researched in many industries. There is a distinct lack of research within the UK Railways concerning renewal and maintenance cost estimating. There is a lack of knowledge about the cost drivers for the Railway renewal and maintenance projects.

- It is observed that predicting cost of Renewal or Maintenance activities within the Railway Industry is very ad-hoc at the early stage of a project. There is a significant lack of a structured methodology to the cost estimating. Furthermore, the amount of data available at the early stage is limited, and that makes cost estimating more challenging.

- The research has identified major factors that affect renewal and maintenance costs in the Railway Industry. The study has also identified major cost drivers based on a series of case studies.

- The research has demonstrated that it is possible to develop a structured cost estimating methodology for Railway renewal and maintenance activities using a pair wise comparison based approach. The methodology is suitable for early stage cost estimating.

- The study has also developed a prototype to implement the methodology.

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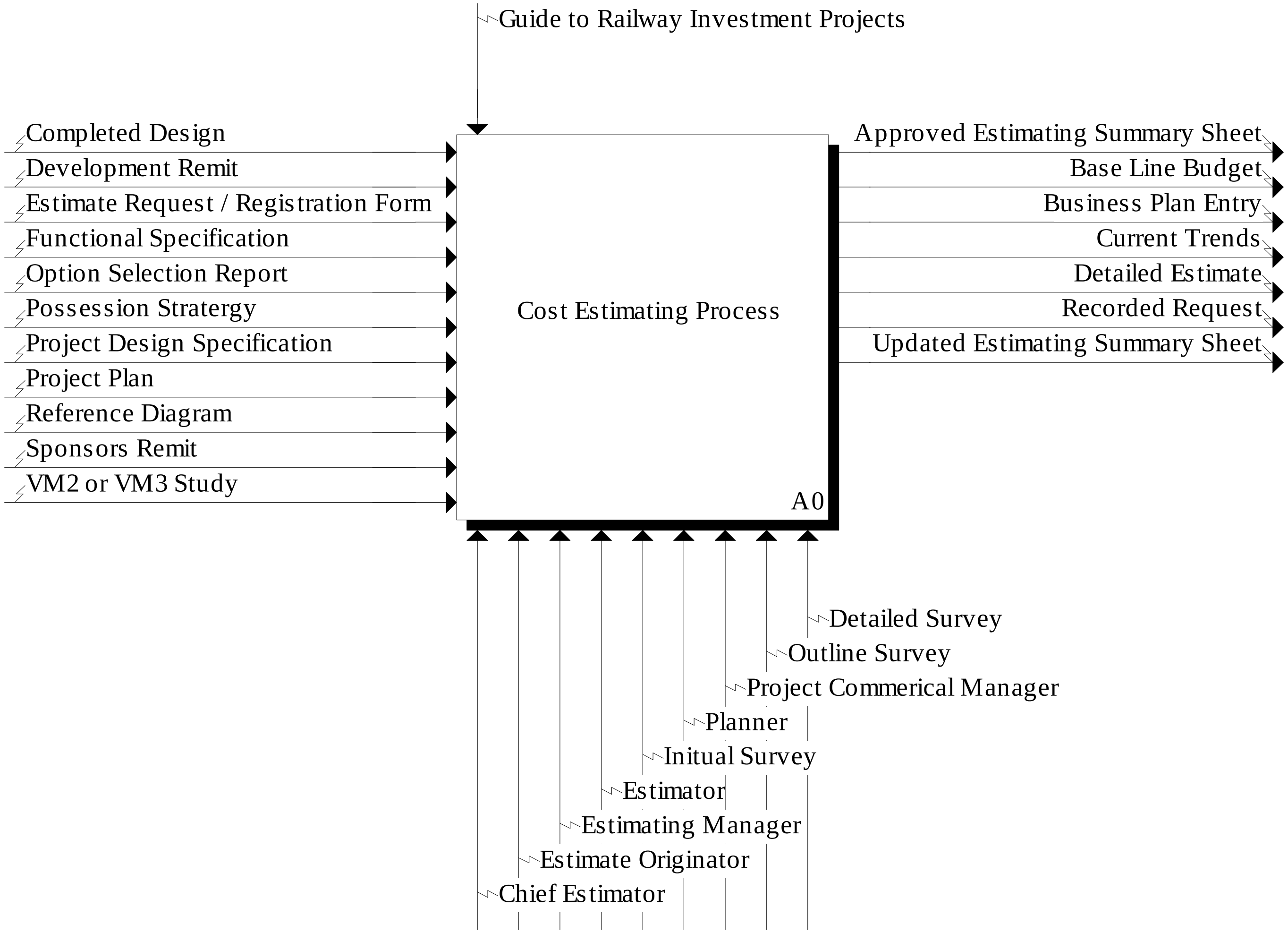
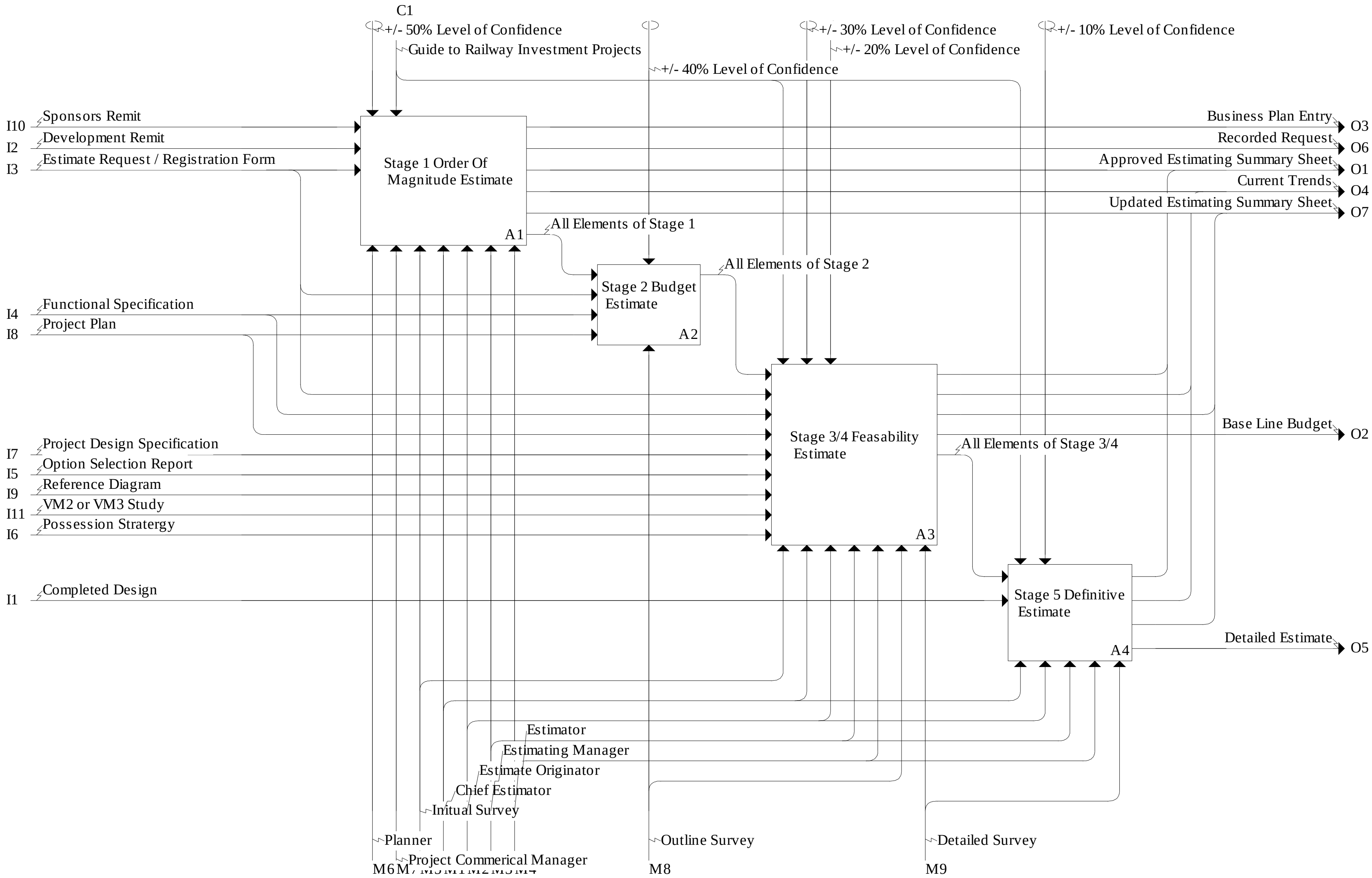
APPENDIX 1 – IDEF0 Process Models


Guide to Railway Investment Projects
Completed Design
Development Remit
Estimate Request / Registration Form
Functional Specification
Option Selection Report
Possession Stratergy
Project Design Specification
Project Plan
Reference Diagram
Sponsors Remit
VM2 or VM3 Study
Cost Estimating Process
A0
Approved Estimating Summary Sheet
Base Line Budget
Business Plan Entry
Current Trends
Detailed Estimate
Recorded Request
Updated Estimating Summary Sheet
Detailed Survey
Outline Survey
Project Commerical Manager
Planner
Initual Survey
Estimator
Estimating Manager
Estimate Originator
Chief Estimator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Guide to Railway Investment Projects
+/- 40% Level of Confidence
+/- 30% Level of Confidence
+/- 20% Level of Confidence
+/- 10% Level of Confidence
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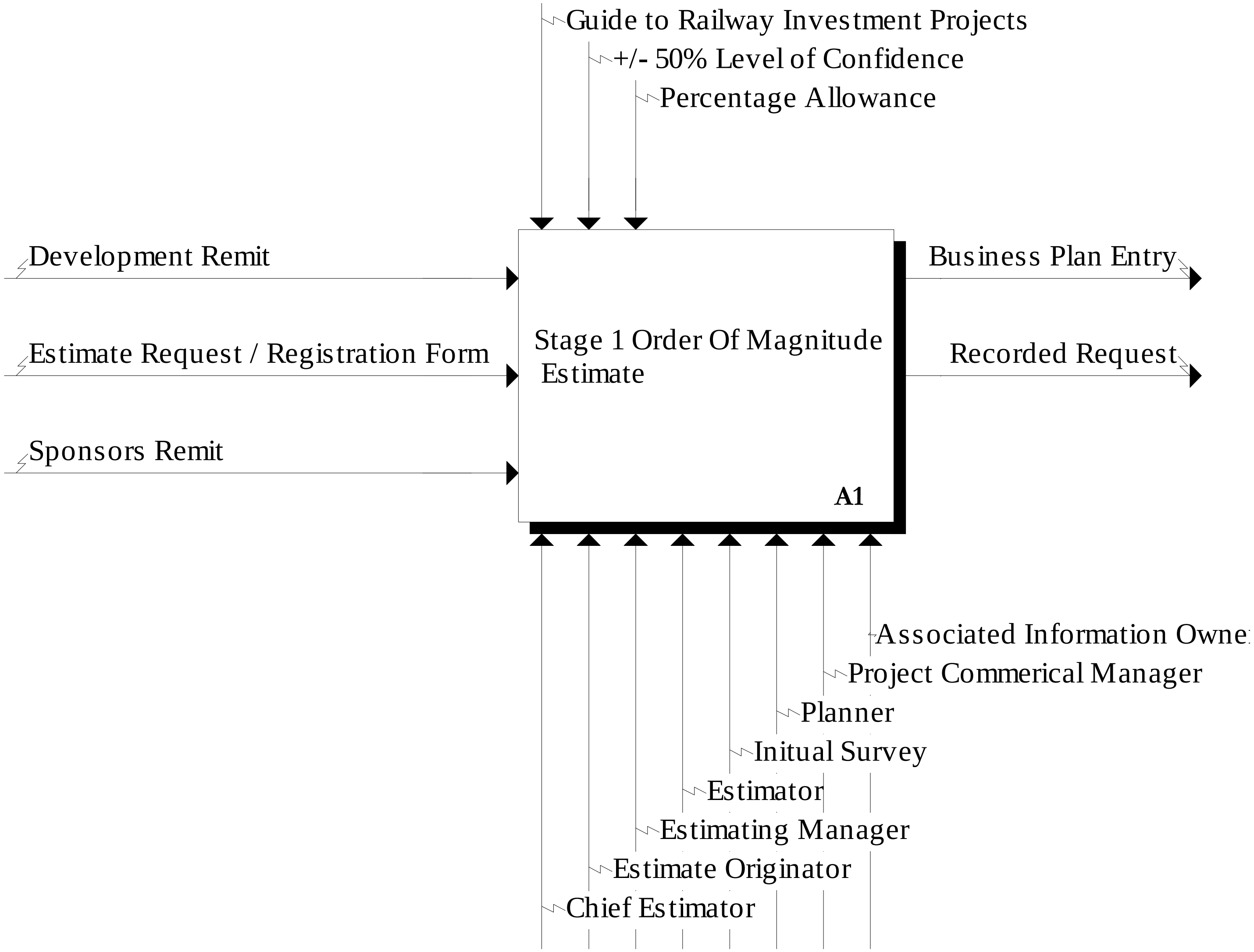
I2 Development Remit
I3 Estimate Request / Registration Form
Stage 1 Order Of Magnitude Estimate
A1
Business Plan Entry O3
Recorded Request O6
Approved Estimating Summary Sheet O1
Current Trends O4
Updated Estimating Summary Sheet O7
All Elements of Stage 1
Stage 2 Budget Estimate
A2
All Elements of Stage 2
I4 Functional Specification
I8 Project Plan
Stage 3/4 Feasability Estimate
A3
Base Line Budget O2
All Elements of Stage 3/4
I7 Project Design Specification
I5 Option Selection Report
I9 Reference Diagram
I11 VM2 or VM3 Study
I6 Possession Stratergy
I1 Completed Design
Stage 5 Definitive Estimate
A4
Detailed Estimate O5
Estimator
Estimating Manager
Estimate Originator
Chief Estimator
Initual Survey
Planner
Project Commerical Manager
Outline Survey
Detailed Survey
M6 M7 M5 M1 M2 M3 M4
M8
M9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Percentage Allowance
Development Remit
Estimate Request / Registration Form
Sponsors Remit
Stage 1 Order Of Magnitude Estimate
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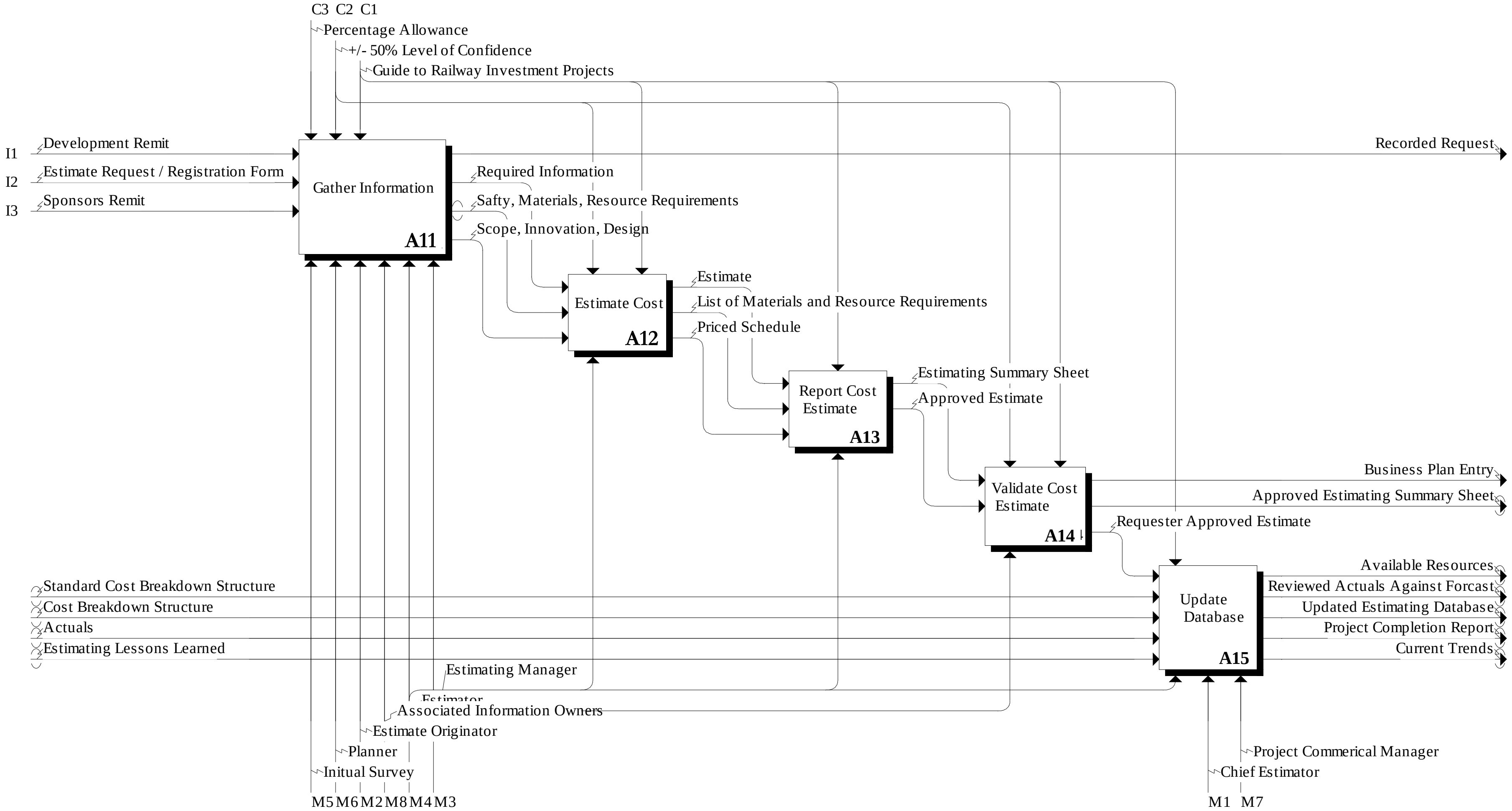
Recorded Request
Associated Information Owne
Project Commerical Manager
Planner
Initual Survey
Estimator
Estimating Manager
Estimate Originator
Chief Estimator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Percentage Allowance
+/- 50% Level of Confidence
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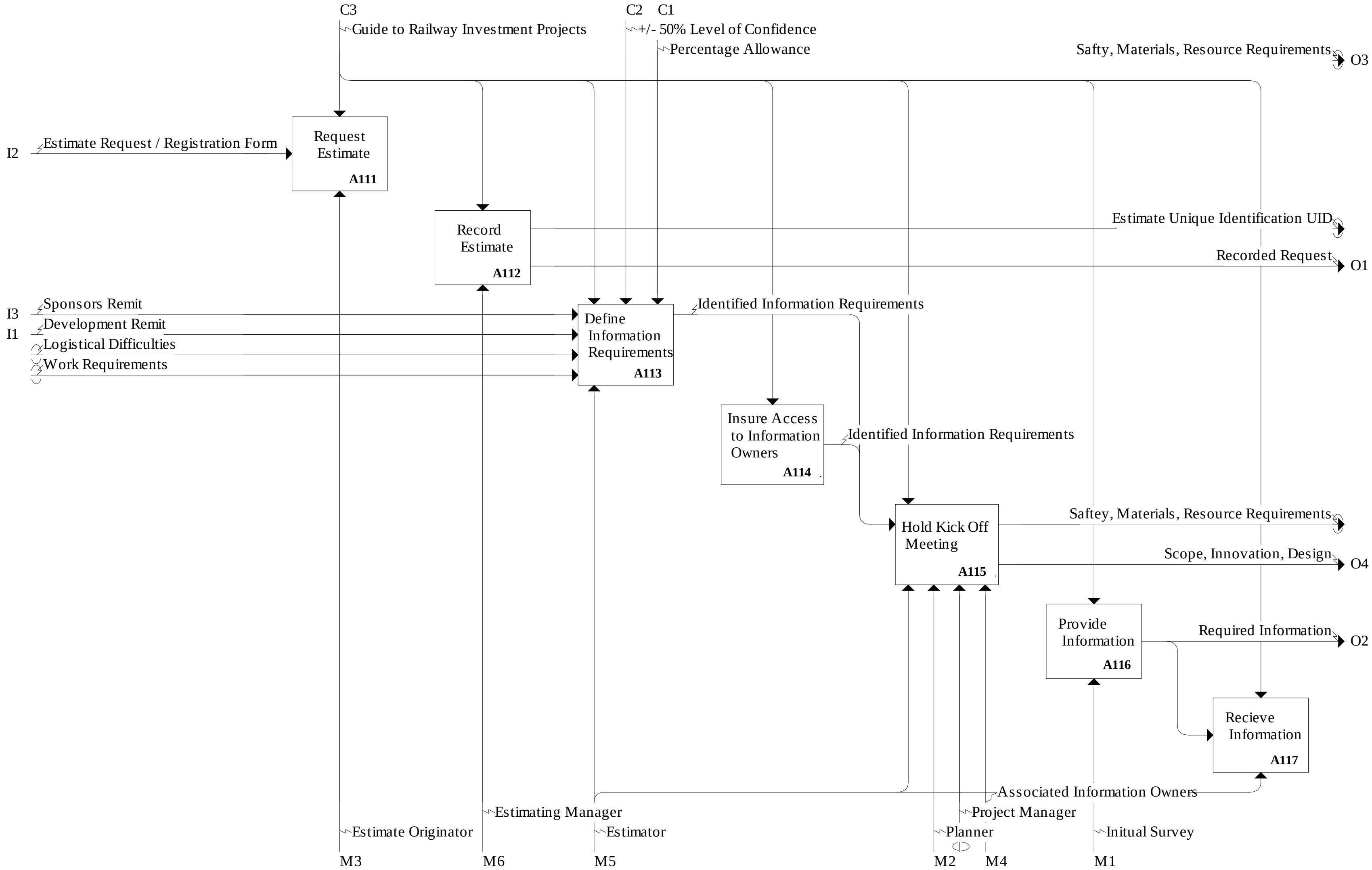
Development Remit
I2
Estimate Request / Registration Form
I3
Sponsors Remit
Gather Information
A11
Required Information
Safty, Materials, Resource Requirements
Scope, Innovation, Design
Recorded Request
O2
Estimate Cost
A12
Estimate
List of Materials and Resource Requirements
Priced Schedule
Report Cost Estimate
A13
Estimating Summary Sheet
Approved Estimate
Validate Cost Estimate
A14
Business Plan Entry
O1
Approved Estimating Summary Sheet
Requester Approved Estimate
Update Database
A15
Available Resources
Reviewed Actuals Against Forcast
Updated Estimating Database
Project Completion Report
Current Trends
Standard Cost Breakdown Structure
Cost Breakdown Structure
Actuals
Estimating Lessons Learned
Estimating Manager
Associated Information Owners
Estimate Originator
Planner
Initual Survey
M5 M6 M2 M8 M4 M3
Project Commerical Manager
Chief Estimator
M1 M7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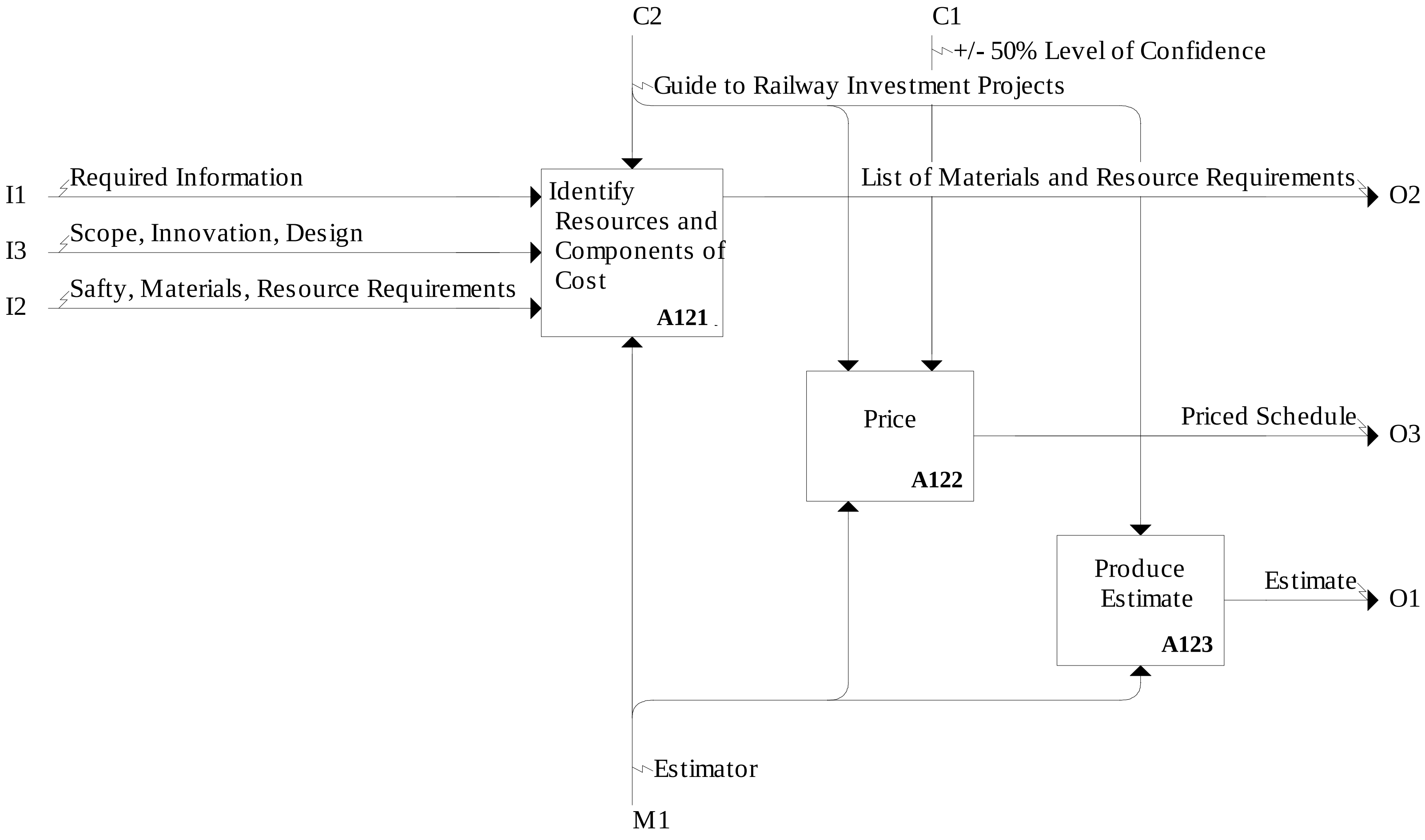
Guide to Railway Investment Projects
C2
C1
+/- 50% Level of Confidence
Percentage Allowance
Safty, Materials, Resource Requirements
O3
I2
Estimate Request / Registration Form
Request Estimate
A111
Record Estimate
A112
Estimate Unique Identification UID
Recorded Request
O1
I3
Sponsors Remit
I1
Development Remit
Logistical Difficulties
Work Requirements
Define Information Requirements
A113
Identified Information Requirements
Insure Access to Information Owners
A114
Identified Information Requirements
Hold Kick Off Meeting
A115
Saftey, Materials, Resource Requirements
Scope, Innovation, Design
O4
Provide Information
A116
Required Information
O2
Recieve Information
A117
Associated Information Owners
Estimating Manager
Project Manager
Estimate Originator
Estimator
Planner
Initual Survey
M3
M6
M5
M2
M4
M1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I3
Scope, Innovation, Design
I2
Safty, Materials, Resource Requirements
Identify Resources and Components of Cost
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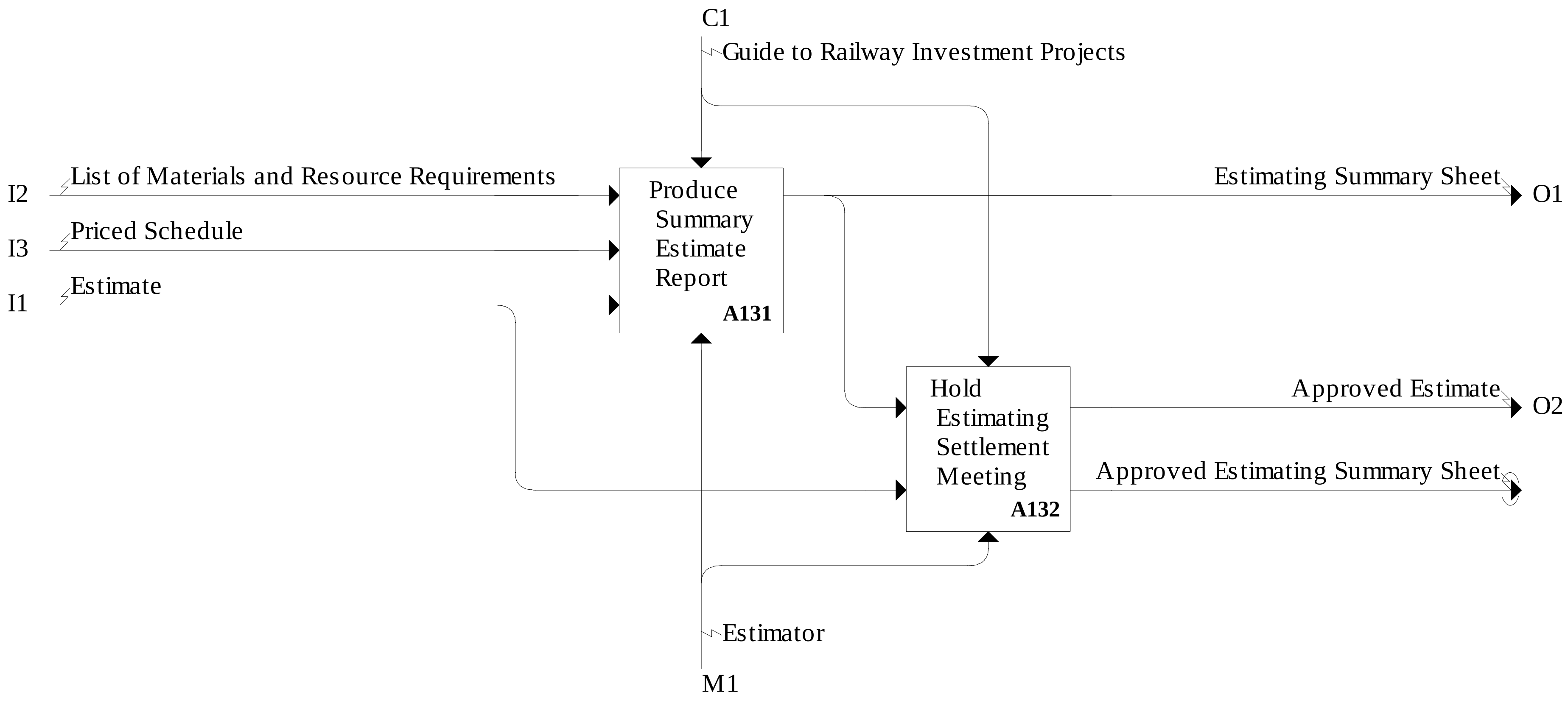
List of Materials and Resource Requirements
O2
Price
A122
Priced Schedule
O3
Produce Estimate
A123
Estimate
O1
Estimator
M1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I3
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I1
Estimate
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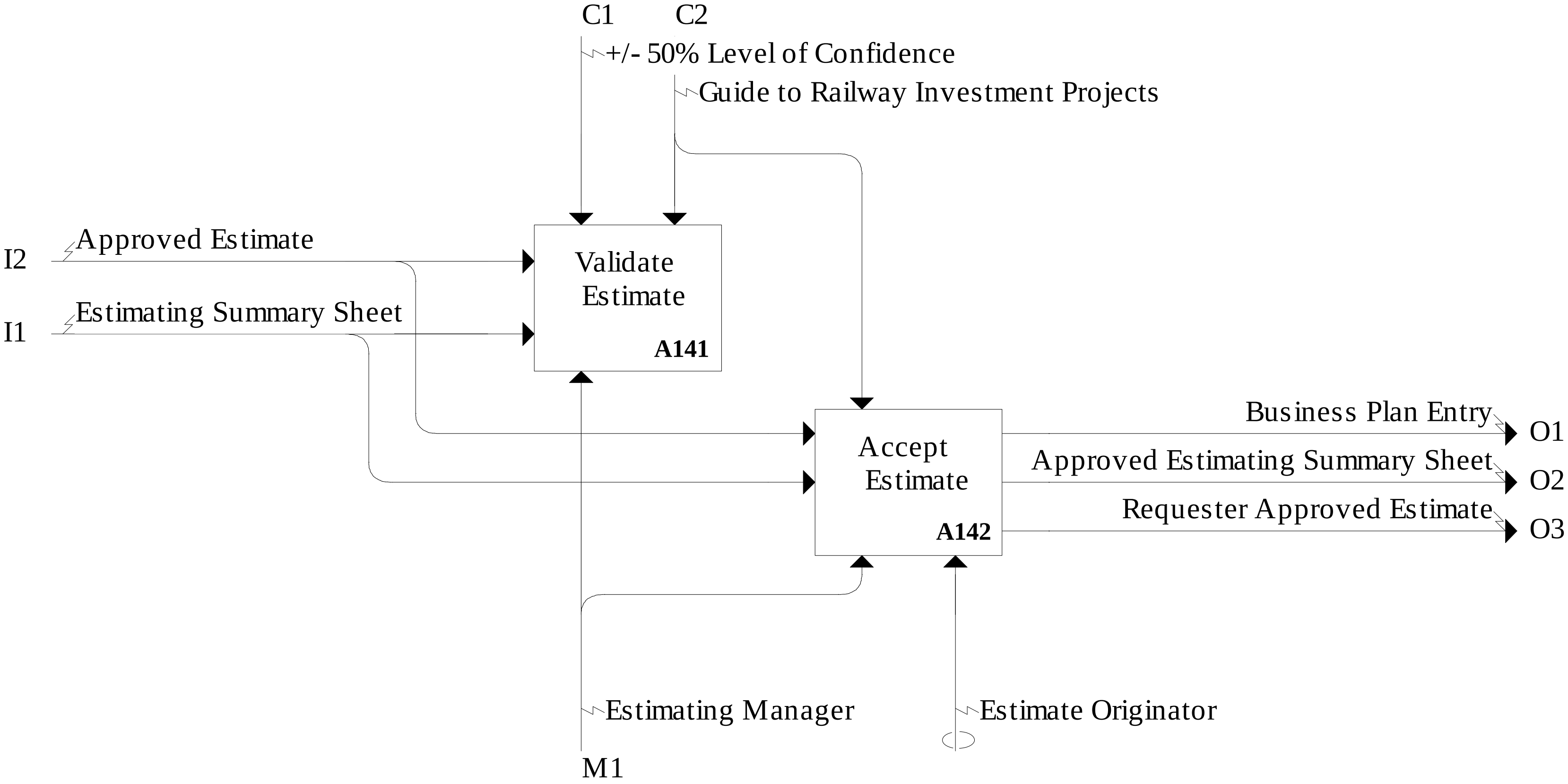
Estimating Summary Sheet
O1
Hold Estimating Settlement Meeting
A132
Approved Estimate
O2
Approved Estimating Summary Sheet
Estimator
M1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C2
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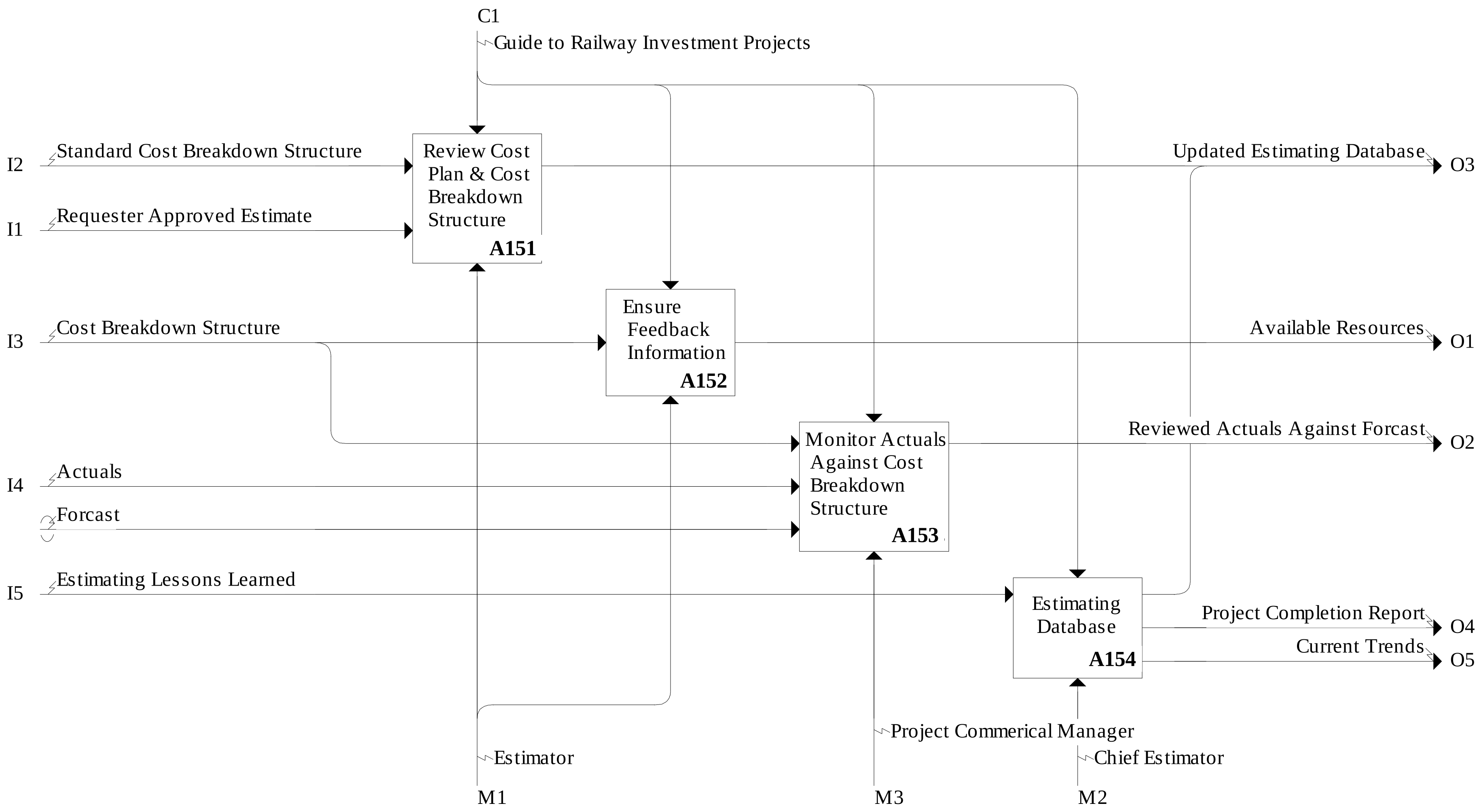
I1
Estimating Summary Sheet
Validate Estimate
A141
Accept Estimate
A142
Business Plan Entry
O1
Approved Estimating Summary Sheet
O2
Requester Approved Estimate
O3
Estimating Manager
Estimate Originator
M1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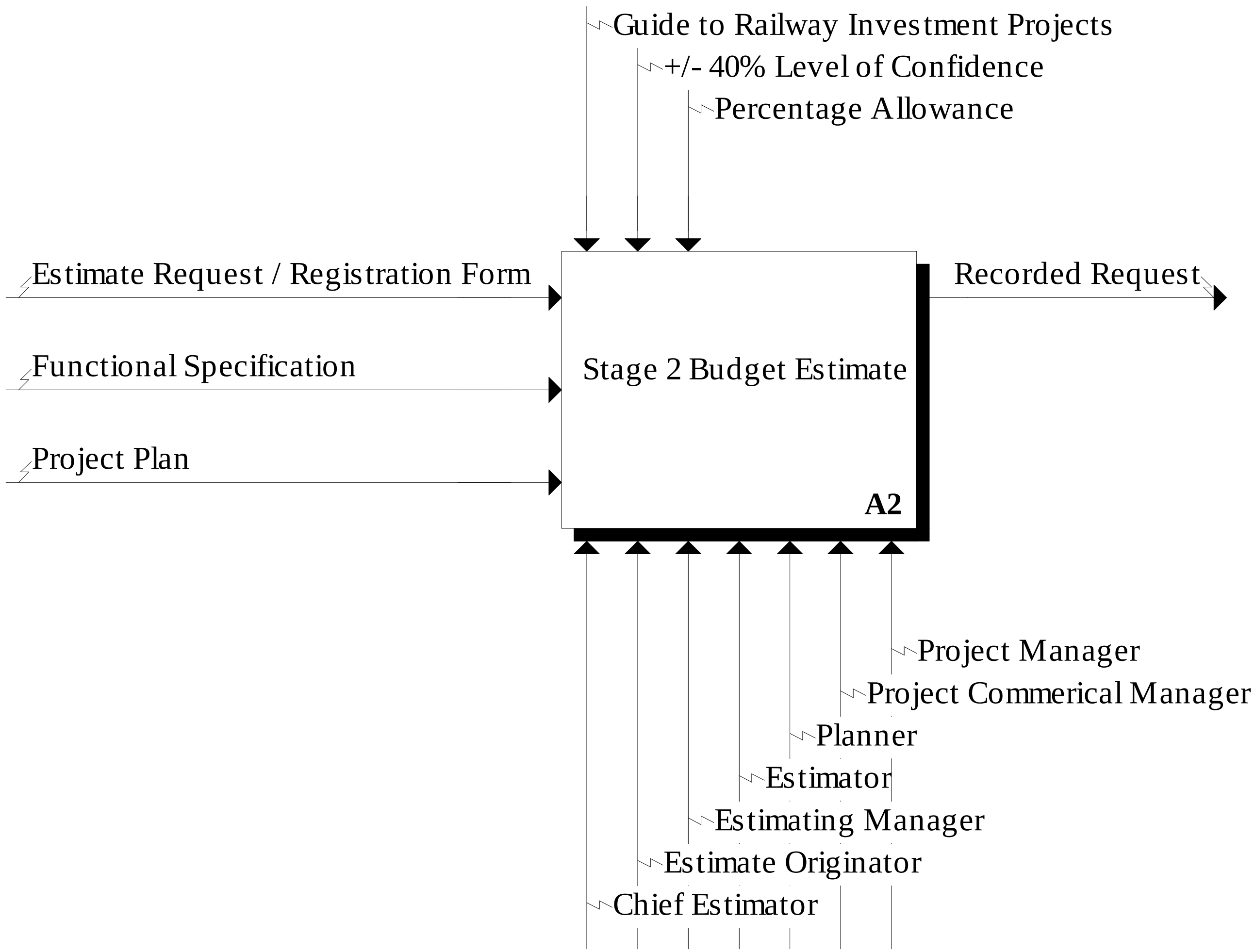
Guide to Railway Investment Projects
I2
Standard Cost Breakdown Structure
I1
Requester Approved Estimate
Review Cost Plan & Cost Breakdown Structure
A151
I3
Cost Breakdown Structure
Ensure Feedback Information
A152
I4
Actuals
Forcast
Monitor Actuals Against Cost Breakdown Structure
A153
I5
Estimating Lessons Learned
Estimating Database
A154
Updated Estimating Database
O3
Available Resources
O1
Reviewed Actuals Against Forcast
O2
Project Completion Report
O4
Current Trends
O5
Estimator
M1
Project Commerical Manager
M3
Chief Estimator
M2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Percentage Allowance
Estimate Request / Registration Form
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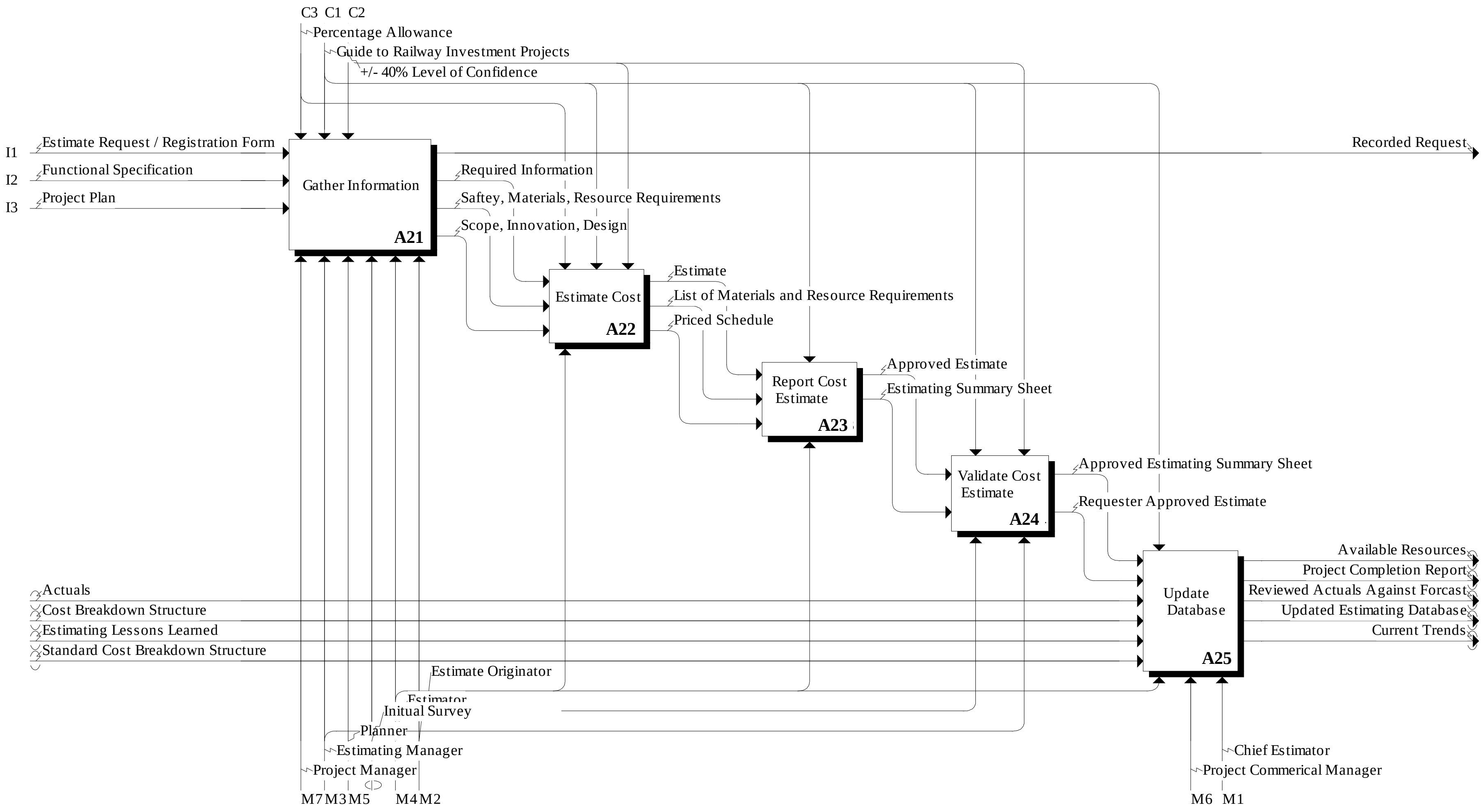
Project Plan
Stage 2 Budget Estimate
A2
Recorded Request
Project Manager
Project Commerical Manager
Planner
Estimator
Estimating Manager
Estimate Originator
Chief Estimator


C3 C1 C2
Percentage Allowance
Guide to Railway Investment Projects
+/- 40% Level of Confidence
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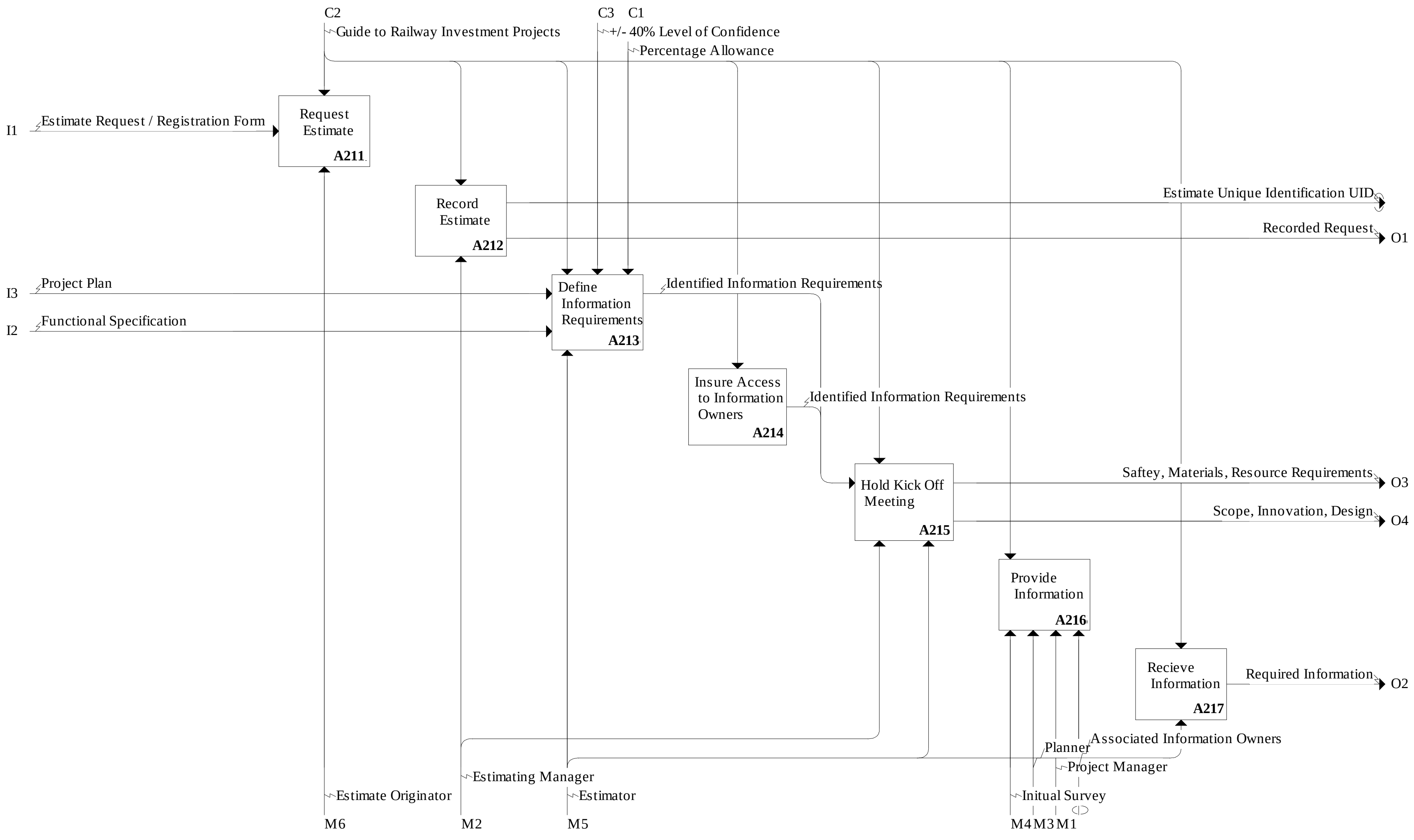
Estimate Request / Registration Form
I2
Functional Specification
I3
Project Plan
Gather Information
A21
Recorded Request
O1
Required Information
Saftey, Materials, Resource Requirements
Scope, Innovation, Design
Estimate Cost
A22
Estimate
List of Materials and Resource Requirements
Priced Schedule
Report Cost Estimate
A23
Approved Estimate
Estimating Summary Sheet
Validate Cost Estimate
A24
Approved Estimating Summary Sheet
Requester Approved Estimate
Update Database
A25
Available Resources
Project Completion Report
Reviewed Actuals Against Forcast
Updated Estimating Database
Current Trends
Actuals
Cost Breakdown Structure
Estimating Lessons Learned
Standard Cost Breakdown Structure
Estimate Originator
Estimator
Initual Survey
Planner
Estimating Manager
Project Manager
M7 M3 M5 M4 M2
Chief Estimator
Project Commerical Manager
M6 M1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Guide to Railway Investment Projects
C3
C1
+/- 40% Level of Confidence
Percentage Allowance
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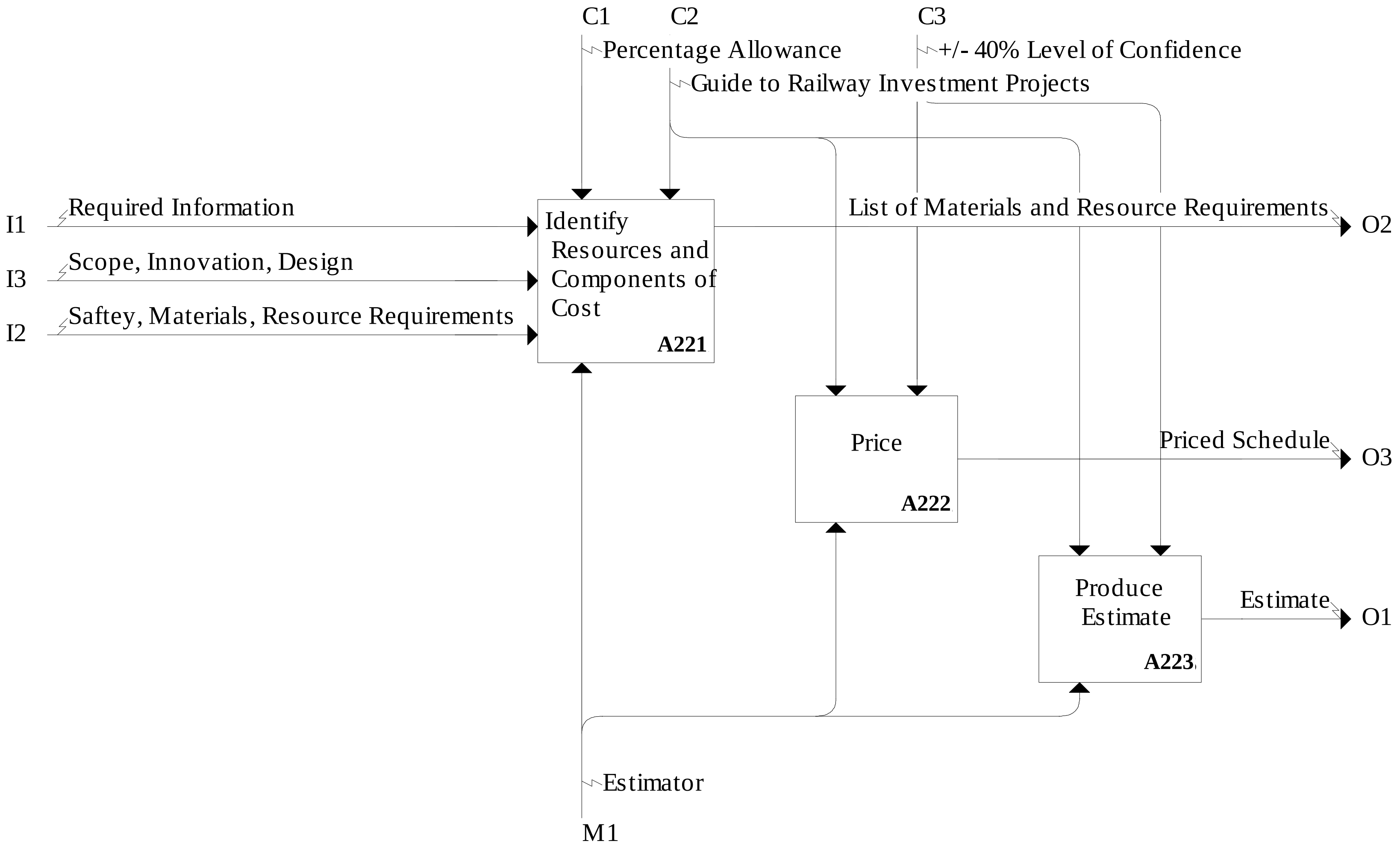
Estimate Request / Registration Form
Request Estimate
A211
Record Estimate
A212
Estimate Unique Identification UID
Recorded Request
O1
I3
Project Plan
I2
Functional Specification
Define Information Requirements
A213
Identified Information Requirements
Insure Access to Information Owners
A214
Identified Information Requirements
Hold Kick Off Meeting
A215
Saftey, Materials, Resource Requirements
O3
Scope, Innovation, Design
O4
Provide Information
A216
Recieve Information
A217
Required Information
O2
Associated Information Owners
Planner
Project Manager
Estimating Manager
Estimate Originator
Estimator
Initual Survey
M6
M2
M5
M4
M3
M1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C2
C3
Percentage Allowance
+/- 40% Level of Confidence
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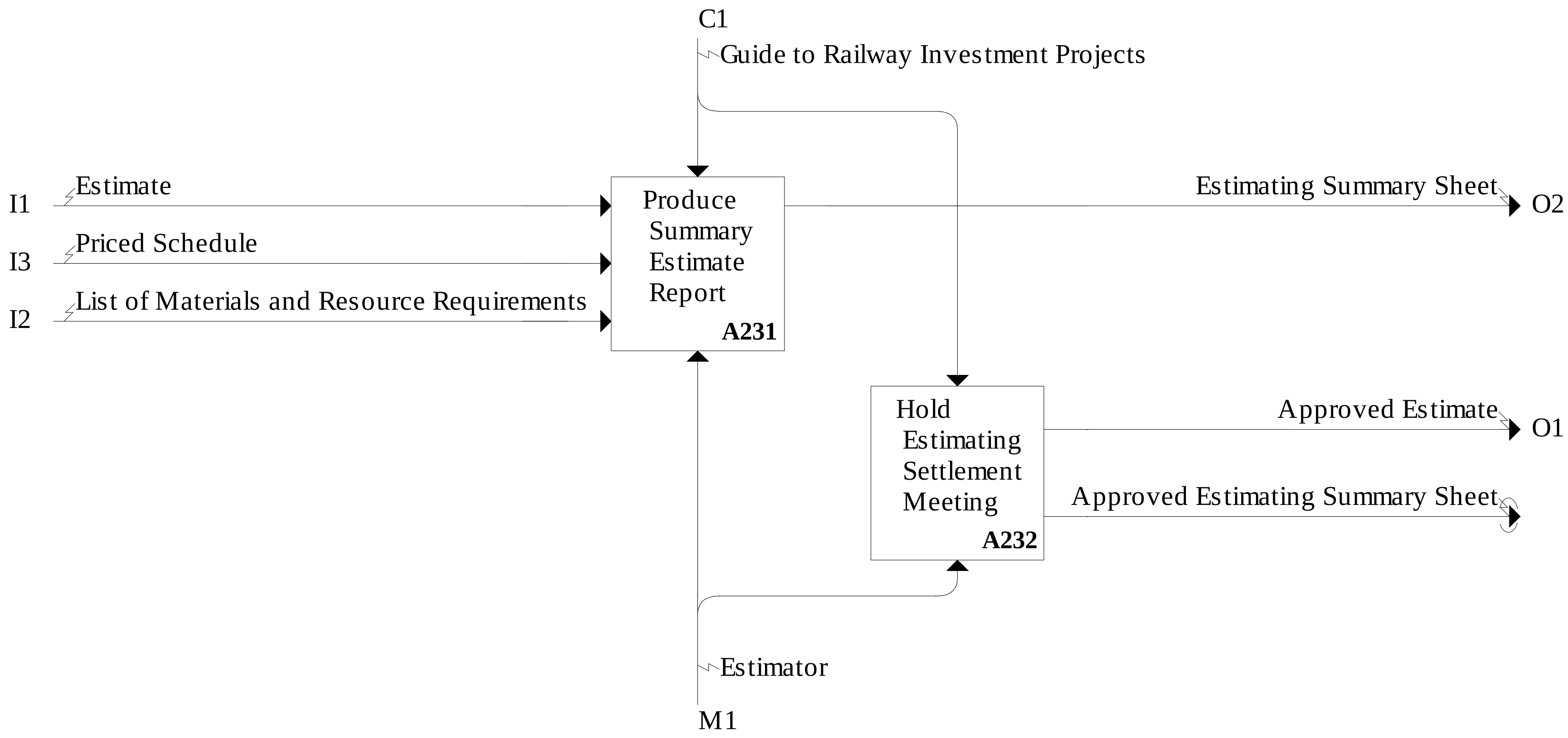
Required Information
I3
Scope, Innovation, Design
I2
Saftey, Materials, Resource Requirements
Identify Resources and Components of Cost
A221
List of Materials and Resource Requirements
O2
Price
A222
Priced Schedule
O3
Produce Estimate
A223
Estimate
O1
Estimator
M1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Guide to Railway Investment Projects
I1
Estimate
I3
Priced Schedule
I2
List of Materials and Resource Requirements
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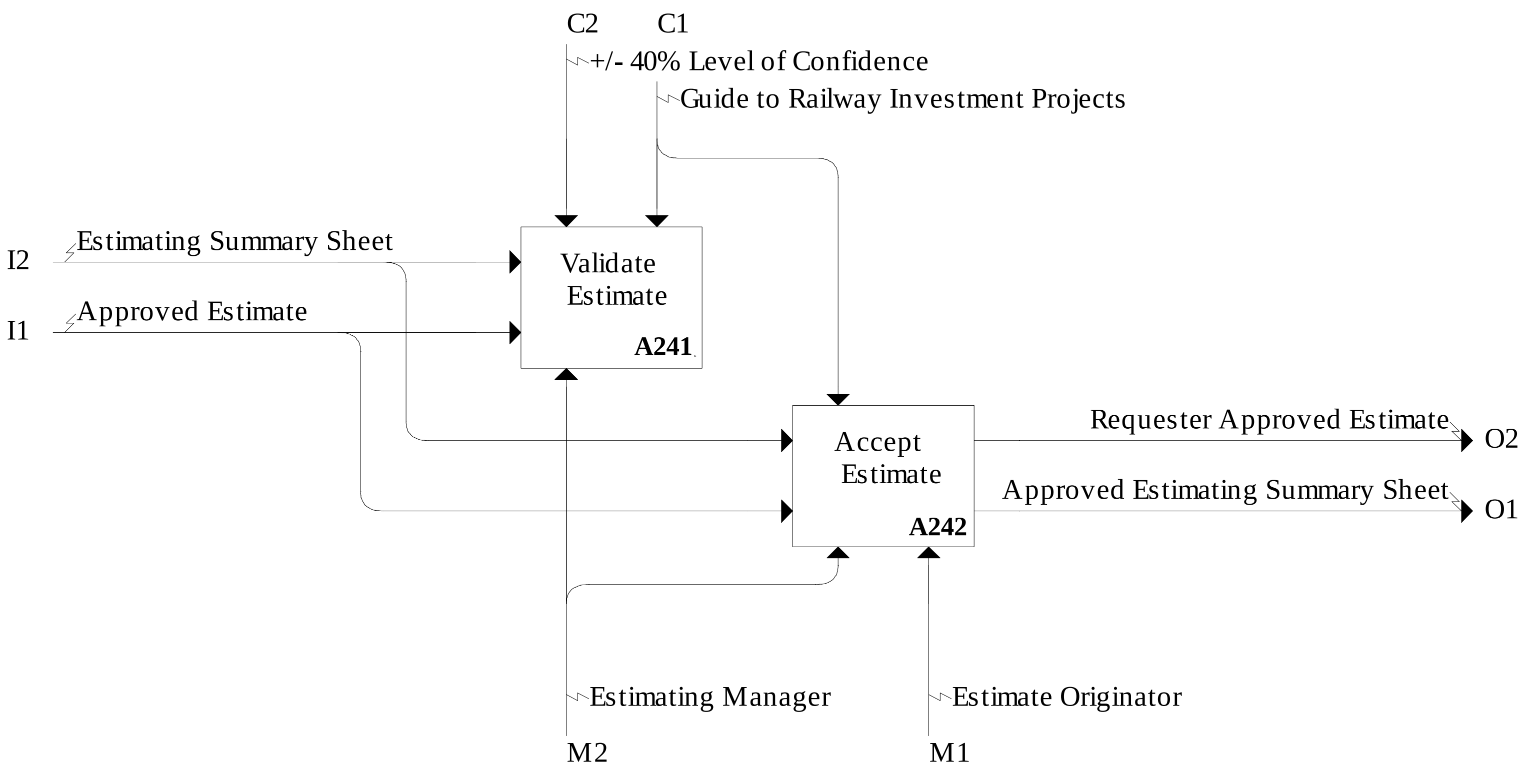
Estimating Summary Sheet
O2
Hold Estimating Settlement Meeting
A232
Approved Estimate
O1
Approved Estimating Summary Sheet
Estimator
M1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C1
+/- 40% Level of Confidence
Guide to Railway Investment Projects
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I1
Approved Estimate
Validate Estimate
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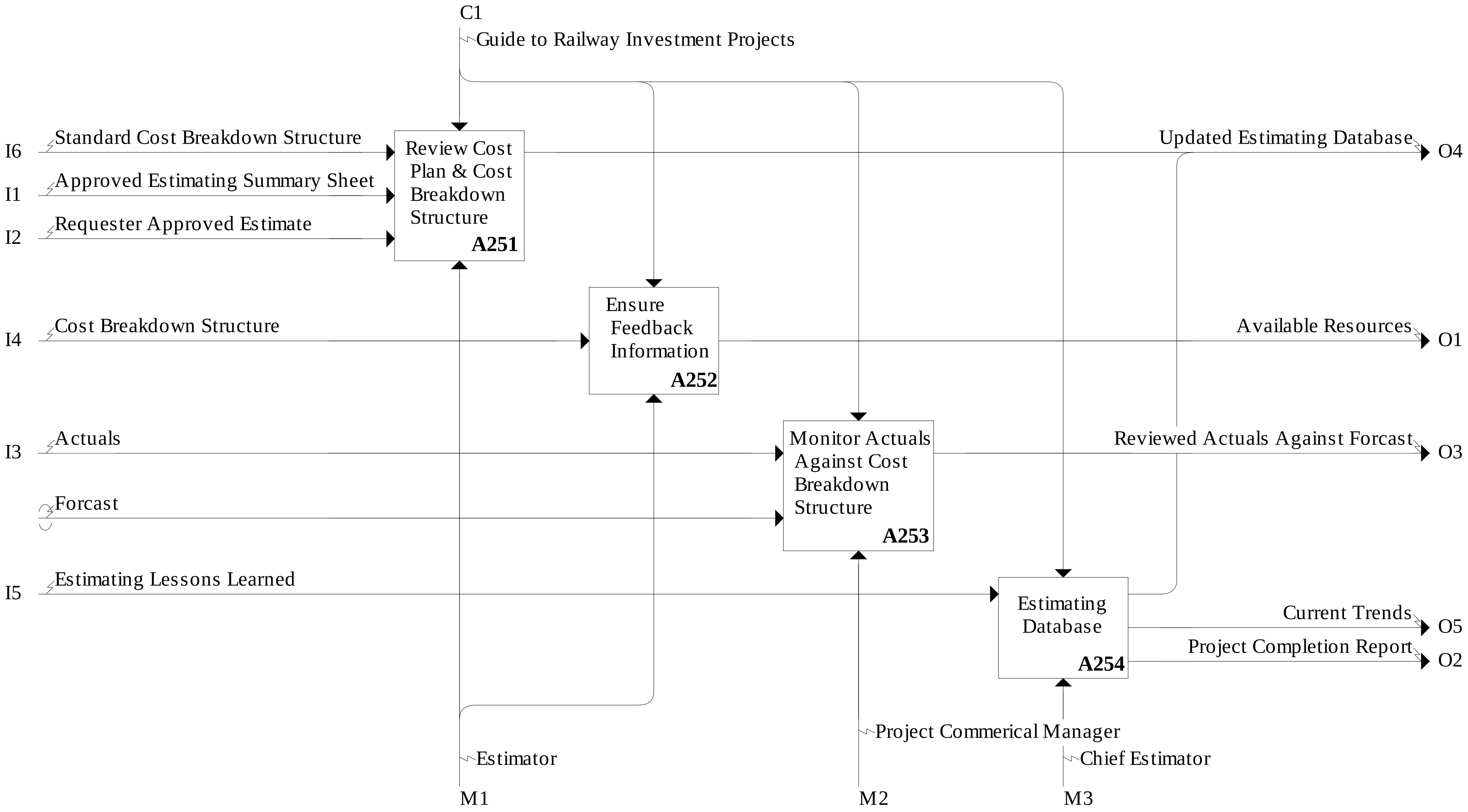
Accept Estimate
A242
Requester Approved Estimate
O2
Approved Estimating Summary Sheet
O1
Estimating Manager
M2
Estimate Originator
M1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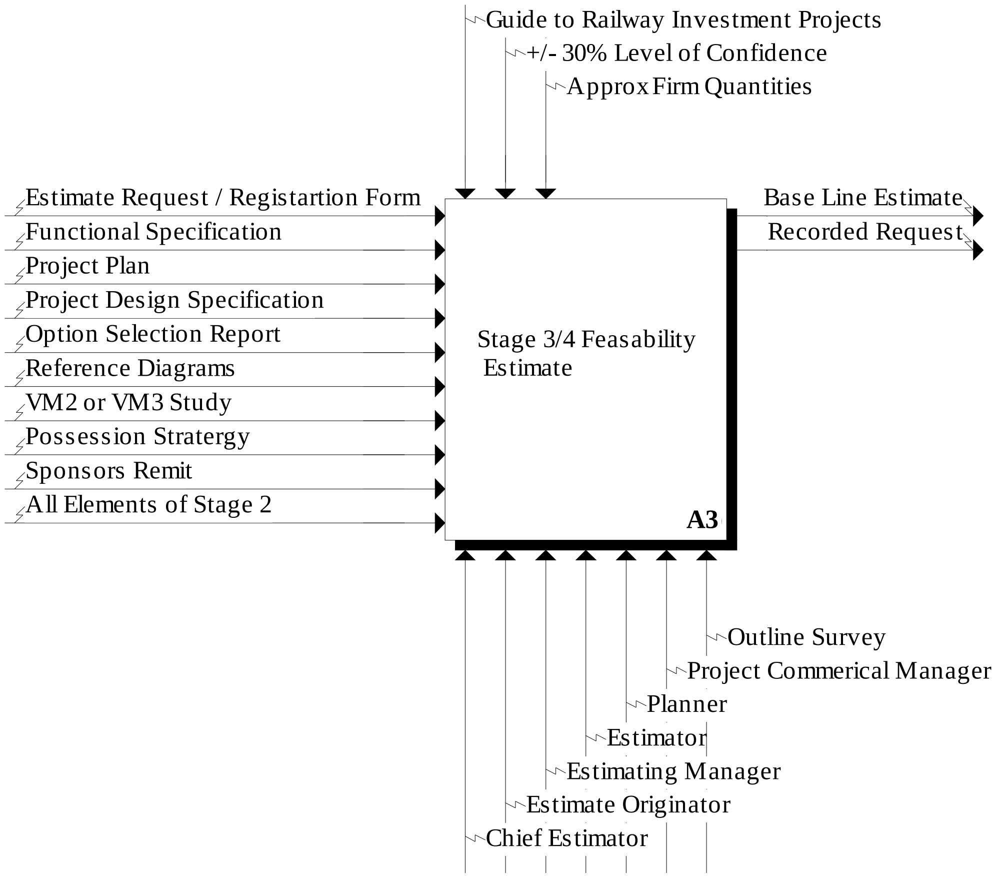
Guide to Railway Investment Projects
I6
Standard Cost Breakdown Structure
I1
Approved Estimating Summary Sheet
I2
Requester Approved Estimate
Review Cost Plan & Cost Breakdown Structure
A251
Updated Estimating Database
O4
I4
Cost Breakdown Structure
Ensure Feedback Information
A252
Available Resources
O1
I3
Actuals
Forcast
Monitor Actuals Against Cost Breakdown Structure
A253
Reviewed Actuals Against Forcast
O3
I5
Estimating Lessons Learned
Estimating Database
A254
Current Trends
O5
Project Completion Report
O2
Project Commerical Manager
Estimator
Chief Estimator
M1
M2
M3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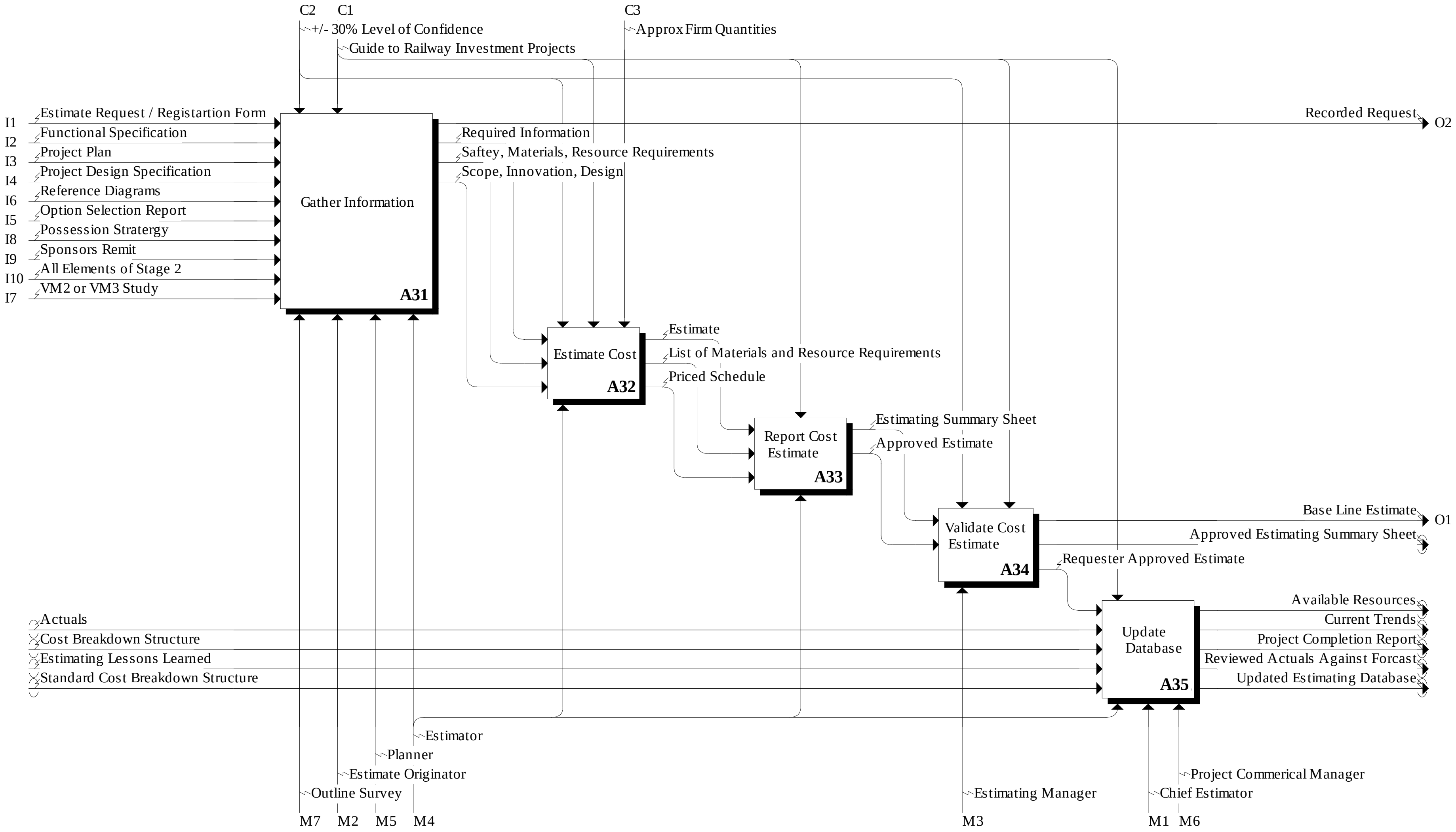
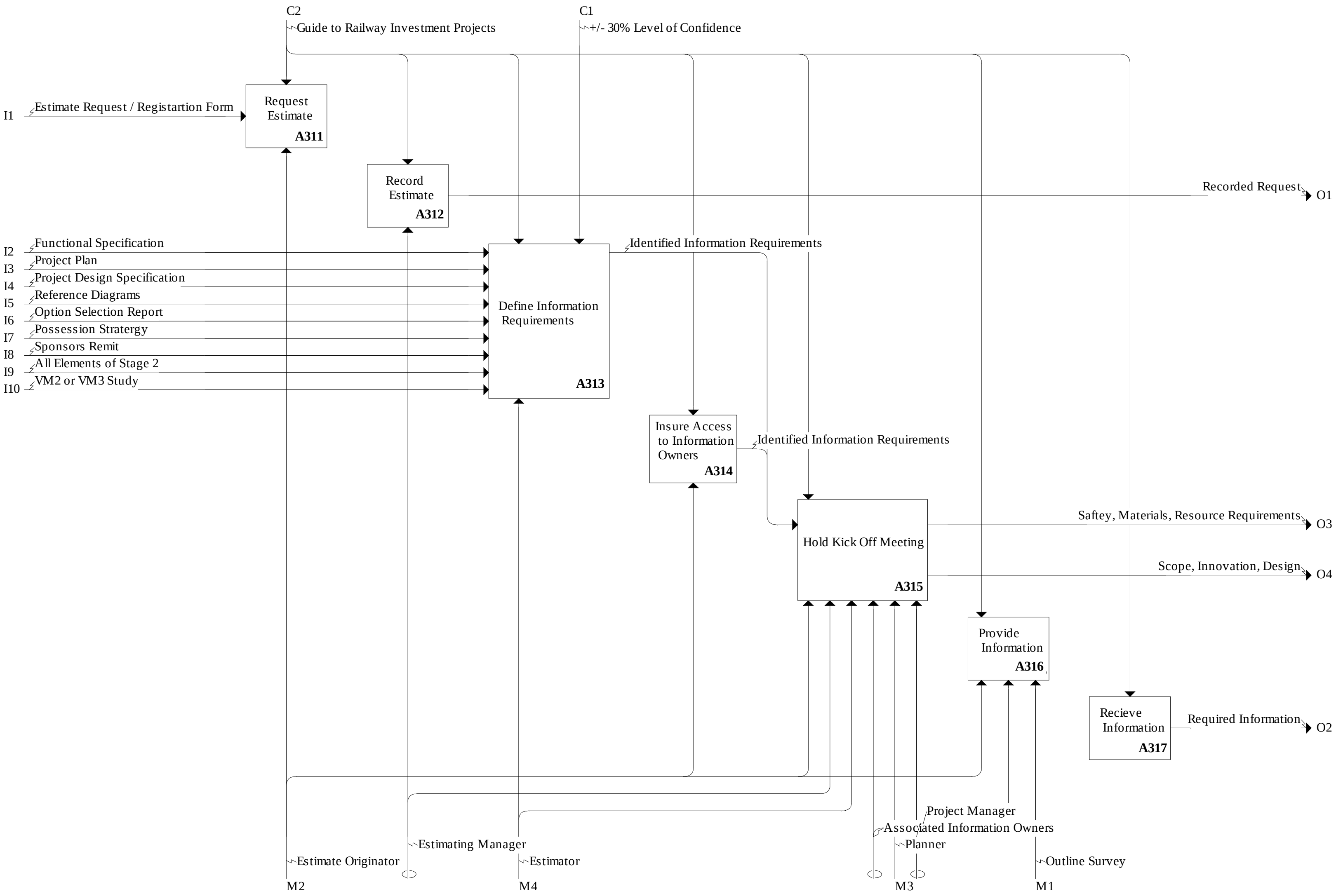
+/- 30% Level of Confidence
Approx Firm Quantities
Estimate Request / Registartion Form
Functional Specification
Project Plan
Project Design Specification
Option Selection Report
Reference Diagrams
VM2 or VM3 Study
Possession Stratergy
Sponsors Remit
All Elements of Stage 2
Stage 3/4 Feasability Estimate
A3
Base Line Estimate
Recorded Request
Outline Survey
Project Commerical Manager
Planner
Estimator
Estimating Manager
Estimate Originator
Chief Estimator


C2
C1
+/- 30% Level of Confidence
Guide to Railway Investment Projects
C3
Approx Firm Quantities
I1
Estimate Request / Registartion Form
I2
Functional Specification
I3
Project Plan
I4
Project Design Specification
I6
Reference Diagrams
I5
Option Selection Report
I8
Possession Stratergy
I9
Sponsors Remit
I10
All Elements of Stage 2
I7
VM2 or VM3 Study
Gather Information
A31
Recorded Request
O2
Required Information
Saftey, Materials, Resource Requirements
Scope, Innovation, Design
Estimate Cost
A32
Estimate
List of Materials and Resource Requirements
Priced Schedule
Report Cost Estimate
A33
Estimating Summary Sheet
Approved Estimate
Validate Cost Estimate
A34
Base Line Estimate
O1
Approved Estimating Summary Sheet
Requester Approved Estimate
Actuals
Cost Breakdown Structure
Estimating Lessons Learned
Standard Cost Breakdown Structure
Update Database
A35
Available Resources
Current Trends
Project Completion Report
Reviewed Actuals Against Forcast
Updated Estimating Database
Estimator
Planner
Estimate Originator
Outline Survey
Estimating Manager
Project Commerical Manager
Chief Estimator
M7
M2
M5
M4
M3
M1
M6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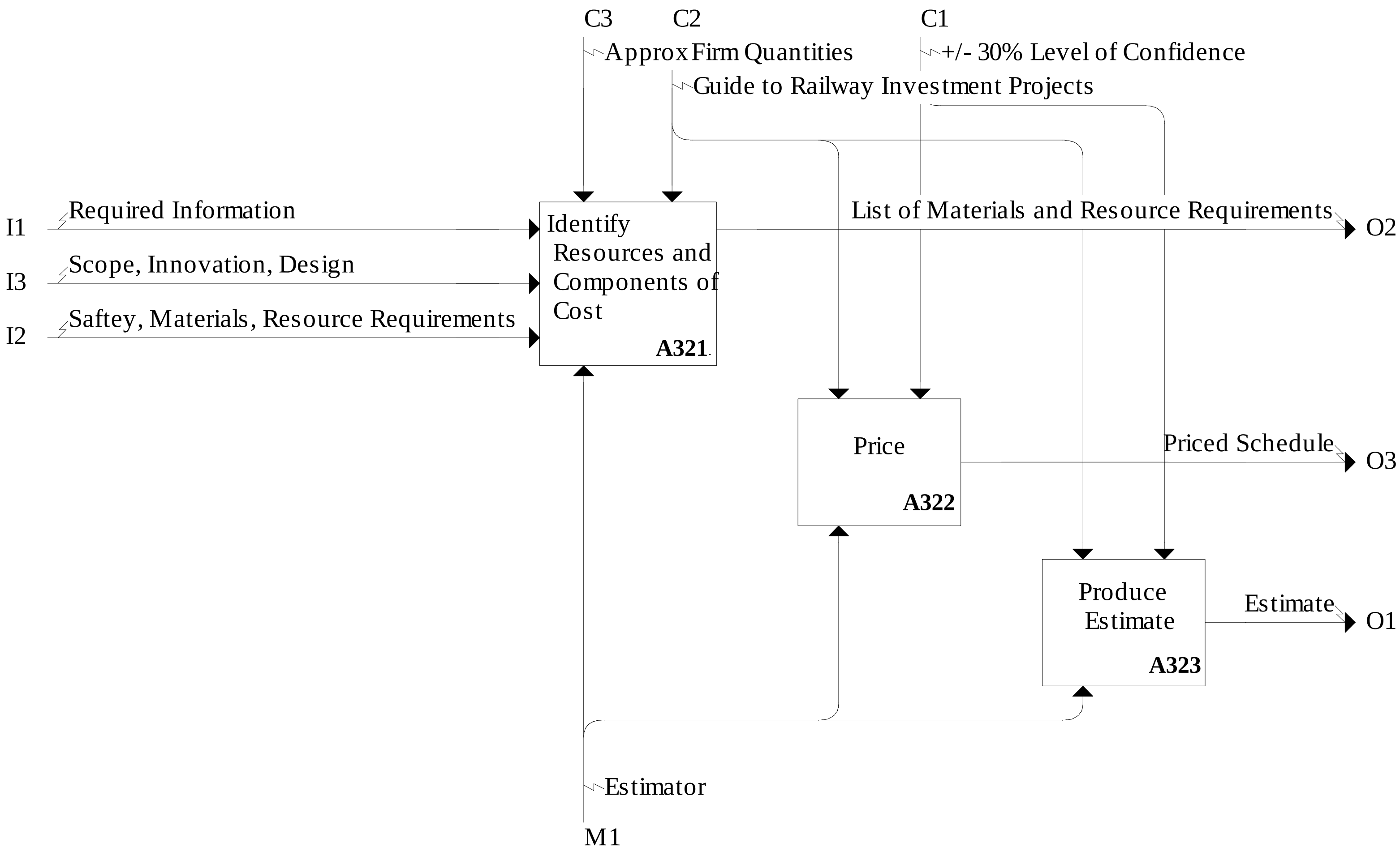
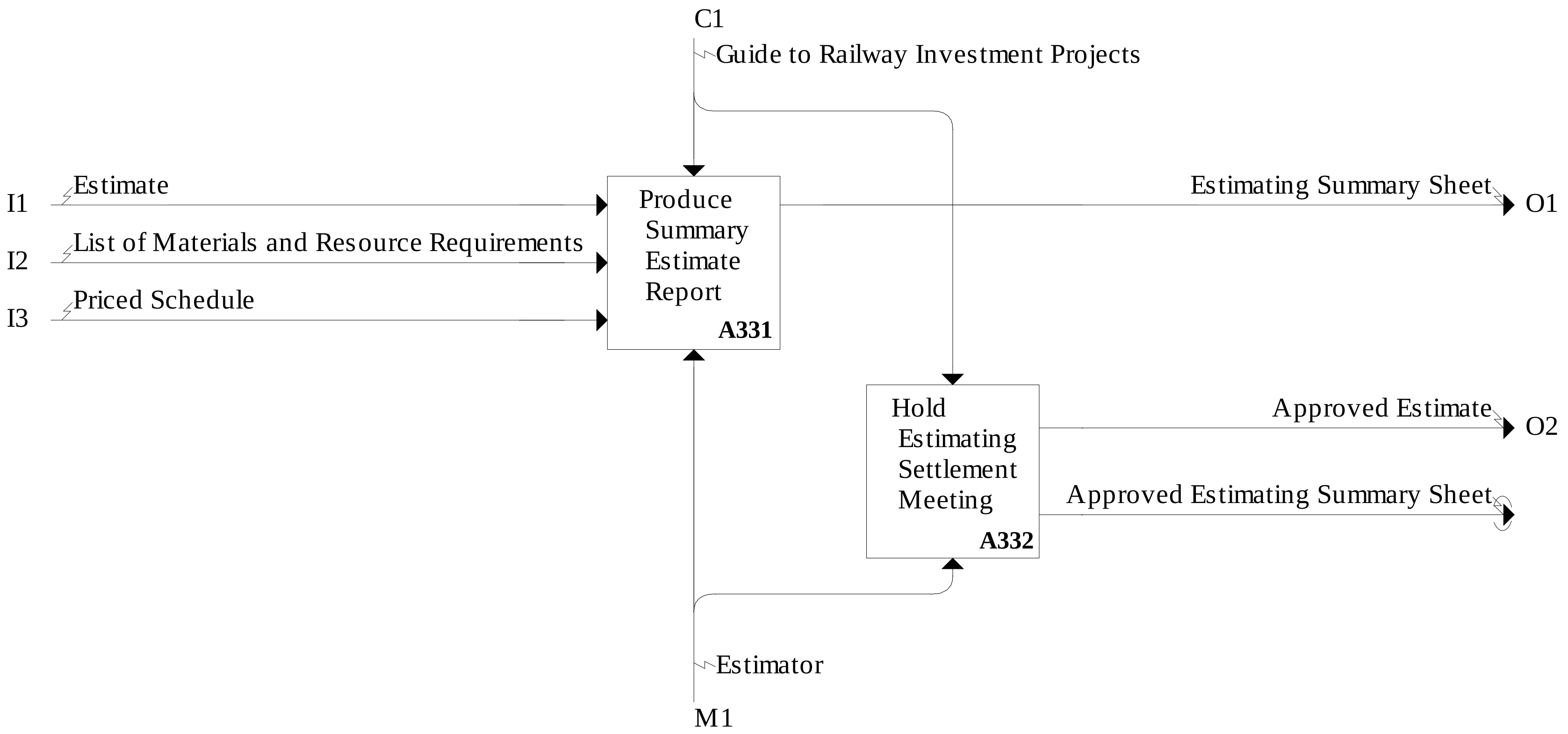
Guide to Railway Investment Projects
C1
+/- 30% Level of Confidence
I1
Estimate Request / Registartion Form
Request Estimate
A311
Record Estimate
A312
Recorded Request
O1
I2
Functional Specification
I3
Project Plan
I4
Project Design Specification
I5
Reference Diagrams
I6
Option Selection Report
I7
Possession Stratergy
I8
Sponsors Remit
I9
All Elements of Stage 2
I10
VM2 or VM3 Study
Define Information Requirements
A313
Identified Information Requirements
Insure Access to Information Owners
A314
Identified Information Requirements
Hold Kick Off Meeting
A315
Saftey, Materials, Resource Requirements
O3
Scope, Innovation, Design
O4
Provide Information
A316
Recieve Information
A317
Required Information
O2
Project Manager
Associated Information Owners
Planner
Estimating Manager
Estimate Originator
Estimator
Outline Survey
M2
M4
M3
M1


C3
C2
C1
Approx Firm Quantities
+/- 30% Level of Confidence
Guide to Railway Investment Projects
I1
Required Information
I3
Scope, Innovation, Design
I2
Saftey, Materials, Resource Requirements
Identify Resources and Components of Cost
A321
List of Materials and Resource Requirements
O2
Price
A322
Priced Schedule
O3
Produce Estimate
A323
Estimate
O1
Estimator
M1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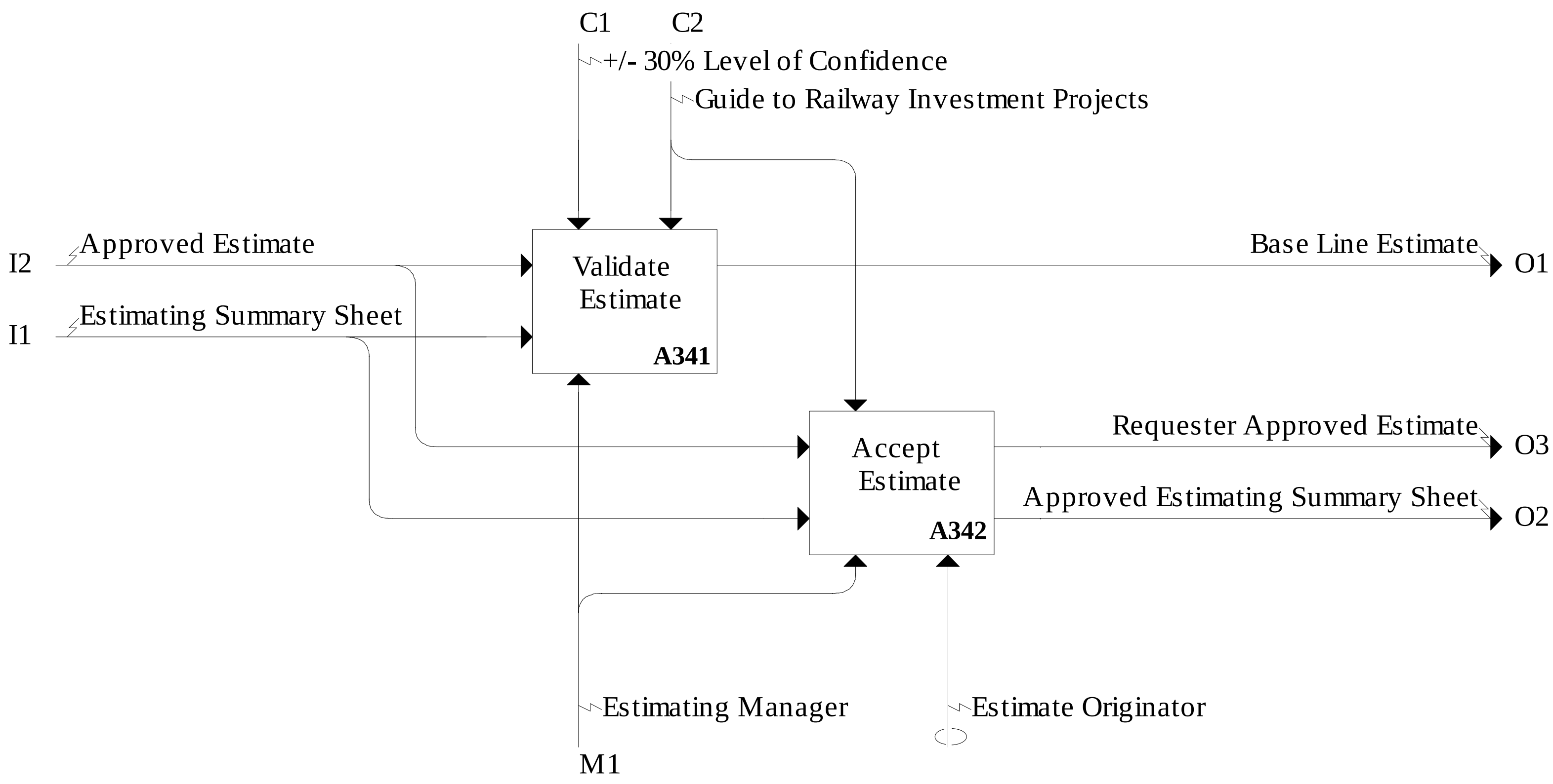
Guide to Railway Investment Projects
I1
Estimate
I2
List of Materials and Resource Requirements
I3
Priced Schedule
Produce Summary Estimate Report
A331
Estimating Summary Sheet
O1
Hold Estimating Settlement Meeting
A332
Approved Estimate
O2
Approved Estimating Summary Sheet
Estimator
M1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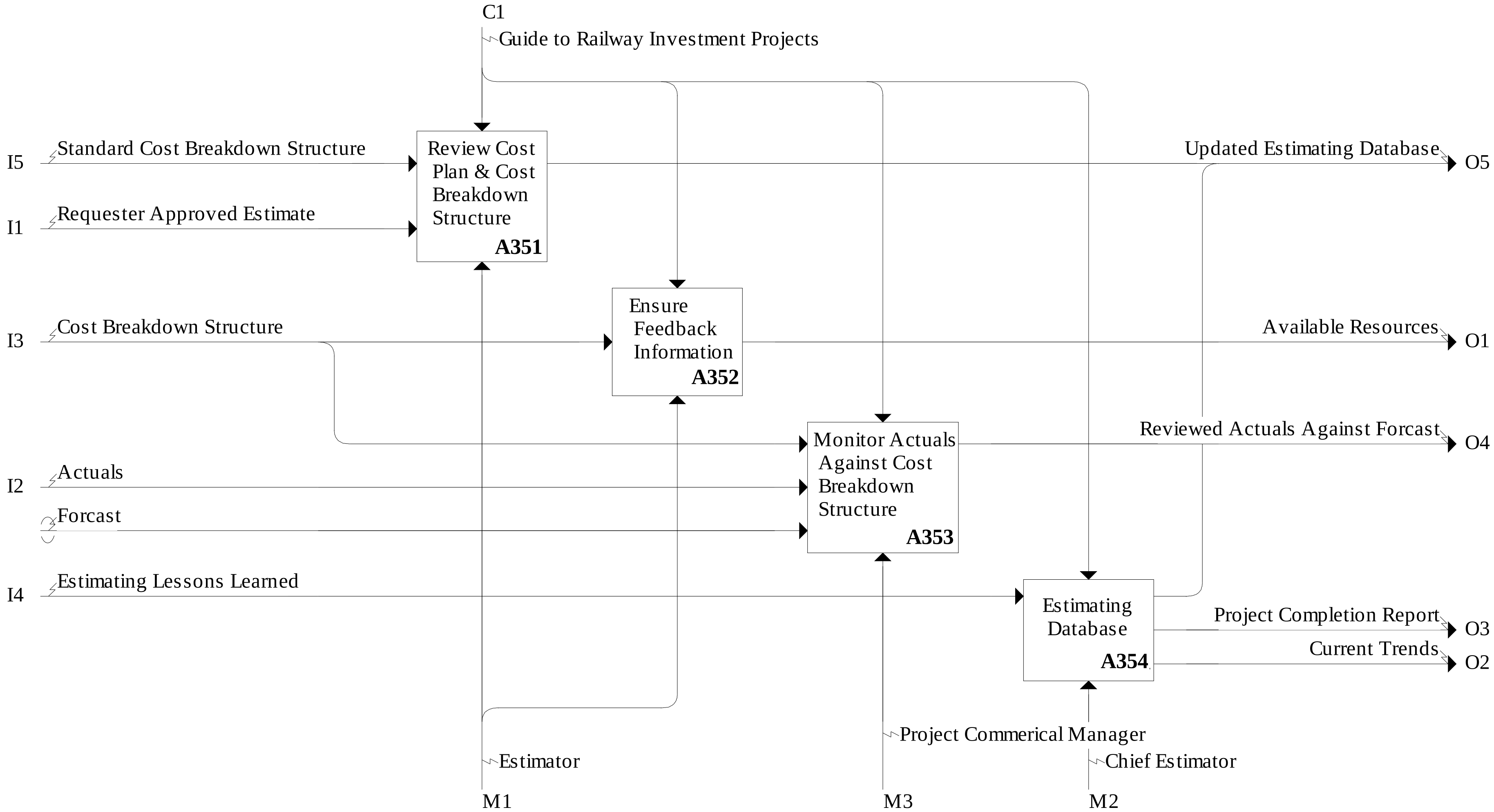
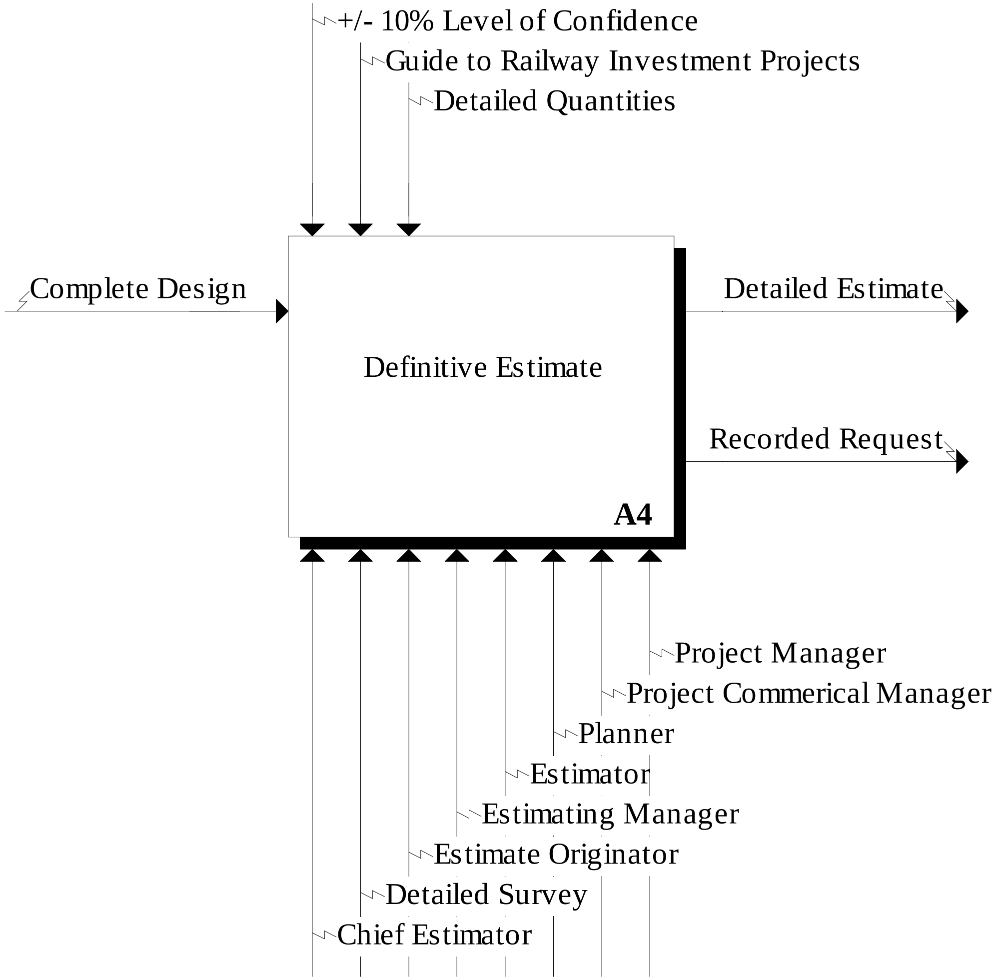
C2
+/- 30% Level of Confidence
Guide to Railway Investment Projects
I2
Approved Estimate
I1
Estimating Summary Sheet
Validate Estimate
A341
Base Line Estimate
O1
Accept Estimate
A342
Requester Approved Estimate
O3
Approved Estimating Summary Sheet
O2
Estimating Manager
Estimate Originator
M1


C1
Guide to Railway Investment Projects
I5
Standard Cost Breakdown Structure
I1
Requester Approved Estimate
Review Cost Plan & Cost Breakdown Structure
A351
Updated Estimating Database
O5
I3
Cost Breakdown Structure
Ensure Feedback Information
A352
Available Resources
O1
Monitor Actuals Against Cost Breakdown Structure
A353
Reviewed Actuals Against Forcast
O4
I2
Actuals
Forcast
I4
Estimating Lessons Learned
Estimating Database
A354
Project Completion Report
O3
Current Trends
O2
Estimator
M1
Project Commerical Manager
M3
Chief Estimator
M2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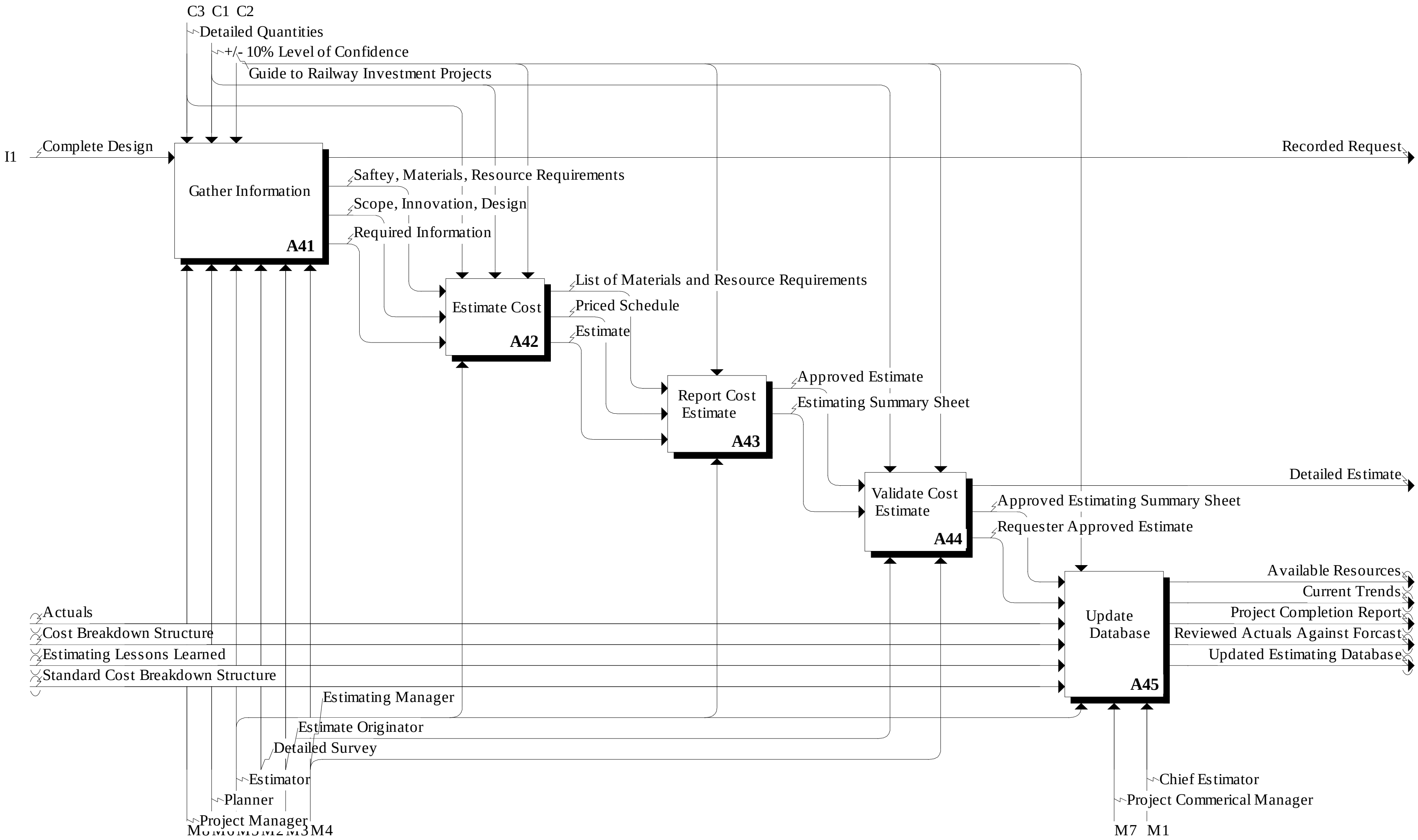
Guide to Railway Investment Projects
Detailed Quantities
Complete Design
Definitive Estimate
A4
Detailed Estimate
Recorded Request
Project Manager
Project Commerical Manager
Planner
Estimator
Estimating Manager
Estimate Originator
Detailed Survey
Chief Estimator


C3 C1 C2
Detailed Quantities
+/- 10% Level of Confidence
Guide to Railway Investment Projects
I1
Complete Design
Gather Information
A41
Recorded Request
O2
Saftey, Materials, Resource Requirements
Scope, Innovation, Design
Required Information
Estimate Cost
A42
List of Materials and Resource Requirements
Priced Schedule
Estimate
Report Cost Estimate
A43
Approved Estimate
Estimating Summary Sheet
Validate Cost Estimate
A44
Detailed Estimate
O1
Approved Estimating Summary Sheet
Requester Approved Estimate
Update Database
A45
Available Resources
Current Trends
Project Completion Report
Reviewed Actuals Against Forcast
Updated Estimating Database
Actuals
Cost Breakdown Structure
Estimating Lessons Learned
Standard Cost Breakdown Structure
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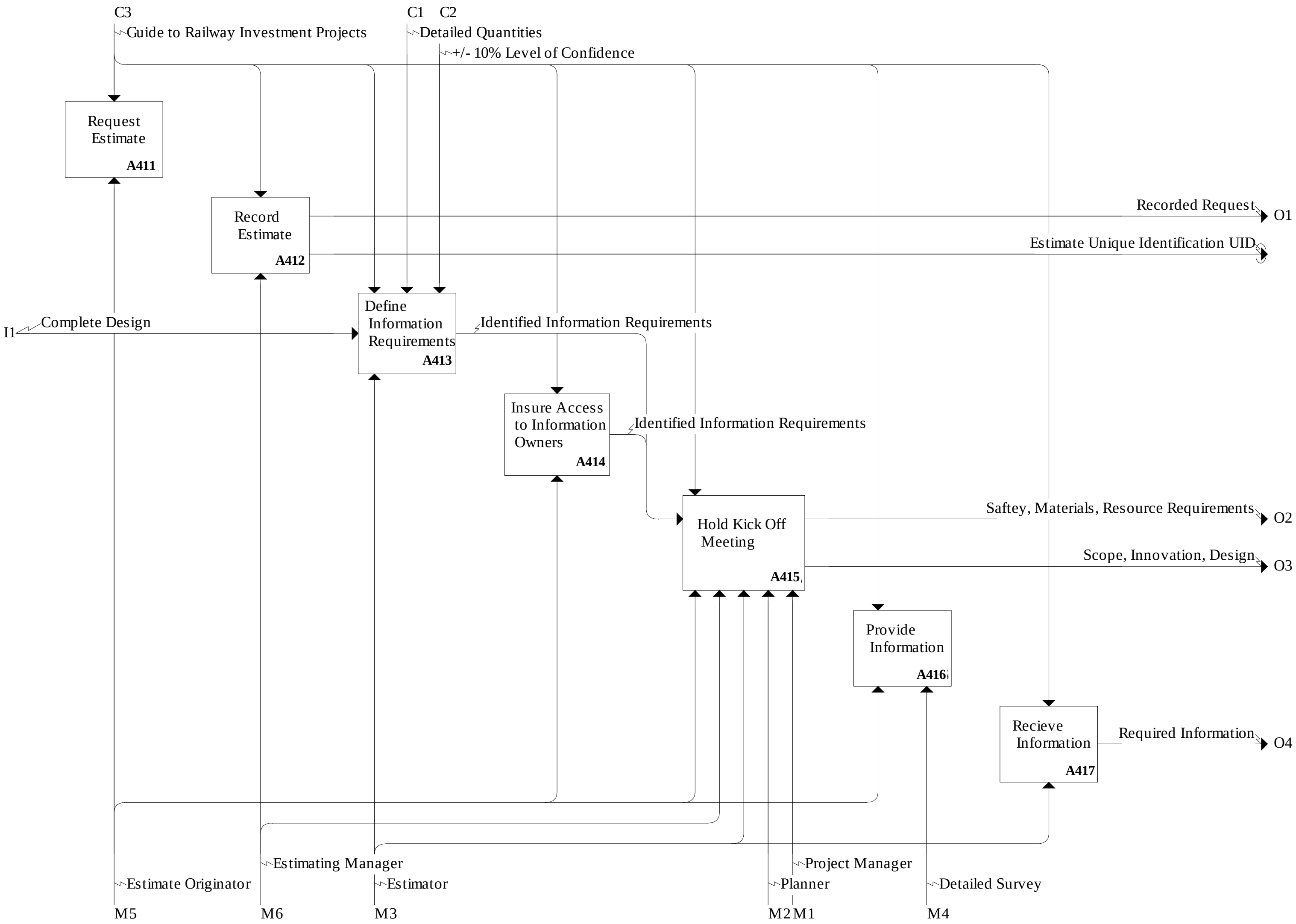
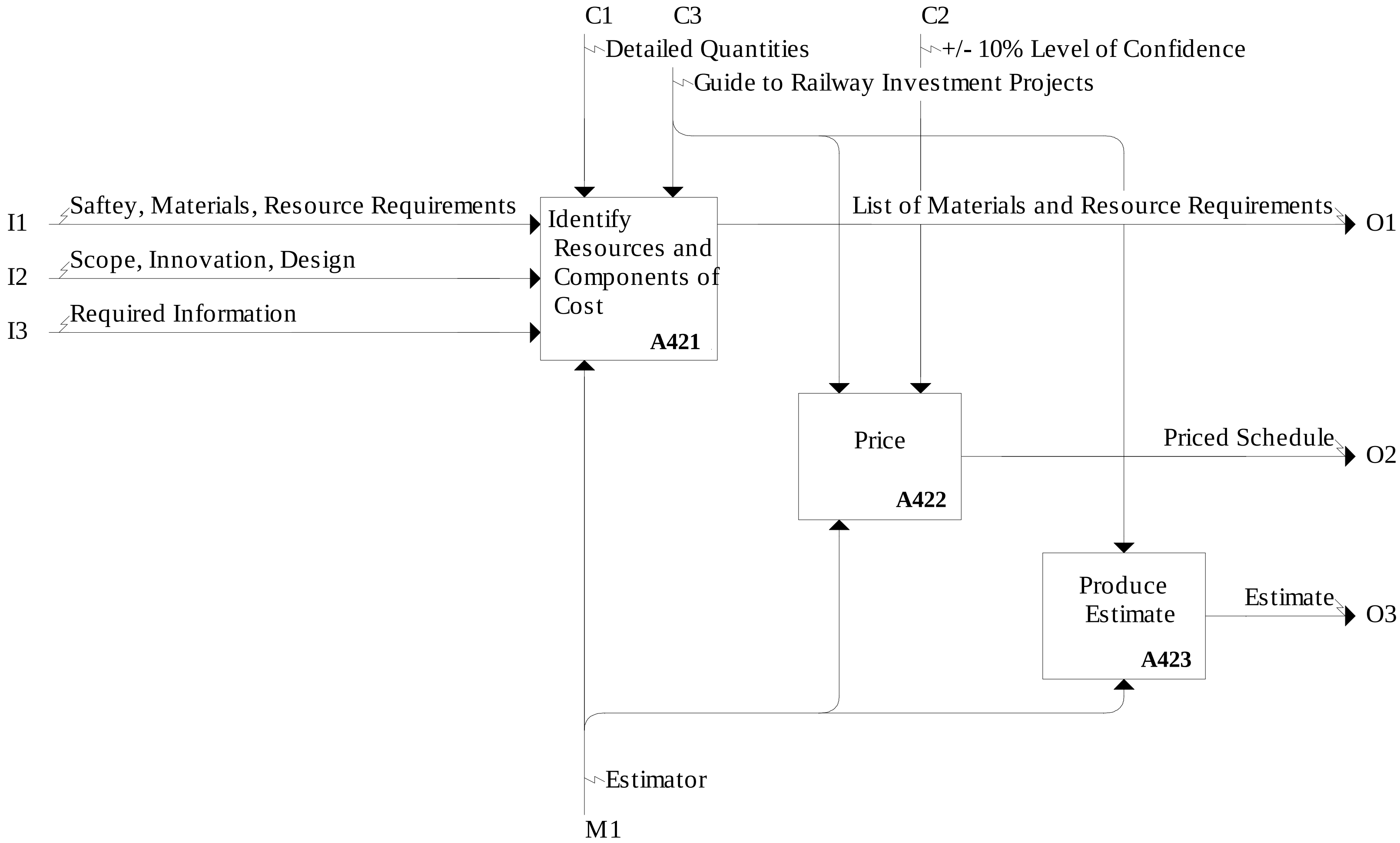
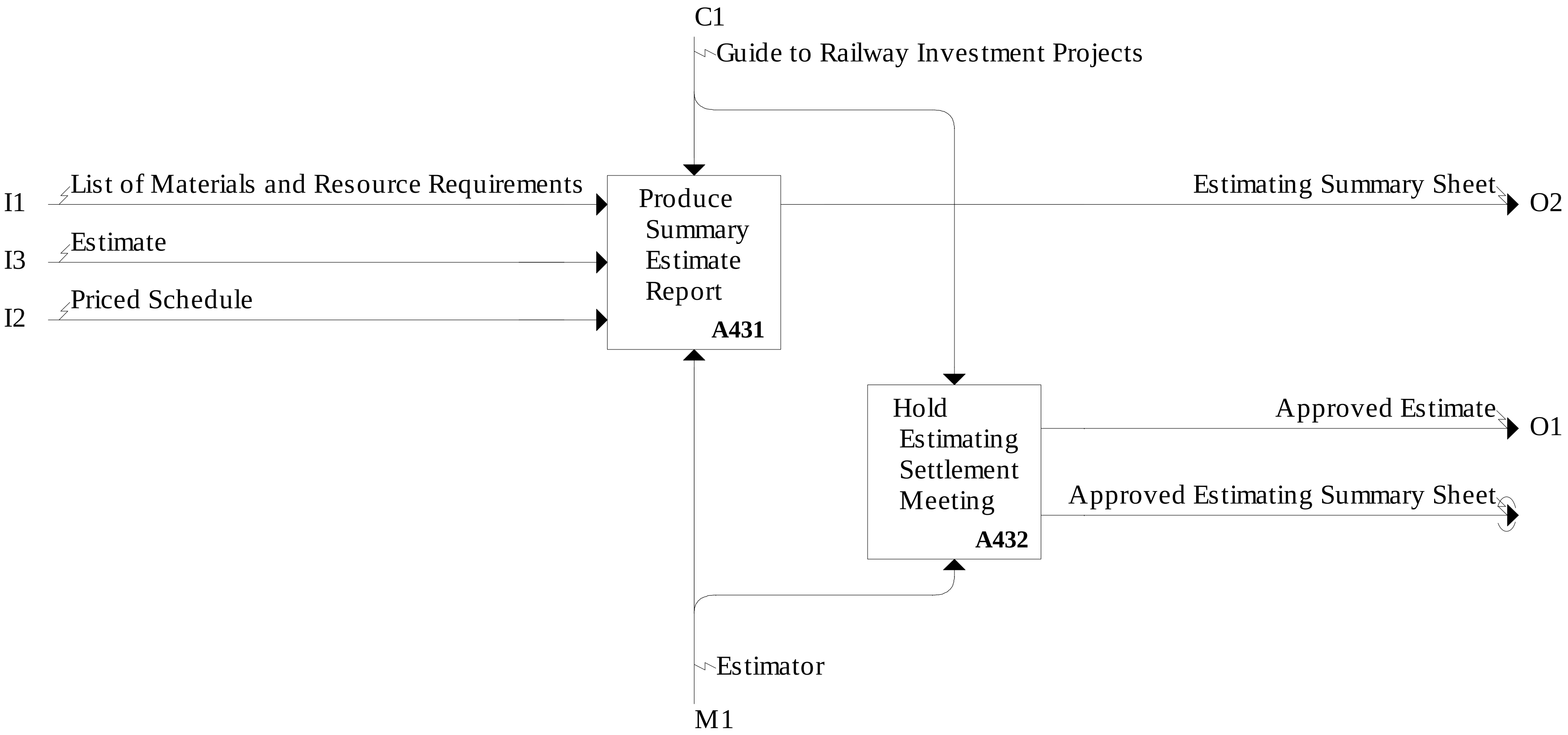
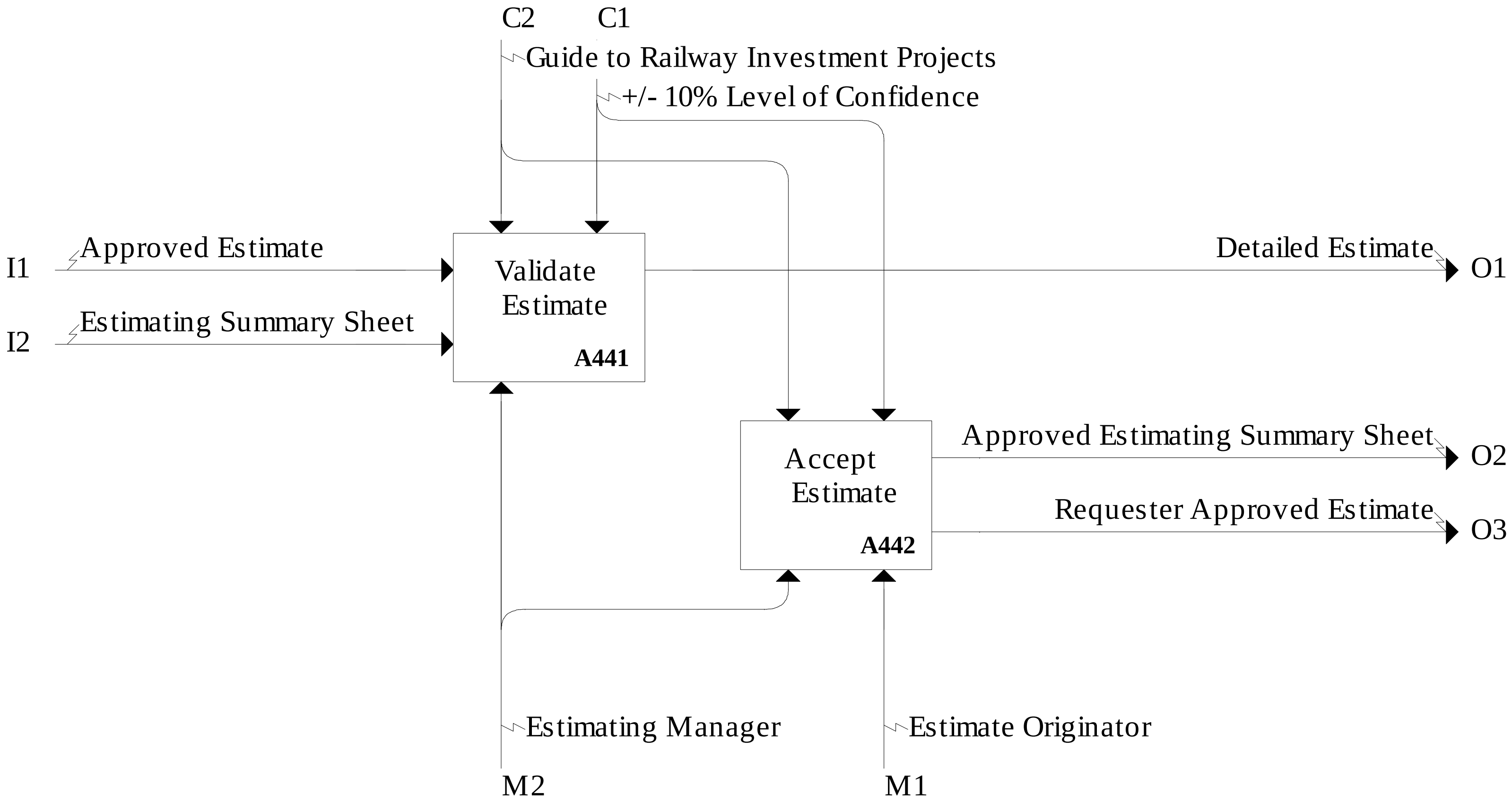
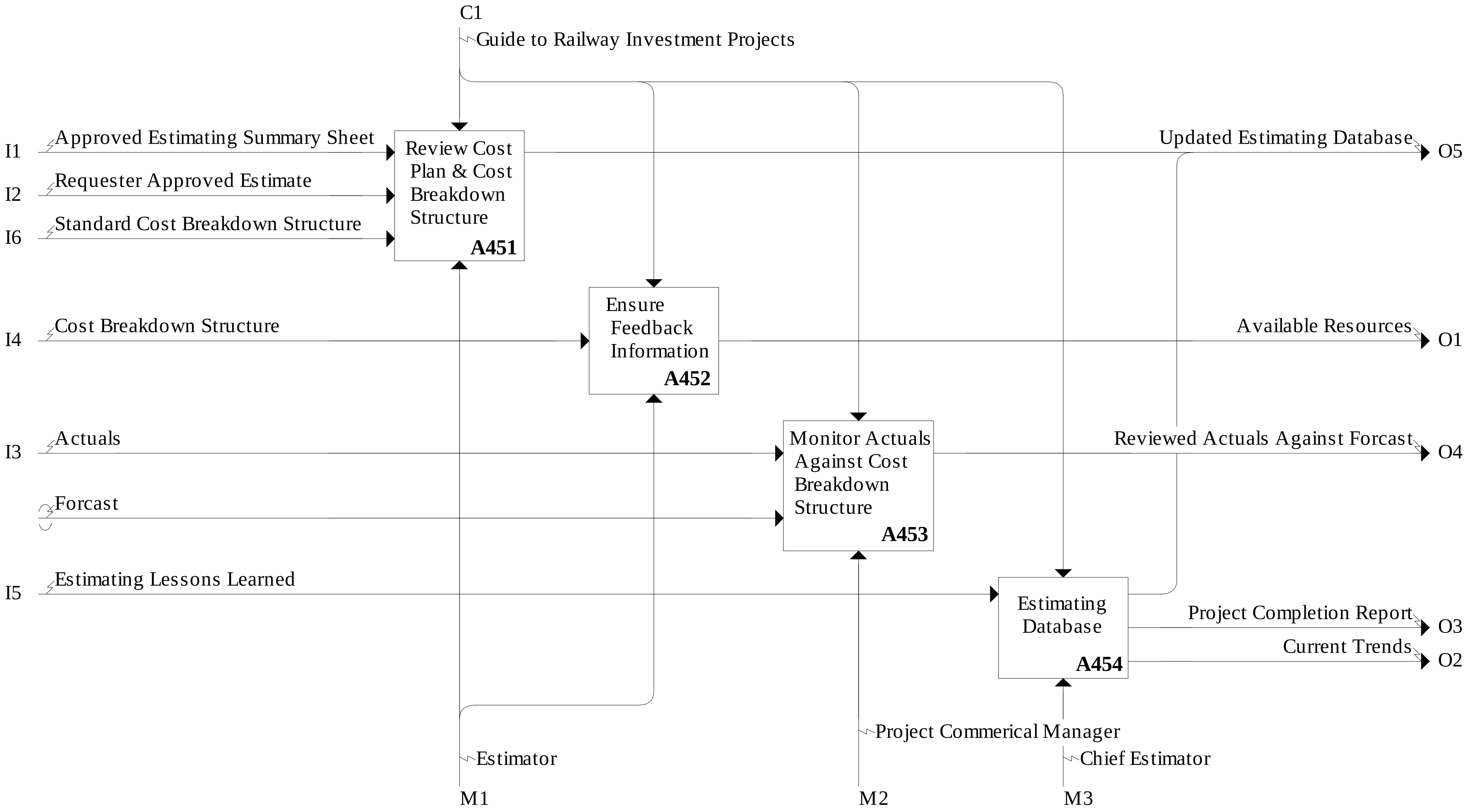
Estimate Originator
Detailed Survey
Estimator
Planner
Project Manager
M4
Chief Estimator
Project Commerical Manager
M7 M1


C3
Guide to Railway Investment Projects
C1
C2
Detailed Quantities
+/- 10% Level of Confidence
Request Estimate
A411
Record Estimate
A412
Recorded Request
O1
Estimate Unique Identification UID
I1
Complete Design
Define Information Requirements
A413
Identified Information Requirements
Insure Access to Information Owners
A414
Identified Information Requirements
Hold Kick Off Meeting
A415
Saftey, Materials, Resource Requirements
O2
Scope, Innovation, Design
O3
Provide Information
A416
Recieve Information
A417
Required Information
O4
Estimating Manager
Project Manager
Estimate Originator
Estimator
Planner
Detailed Survey
M5
M6
M3
M2
M1
M4


C1
C3
C2
Detailed Quantities
+/- 10% Level of Confidence
Guide to Railway Investment Projects
I1
Saftey, Materials, Resource Requirements
I2
Scope, Innovation, Design
I3
Required Information
Identify Resources and Components of Cost
A421
List of Materials and Resource Requirements
O1
Price
A422
Priced Schedule
O2
Produce Estimate
A423
Estimate
O3
Estimator
M1


C1
Guide to Railway Investment Projects
I1
List of Materials and Resource Requirements
I3
Estimate
I2
Priced Schedule
Produce Summary Estimate Report
A431
Estimating Summary Sheet
O2
Hold Estimating Settlement Meeting
A432
Approved Estimate
O1
Approved Estimating Summary Sheet
Estimator
M1


C2
C1
Guide to Railway Investment Projects
+/- 10% Level of Confidence
I1
Approved Estimate
I2
Estimating Summary Sheet
Validate Estimate
A441
Detailed Estimate
O1
Accept Estimate
A442
Approved Estimating Summary Sheet
O2
Requester Approved Estimate
O3
Estimating Manager
M2
Estimate Originator
M1


C1
Guide to Railway Investment Projects
I1
Approved Estimating Summary Sheet
I2
Requester Approved Estimate
I6
Standard Cost Breakdown Structure
Review Cost Plan & Cost Breakdown Structure
A451
Updated Estimating Database
O5
I4
Cost Breakdown Structure
Ensure Feedback Information
A452
Available Resources
O1
I3
Actuals
Forcast
Monitor Actuals Against Cost Breakdown Structure
A453
Reviewed Actuals Against Forcast
O4
I5
Estimating Lessons Learned
Estimating Database
A454
Project Completion Report
O3
Current Trends
O2
Project Commerical Manager
Estimator
Chief Estimator
M1
M2
M3

APPENDIX 2 – Cost Estimating Process Knowledge Elicitation Workshop

Workshop Facilitator: Daniel Ling

Cost Estimating Process Knowledge Elicitation Workbook

This document explains the procedures involved in today's knowledge elicitation exercise. Please read it carefully.

Workshop Process

Aim: To understand switch and crossing maintenance & renewal cost estimating processes. To develop a process map.

Method XPat knowledge elicitation methodology

Procedure: Post it notes, Structured Interview, Probe Questions, Brown Paper

Time period: Three 40 minute sessions, Three 10 min breaks

The XPat methodology adopted consists of 4 main stages.

- Stage 1: Process map development
- Stage 2: IDEF0 model development and process glossary
- Stage 3: Detailed knowledge elicitation, (activities which will add value to the business and expert reasoning process)
- Stage 4: Validation

This workshop is concerned with Stage 1.

The workshop process will consist of 3 areas of analysis, output, inputs and process and will be completed in that order through the use of a structured interview using probe questions.

Rules

1. Please write all answers to the probe questions on individual post it notes
2. Please use block capitals
3. Please mark each post-it with the corresponding probe identity.

Stage 1: Process map development

XPAT Probe Questions

Output Probe Questions

Table 1: List of structured probe questions for output view of functions at the Top-level.

Probe Identity	Probe Questions	Rationale for a probe question
O1	List all output from the process?	To identify specific outputs from the process in terms of information deliverables states product and results. To define types of output. To provide support for constructing IDEF0 process model.
O2	Why would you need that output?	To generate rules for output information. IF <condition> THEN <action>
O3	How would you get that output?	To determine acquisition or reuse process.
O4	How would you use	To generate detail level rules.

	that output?	IF <condition> THEN <action>
O5	What is the source of output?	To identify sources of output and interactions
O6	When would you generate this output?	To reveal specific or generic frequency of outputs To generate a detail level rule specific or generic output. IF <condition> THEN <action>
O7	What is the frequency of output?	To determine the dynamic nature of output (e.g. time relative to output – Hourly, Daily, Weekly, as and when required)

Input Probe Questions

Table 2: List of structured probe questions for input view of functions at the Top-level.

Probe Identit y	Probe Questions	Rationale for a probe question
I1	List all input to the process?	To identify specific inputs to the process in terms of information needs, states, problem and material. To define types of input. To provide support for constructing IDEF0 process model.
I2	Why would you need that input?	To generate rules for input information. IF <condition> THEN <action>
I3	How would you get that input?	To determine acquisition process
I4	How would you use that input?	To generate detail level rule. IF <condition> THEN <action>
I5	What is the source of input?	To identify sources of input and interactions
I6	What is the frequency of input?	To determine the dynamic nature of input (e.g. time relative to input – Hourly, Daily, Weekly, as and when required)
I7	When would you generate this input?	To reveal specific or generic frequency of inputs. To generate a detail level rule specific or generic input. IF <condition> THEN <action>
I8	What is the relationship between inputs and output elements?	To reveal the nature of relationships as either specific or generic.

Process Probe Questions

Terms	Description
Activities	"an activity describes a step in a problem solving process" [8].
Task	"a task defines a reasoning goal in terms of an input-output pair" [7]
Methods	"a method describes how a task can be realised through a decomposition into sub functions plus a control regimen over the execution of the sub

	functions." [7]
Guides	a guide provides directions or applies a constraint to a problem solving process e.g. standards, policies, rules and events. The are two types of constraints. A hard constraint is a physical constraint that must not be violated. Soft constraint. A soft constraint is a policy constraint that can be relaxed.
Metrics	A metric describes how a process is measured in qualitative or quantitative terms.
Enablers	An enabler provides the means to solve problem e.g. human resources, tools, systems, equipment, and facilities.
Assumptio ns	An assumption describes beliefs, ideas and or proof that a process is true or false.
FAQ's	Frequently Asked Questions are illustrative examples, which can be used to enhance a future knowledge system.

Table 3: List of structured probe questions giving a process view at the Top-level.

Probe Identity	Probe Questions	Rationale for a probe question
P1	List all activities performed in a process?	To identify the steps in a problem solving process.
P2	In what context would you do that?	To identify matching input/output of an activity
P3	List all tasks specific to an activity?	To determine the type of task and subtasks of an activity. To decompose tasks into subtasks.
P4	List all methods specific to each task?	To determine what method is for specific tasks. To decompose method in sub functions.
P5	List all guides specific to a task?	To identify guideline for specific task and sub tasks E.g. constraint/control related to a task such as policies, standards, rules, and events. To identify types of constraints (Hard constraints or Soft Constraints) To generate more rules for a task. To provide support for constructing IDEF0 process model.
P6	When would you use these guides?	To reveal appropriate timing to use a guide.
P7	How would you use these guides?	To generate detail rules for a guide. IF <condition> THEN <action>
P8	What preferences can be made?	To reveal the choice in decision making. To generate rule for making

		decisions.
P9	List all enablers specific to a task?	To determine who does what. To determine what tool is used. To determine what system is used. To determine what equipment is used. To determine interaction between people and system To determine the rules for using the system or tool. To provide support for constructing IDEF0 process model.
P10	When would you need that?	To reveal the frequency of participation.
P11	Why would you need that?	To generate rules for an enabler specific to a task. IF <condition> THEN <action>
P12	Who will need that?	To determine the rule for interaction.
P13	What are alternative enablers?	To generate more rules. IF <condition> is not available THEN <action>
P14	List all metrics the metrics for a specific task?	To generate rules for completion or state of a task.
P15	Why would you need that?	To generate rules for a measure specific to a task. IF <condition> THEN <action>
P16	How would you use this measure?	To generate detail level rules for metric. IF <condition> THEN <action>
P17	When would you need this metrics?	To reveal the generality of the rule and generate other rules.
P18	What are alternative measures?	To generate more rules. IF <condition> is not available THEN <action> IF <condition> is false THEN <action>
P19	List all assumptions for a task?	To identify the decision-making patterns. To provide additional information about a process
P20	List sources of Frequently asked questions?	To identify additional sources of knowledge.

Stage 3: Detailed Knowledge Elicitation

After developing the process map the expert will decide which activities will add value to the business process. The following questions will then be asked to the expert to identify their reasoning process.

Probe Identity	**Probe Questions**	**Rationale for a probe question**
D1	What do you do?	To establish a task description..
D2	Why would you do this task?	To convert a task description into a rule. >
D3	When would you do this task?	To reveal the nature of a task as specific or generic to an activity. To generate more rules.
D4	How would you do that?	To reveal description of problem solving method and reasoning patterns for a specific task. To generate rules for a method.
D5	Why would you do that?	To convert method description into a rule for a task.
D6	What do you do when that happen?	To establish method for responding to unusual event.

APPENDIX 3 – Cost Estimating Process Knowledge Validation Workbook

Workshop Facilitator: Daniel Ling

Cost Estimating Process Knowledge Validation Workbook

This document explains the procedures involved in today's knowledge elicitation exercise. Please read it carefully

Workshop Process

Aim: To validate the elicited maintenance & renewal cost estimating processes.

Method: Expert Review

Procedure: Presentation and review of IDEF0 diagram results

Time period: 2 hour session

Rules

Please indicate understanding of the information provided before answering the validation questions.

The workshop will be structured into 3 stages.

- Stage 1 - The facilitator will present the aims and objectives of this workshop.
- Stage 2 - The facilitator will present the IDEF0 diagrams and "walk through" the information contained within the diagrams. Once the facilitator and interviewee understand the presented diagrams move to Stage 3
- Stage 3 - is concerned with the interviews answering the following questions.

Maintenance and Renewal Cost Estimating IDEF0 Process Model Validation Questionnaire

Mr Daniel Ling
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School of Industrial & Manufacturing Science
Building 53, Cranfield University
Cranfield
Bedfordshire MK43 0AL
Tel: +44 (0) 1234 754073 Ext. 2872
Fax: +44 (0) 1234 750852
E-mail: d.j.ling.2001@cranfield.ac.uk

Introduction:

Dear Participant,

This questionnaire provides the basis for validation of the accompanying IDEF0 maintenance and renewal cost estimating process models.

Please review the models and answer the questions contained in this questionnaire:

The content of this questionnaire will be kept CONFIDENTIAL

SECTION 1: CONTACT DETAILS

Please fill this section with your contact details.

Name/ Position:
Address:

Postcode:

Tel:

Fax:

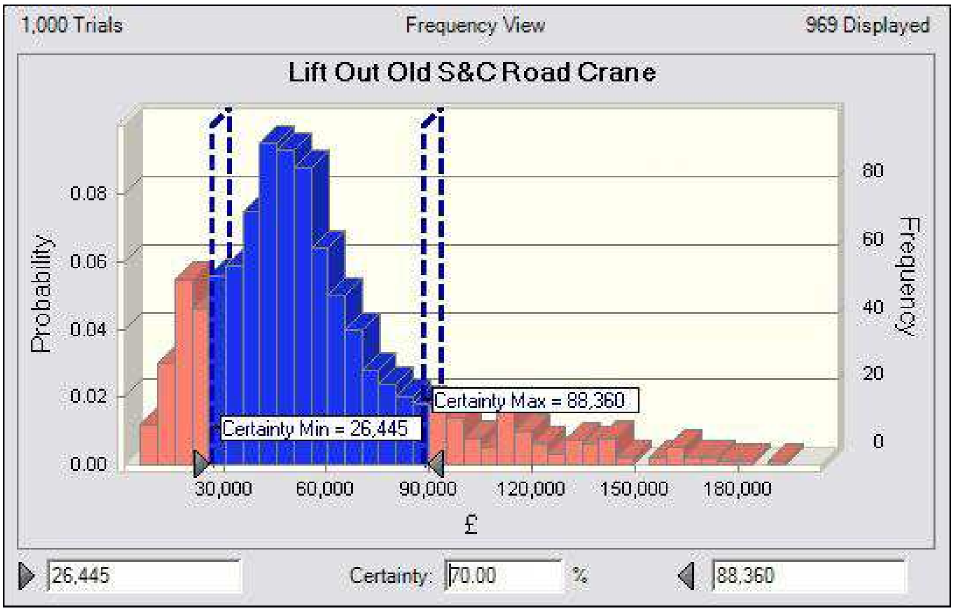
E-mail:

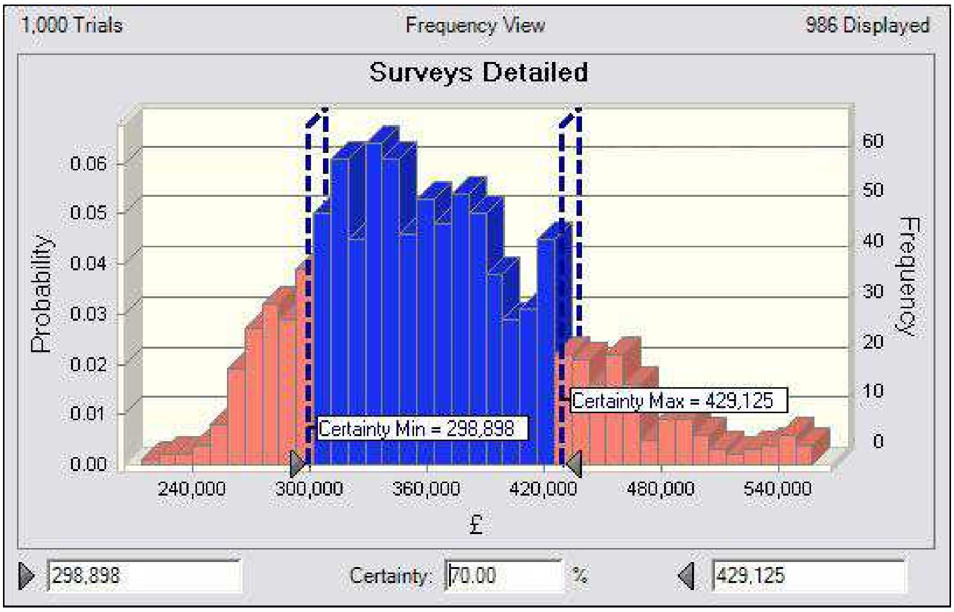
SECTION 2: VALIDATION QUESTIONS

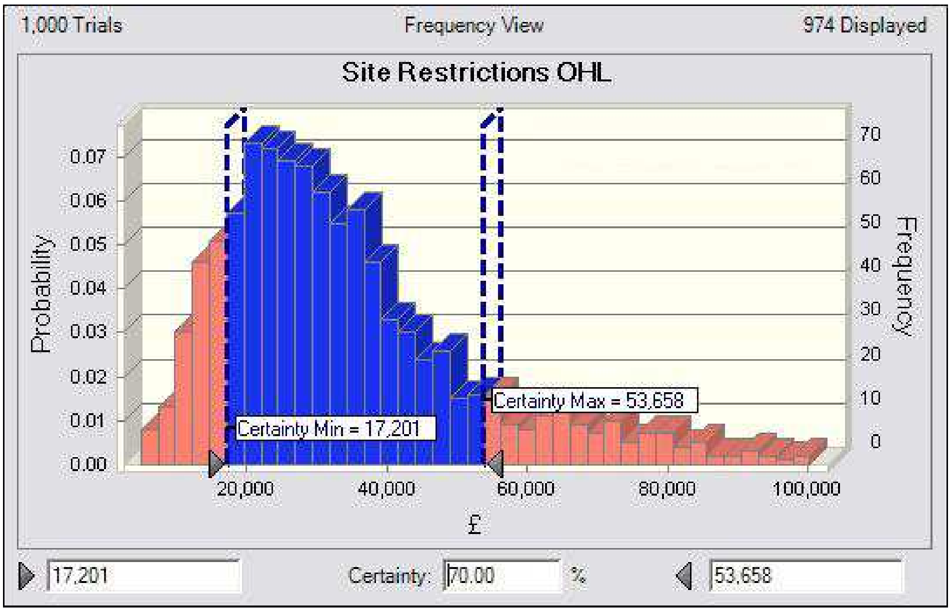
Questions	Yes	No
Are all fuctions correct?		
Are all inputs to each function correct?		
Are all controls to each fuction correct?		
Are all mechanisums to each fuction correct?		
Are all outputs from each fuctions correct?		
Are there any additional fuctions, inputs, controls,mechanisums or outputs not illistrated in the models?		
Is the order of processes correct at each stage?		
Do the models accuratly represent the cost estaimting process at each stage in the project life cycle.		

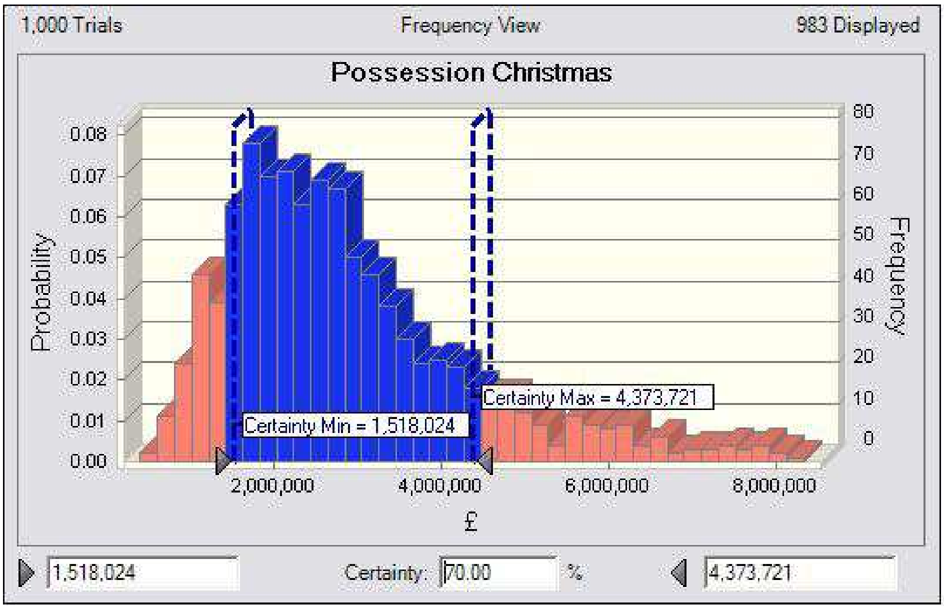
Thank you for taking the time to complete this questionnaire

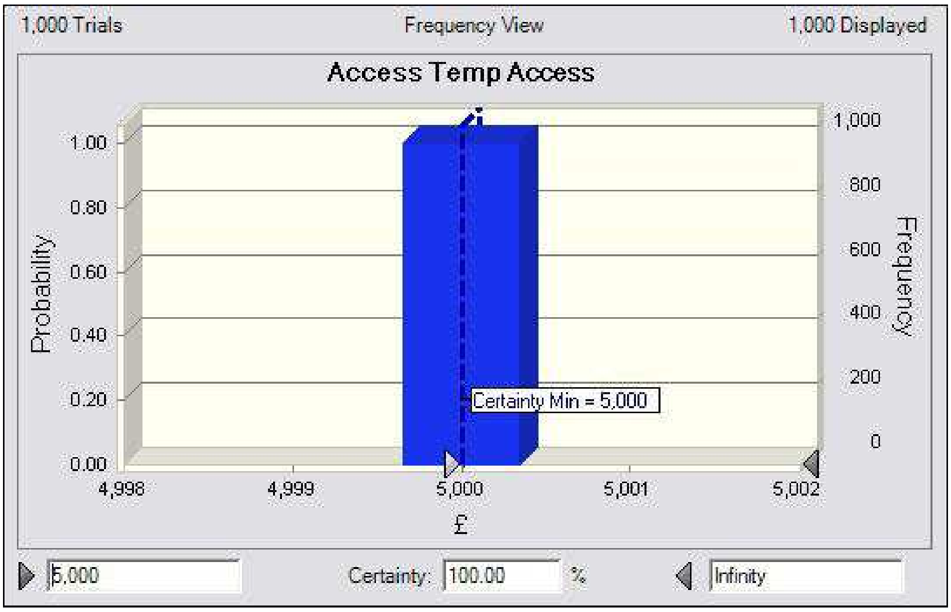
APPENDIX 4 – Monte Carlo Simulation Results

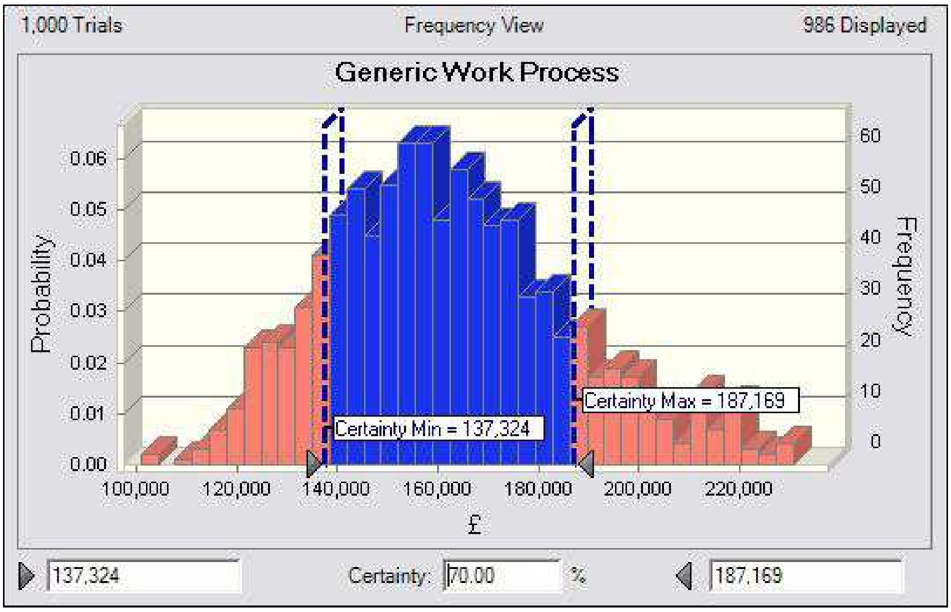

1,000 Trials
Frequency View
969 Displayed
Lift Out Old S&C Road Crane
Probability
0.08
0.06
0.04
0.02
0.00
80
60
40
20
0
Frequency
Certainty Max = 88,360
Certainty Min = 26,445
30,000
60,000
90,000
120,000
150,000
180,000
£
26,445
Certainty: 70.00 %
88,360


1,000 Trials
Frequency View
986 Displayed
Surveys Detailed
Probability
0.06
0.05
0.04
0.03
0.02
0.01
0.00
60
50
40
30
20
10
0
Frequency
Certainty Max = 429,125
Certainty Min = 298,898
240,000
300,000
360,000
420,000
480,000
540,000
£
298,898
Certainty: 70.00 %
429,125


1,000 Trials
Frequency View
974 Displayed
Site Restrictions OHL
Probability
Frequency
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
70
60
50
40
30
20
10
0
Certainty Min = 17,201
Certainty Max = 53,658
20,000
40,000
60,000
80,000
100,000
£
17,201
Certainty: 70.00 %
53,658


1,000 Trials
Frequency View
983 Displayed
Possession Christmas
Probability
Frequency
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
80
70
60
50
40
30
20
10
0
Certainty Min = 1,518,024
Certainty Max = 4,373,721
2,000,000
4,000,000
6,000,000
8,000,000
£
1,518,024
Certainty: 70.00 %
4,373,721


1,000 Trials
Frequency View
1,000 Displayed
Access Temp Access
Probability
1.00
0.80
0.60
0.40
0.20
0.00
Frequency
1,000
800
600
400
200
0
Certainty Min = 5,000
4,998
4,999
5,000
5,001
5,002
£
5,000
Certainty: 100.00 %
Infinity


1,000 Trials
Frequency View
986 Displayed
Generic Work Process
Probability
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Frequency
60
50
40
30
20
10
0
Certainty Min = 137,324
Certainty Max = 187,169
100,000
120,000
140,000
160,000
180,000
200,000
220,000
£
137,324
Certainty: 70.00 %
187,169

APPENDIX 5 – Renewal Project Scenario Questionnaire

This Questionnaire has been designed to extract the project alternatives for S&C renewal Project.

Example

PMCS Nr	Location	Nr of units	Type of units	Crossover/Turnout/diamond etc	Cost
Example	Cranfield North	7	113A	2 No. Cvs9.25 crossovers, 5 No. Cvs9.25 turnouts,	£200,13.00

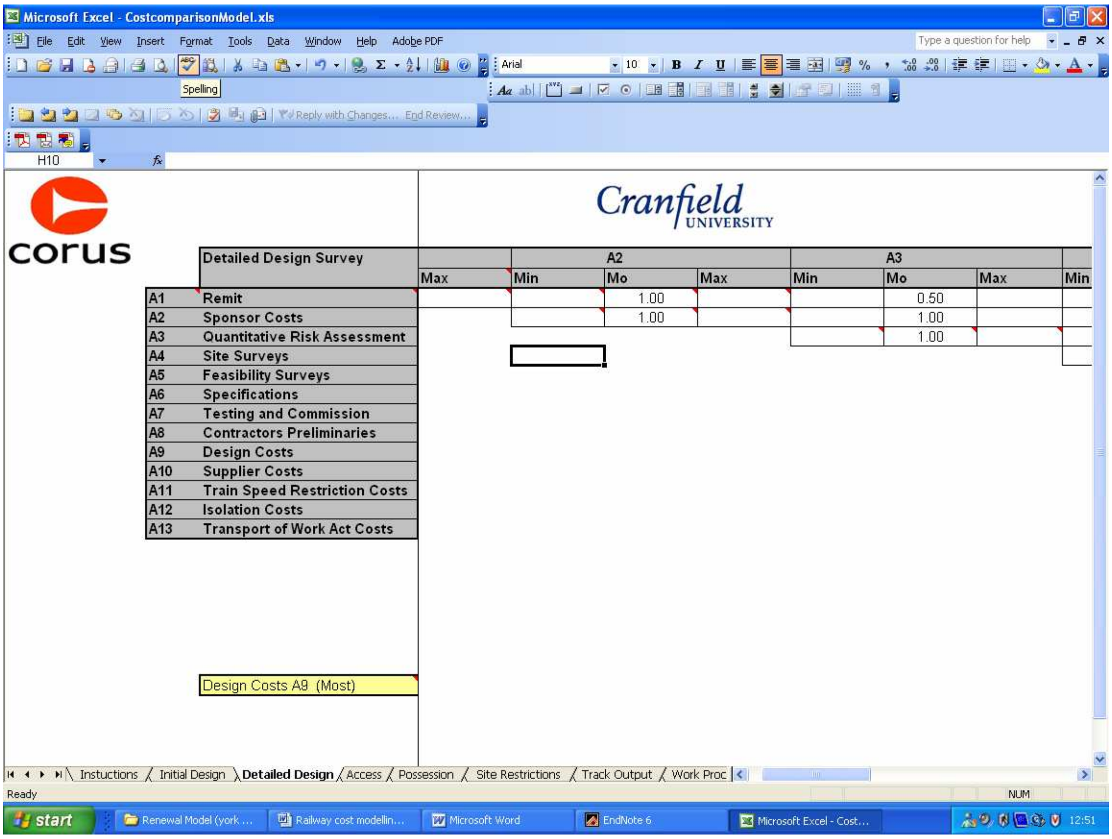
Survey	Access	Possession	Site Restrictions	Output	Work Process A	Work Process B	Work Process C
❑ Outline	❑ Rail Only	❑ Green	❑ OHL	**0-50**	One Unit	Remove S&C	Piece Meal
❑ Detailed	❑ Temporary Access	❑ Normal (weekend)	❑ Third Rail	❑ Slow	❑ Track Lifting Gear	❑ Life out One Piece Road Crane	❑ True Crane
	❑ Access Rd	❑ Christmas	❑ OHL + third Rail	❑ Line Speed	❑ Road Crane	❑ Life out One Piece KGT or Excavator	❑ Road Rail Excavator
	❑ Distant Access	❑ Blockade		**50+100**	❑ Rail Crane	❑ Life out One Piece Rail wheel fitted vehicle	❑ Hyab Unit
				❑ Slow		❑ Life out Piece Meal	
				❑ High			
				❑ Line Speed			
				100+			
				❑ Slow			
				❑ High			
				❑ Line Speed			

Please complete the project scenario by pacing an x in the appropriate alternative relating to the S&C renewal project in question. If you do not have quantitative data available for reference please use you experience/memory of completing the project.

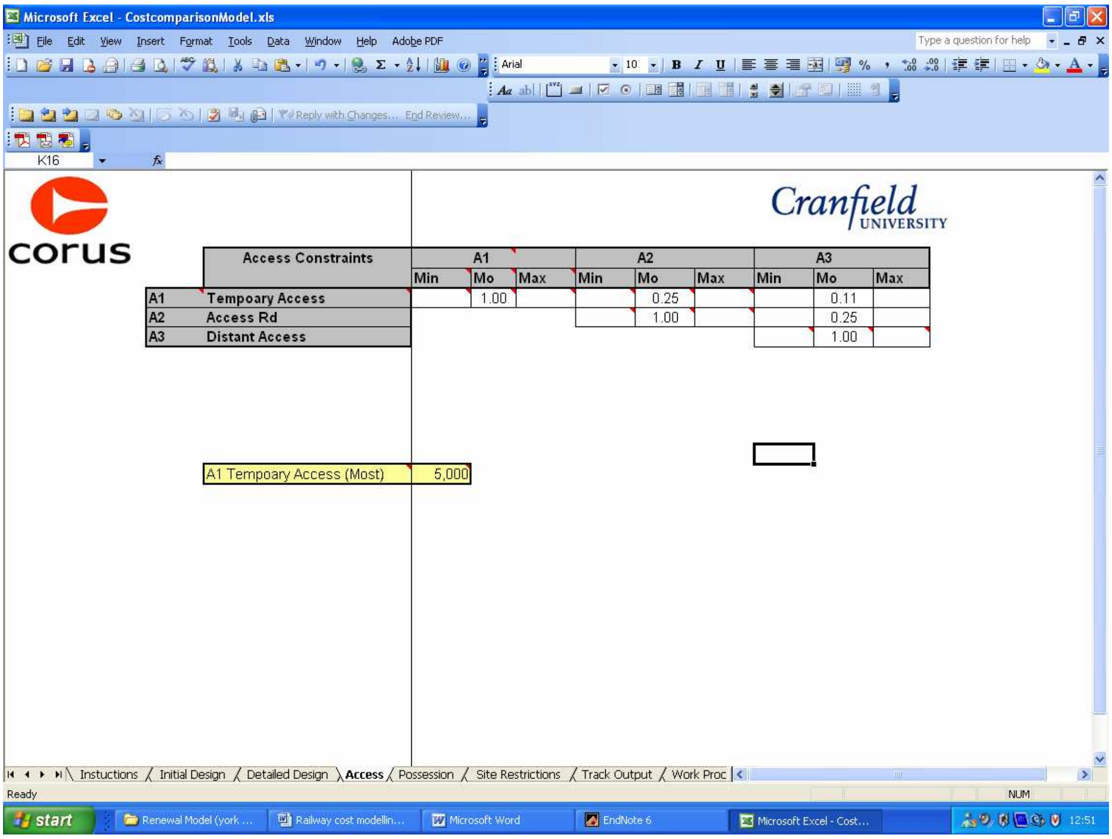
Example, this particular project in Cranfield North have had detailed survey completed, access as only rail only a blockade possession with overhead line and the track output was 50 + 100 line speed and work was done peace meal by hyab unit.

Thanks you for completing the questionnaire.

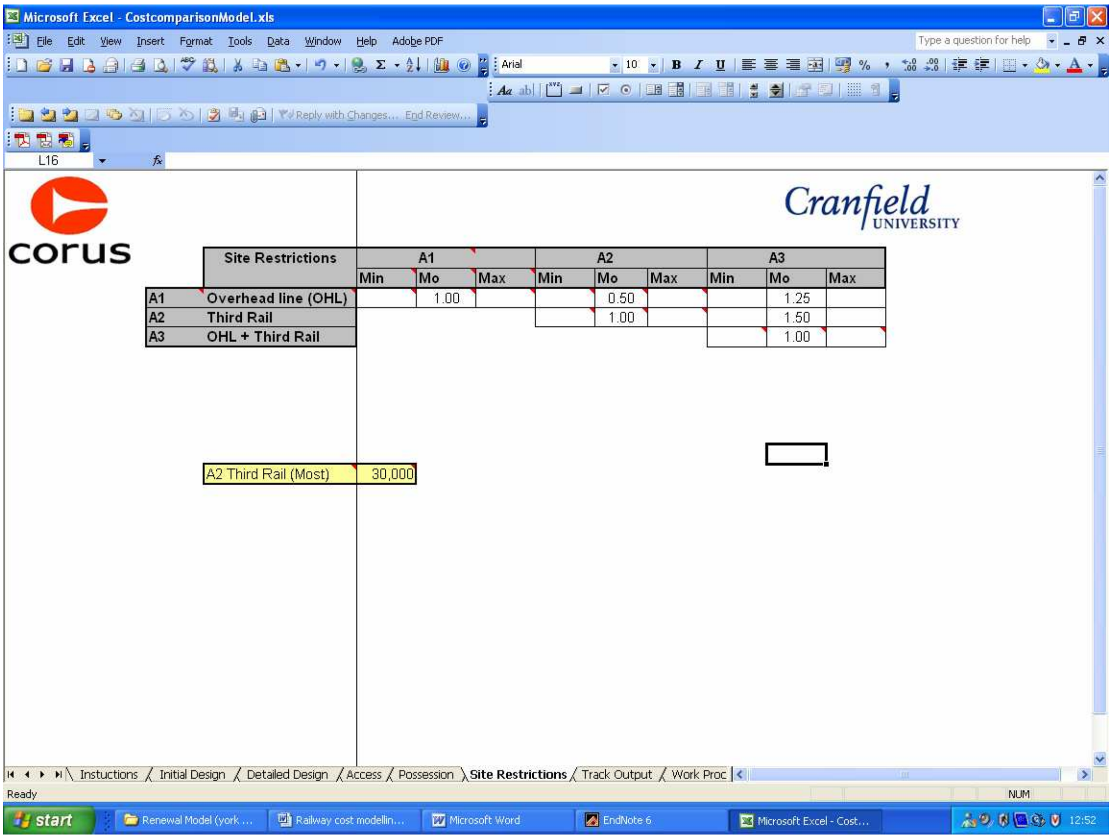
APPENDIX 6 – Screenshots of Matrixes Developed in Excel Worksheets



Detailed design Survey Matrix



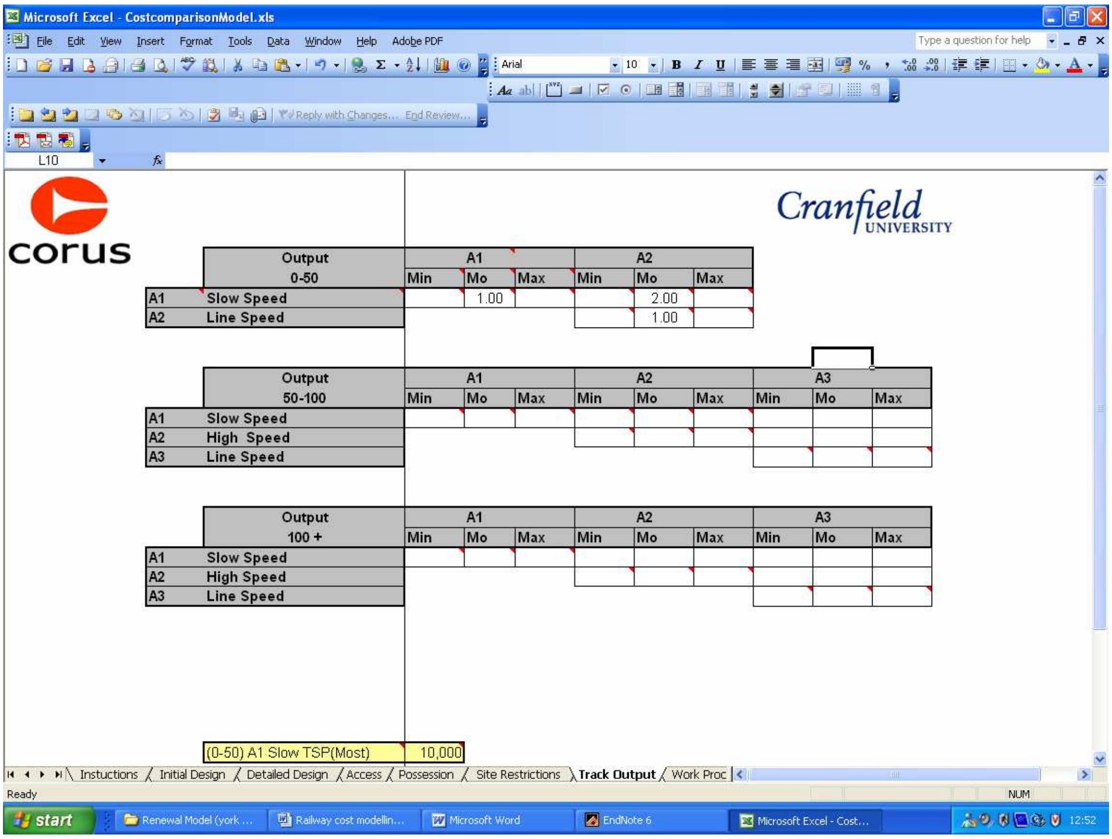
Access Constraints Matrix



	Site Restrictions	A1 Min	A1 Mo	A1 Max	A2 Min	A2 Mo	A2 Max	A3 Min	A3 Mo	A3 Max
A1	Overhead line (OHL)		1.00			0.50			1.25	
A2	Third Rail					1.00			1.50	
A3	OHL + Third Rail								1.00	

A2 Third Rail (Most)	30,000

Site Restrictions Matrix



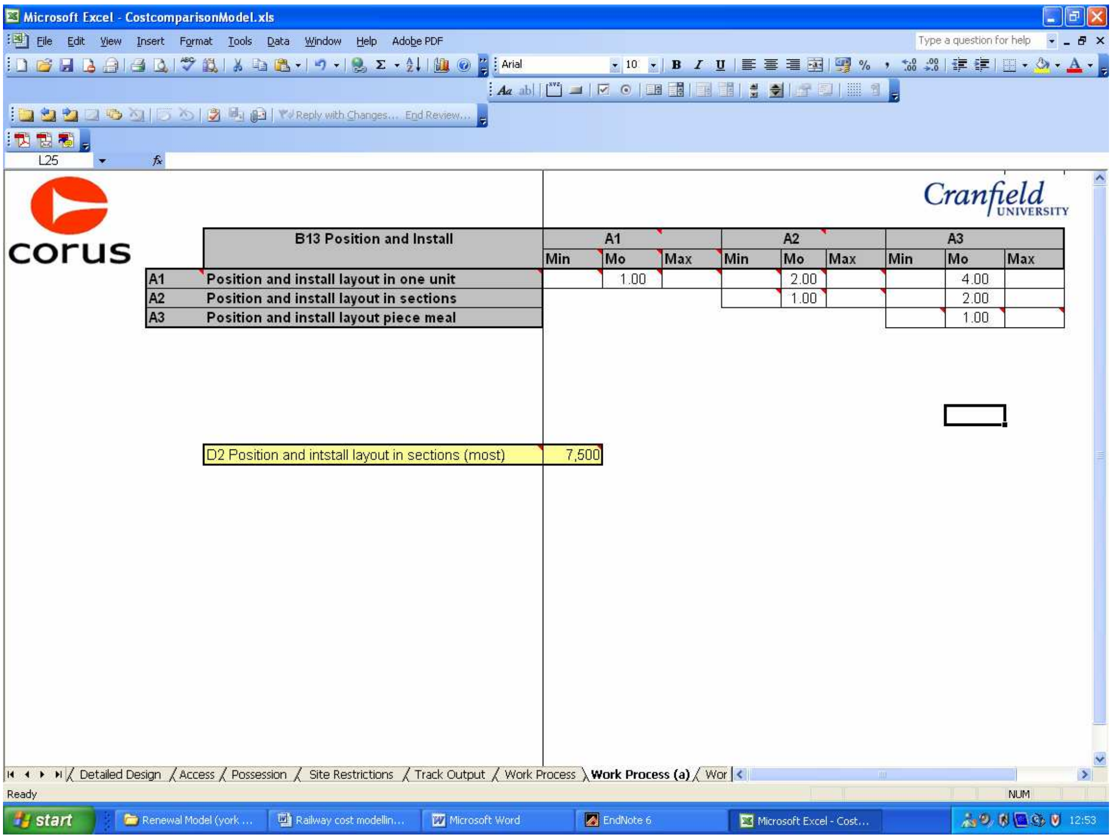
	Output 0-50	A1 Min	A1 Mo	A1 Max	A2 Min	A2 Mo	A2 Max
A1	Slow Speed		1.00			2.00	
A2	Line Speed					1.00	

	Output 50-100	A1 Min	A1 Mo	A1 Max	A2 Min	A2 Mo	A2 Max	A3 Min	A3 Mo	A3 Max
A1	Slow Speed									
A2	High Speed									
A3	Line Speed									

	Output 100 +	A1 Min	A1 Mo	A1 Max	A2 Min	A2 Mo	A2 Max	A3 Min	A3 Mo	A3 Max
A1	Slow Speed									
A2	High Speed									
A3	Line Speed									

(0-50) A1 Slow TSP(Most)	10,000

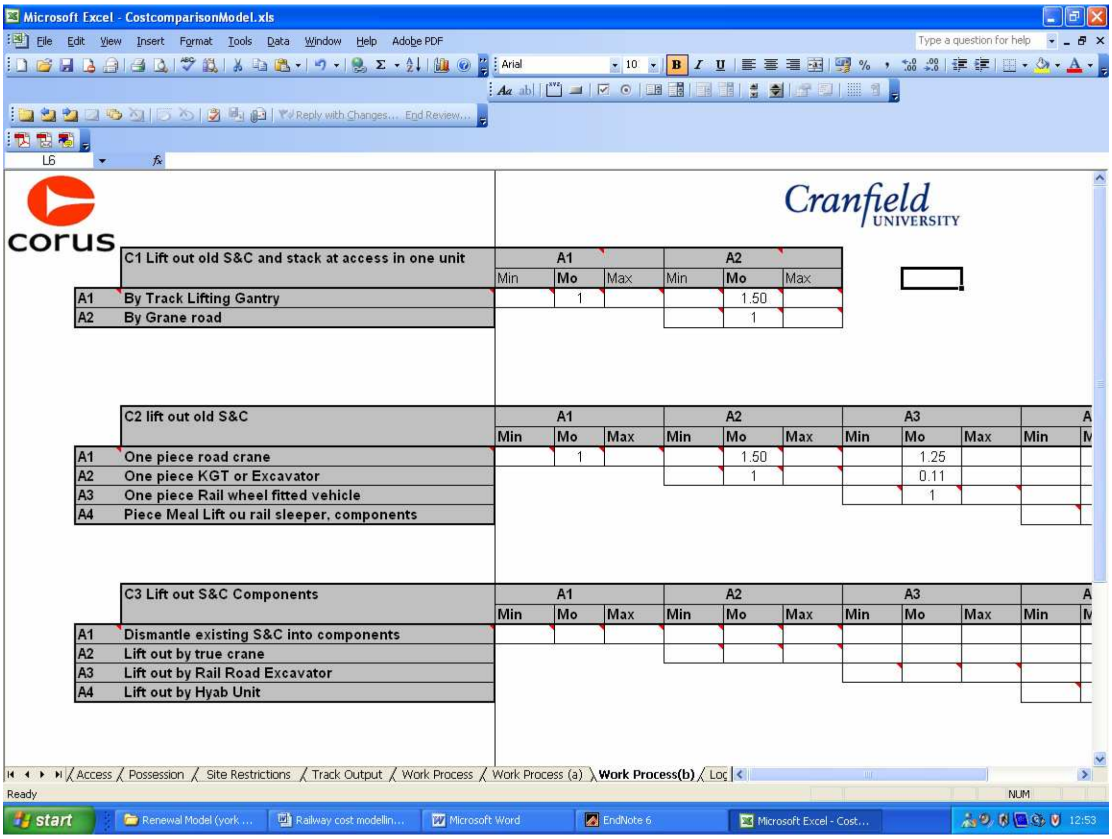
Work Process A Matrix



B13 Position and Install	A1 Min	A1 Mo	A1 Max	A2 Min	A2 Mo	A2 Max	A3 Min	A3 Mo	A3 Max
A1 Position and install layout in one unit		1.00			2.00			4.00	
A2 Position and install layout in sections					1.00			2.00	
A3 Position and install layout piece meal								1.00	

D2 Position and intstall layout in sections (most)	7,500

Work Process B Matrix

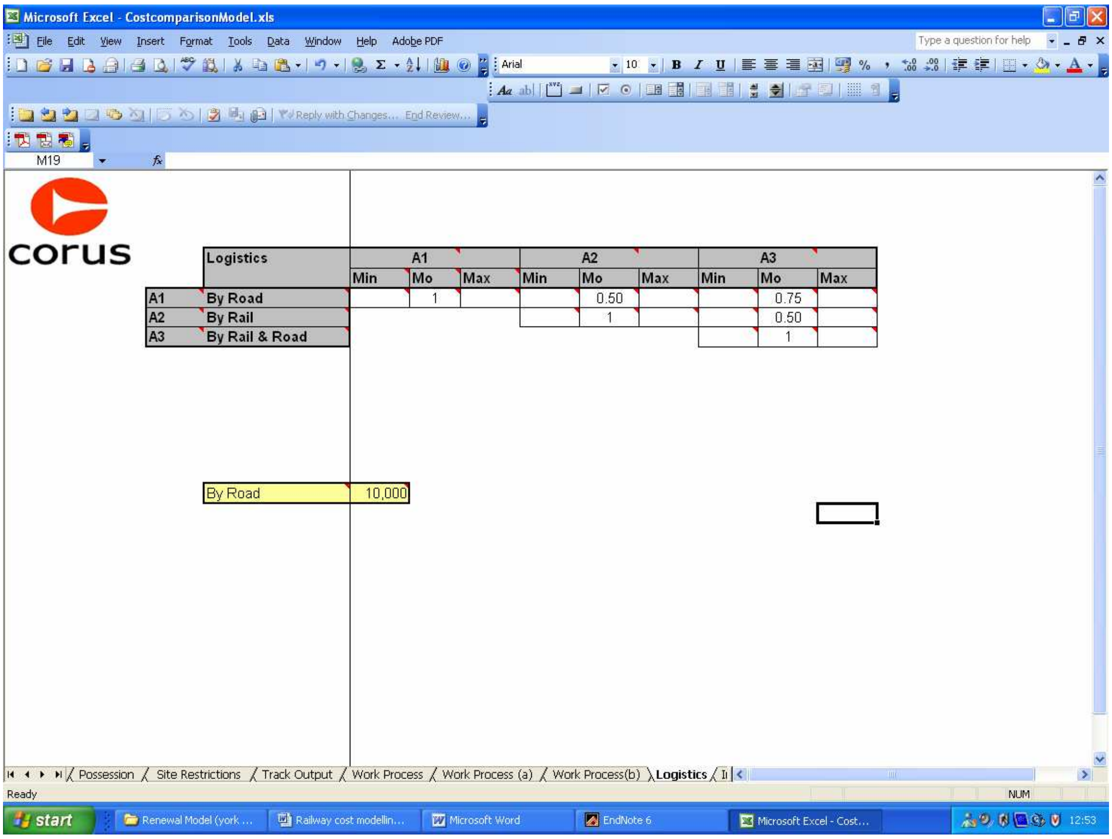


C1 Lift out old S&C and stack at access in one unit	A1 Min	A1 Mo	A1 Max	A2 Min	A2 Mo	A2 Max
A1 By Track Lifting Gantry		1			1.50	
A2 By Grane road					1	

C2 lift out old S&C	A1 Min	A1 Mo	A1 Max	A2 Min	A2 Mo	A2 Max	A3 Min	A3 Mo	A3 Max	A… Min	A… M…
A1 One piece road crane		1			1.50			1.25			
A2 One piece KGT or Excavator					1			0.11			
A3 One piece Rail wheel fitted vehicle								1			
A4 Piece Meal Lift ou rail sleeper, components											

C3 Lift out S&C Components	A1 Min	A1 Mo	A1 Max	A2 Min	A2 Mo	A2 Max	A3 Min	A3 Mo	A3 Max	A… Min	A… M…
A1 Dismantle existing S&C into components											
A2 Lift out by true crane											
A3 Lift out by Rail Road Excavator											
A4 Lift out by Hyab Unit											

Work Process C Matrix



	Logistics	A1			A2			A3		
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	By Road		1			0.50			0.75	
A2	By Rail					1			0.50	
A3	By Rail & Road								1	

By Road	10,000

Logistic Matrix

APPENDIX 7- Usability Questionnaire

COMpairCOST Model Validation Feedback Questionnaire USABILITY

Name:	Date:
Position:	Facilitator:

Please help us by reviewing the model and completing this questionnaire.

Please circle the appropriate number below. **1=Definitely No, 10=Definitely Yes**

1. Was the model easy to use? 1 2 3 4 5 6 7 8 9 10

Explain the reason for your choice.

2. Does having the range estimating feature add benefit? 1 2 3 4 5 6 7 8 9 10

Explain the reason for your choice.

3. Are there adequate features? 1 2 3 4 5 6 7 8 9 10

Explain the reason for your choice. What other features would you like to see?

4. Is the interface easy to understand? 1 2 3 4 5 6 7 8 9 10

Explain the reason for your choice.

5. Is entering data to the matrix simple? 1 2 3 4 5 6 7 8 9 10

Explain the reason for your choice.

6. Is the model easy to navigate around? 1 2 3 4 5 6 7 8 9 10

Explain the reason for your choice.

7. How could the tool be improved?

8. Do you have a clear understanding of how to operate the model?

Explain the reason for your choice. 1 2 3 4 5 6 7 8 9 10

Comments: **Mos**t beneficial part of the model. Comments: **Least** beneficial part of the model.

Other comments or recommendations for improvement.

APPENDIX 8- Populated Square Matrix

Results of the Pairwise Comparisons Populated by a Switch and Crossing Renewal Expert with Ratio Scores for Doncaster Scenario, Case Study One

Cost	Survey																																							
			A1			A2			A3			A4			A5			A6			A7			A8			A9			A10			A11			A12			A13	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Remit		1.00			1.00			0.50			0.14			0.20			0.20						0.11			0.11									1.00				
A2	Sponsor Costs		1.00			1.00			1.00			5.00			0.50			0.20						0.11			0.20									1.00				
A3	QRA		2.00			1.00			1.00			1.00			2.00			0.50						0.14			0.25									5.00				
A4	Site Surveys		7.00			0.20			1.00			1.00			2.00			1.00						0.25			0.25									5.00				
A5	Feasibility Surveys		5.00			2.00			0.50			0.50			1.00			0.50						0.14			0.14									3.00				
A6	Specifications		5.00			5.00			2.00			1.00			2.00			1.00						0.25			0.33									3.00				
A7	Testing and Commission																																							
A8	Contractors Preliminaries		9.00			9.00			7.00			4.00			7.00			4.00						1.00			1.00									9.00				
A9	Design Costs		9.00			5.00			4.00			4.00			7.00			3.00						1.00			1.00									9.00				
A10	Supplier Costs																																							
A11	TSR/PSR Costs																																							
A12	Isolation Costs		1.00			1.00			0.20			0.20			0.33			0.33						0.11			0.11									1.00				
A13	TWA Costs																																							

Cost	Access									
			A1			A2			A3	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Tempoary Access		1			0.25			0.11	
A2	Access Rd		4			1			0.25	
A3	Distant Access		9			4			1	

Cost	Possession													
			A1			A2			A3			A4		
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	
A1	Green		1			0.33			0.111			0.33		
A2	Normal (Weekend)		2			1			0.33			0.33		
A3	Christmas		6			2			1			2		
A4	Blockade		2			1			0.5			1		

Cost	Site Restrictions									
			A1			A2			A3	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	OHL		1			0.33			0.33	
A2	Third Rail		2			1			0.33	
A3	OHL + Third Rail		3			3			1	

Cost	Output						
	0-50		A1			A2	
		Min	Mo	Max	Min	Mo	Max
A1	Slow		1			2	
A2	Line Speed		0.5			1	

Cost	Position & Install Work Process								
			D1			D2			C3
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
D1	Position and install layout in one unit		1.00			2.00			4.00	
D2	Position and install layout in sections		0.50			1.00			2.00	
D3	Position and install layout piece meal		0.25			0.50			1.00	

Cost	C1 Lift out old S&C and stack at access in one unit						
		A1			A2		
		Min	Mo	Max	Min	Mo	Max
A1	By Track Lifting Gantry		1.00			2.00	
A2	By Grane road		0.50			1.00	

Cost	C2 lift out old S&C													
		A1			A2			A3			A4			
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	
A1	One piece road crane		1.00			2.00			1.00			4.00		
A2	One piece KGT or Excavator		0.50			1.00			0.11			3.00		
A3	One piece Rail wheel fitted vehicle		1.00			9.00			1.00			3.00		
A4	Piece Meal Lift ou rail sleeper, components		0.25			0.33			0.33			1.00		

Onsite Costs																												
Generic Work Process		A1			A2			A3			A5			A6			A7			A8			A9			A10		
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Pre Build Sections,switch nose crossing plain line		1.00			8.00			9.00			8.00			3.00			8.00			5.00			3.00			8.00	
A2	Disconnect & remove S&T equip		0.13			1.00			2.00			1.00			0.33			1.00			0.33			0.33			1.00	
A3	Undo & remove fishplates		0.11			0.50			1.00			0.33			0.14			0.33			0.25			0.14			0.33	
A5	Position spoil train		0.13			1.00			3.00			1.00			0.33			1.00			1.00			0.33			1.00	
A6	Excavate to 300mm load spoil train		0.33			3.00			7.00			3.00			1.00			3.00			2.00			1.00			3.00	
A7	Dozer & profile bottom of excavation		0.13			1.00			3.00			1.00			0.33			1.00			0.33			0.33			1.00	
A8	Expose &repair failed drain		0.20			3.00			4.00			1.00			0.50			3.00			1.00			0.14			2.00	
A9	Upload bottom ballast		0.33			3.00			7.00			3.00			1.00			3.00			7.00			1.00			3.00	
A10	Dozer profile & compact ballast		0.13			1.00			3.00			1.00			0.33			1.00			0.50			0.33			1.00	
A11	Set up lifting equipment		0.33			3.00			7.00			1.00			1.00			3.00			7.00			1.00			3.00	
A12	Move layout to site layout tempoarty track		0.20			2.00			4.00			1.00			0.50			2.00			1.00			0.50			3.00	
A14	Remove tempoarty track if applicable		0.11			1.00			3.00			1.00			0.33			1.00			0.50			0.33			1.00	
A15	Move lifting equip clear of positioned layout		0.11			1.00			3.00			1.00			0.33			1.00			0.50			0.33			1.00	
A16	Relay Adjoining plain line		0.20			3.00			5.00			1.00			0.50			0.50			1.00			0.50			3.00	
A17	Cut in closures do up fish plates		0.20			3.00			5.00			1.00			0.50			3.00			1.00			0.50			3.00	
A18	S&T, Fit cabling		0.20			3.00			5.00			1.00			0.50			3.00			1.00			0.50			3.00	
A19	Upload top ballast		0.33			3.00			7.00			3.00			1.00			3.00			3.00			1.00			3.00	
A20	Tamp S&C		0.11			1.00			2.00			1.00			0.33			1.00			0.50			0.33			1.00	
A21	S&T test & commission layout		0.20			3.00			5.00			1.00			0.50			3.00			1.00			0.50			3.00	
A22	Box in tidy		0.20			3.00			5.00			1.00			0.50			3.00			1.00			0.50			2.00	
A23	Give up possession		0.11			0.50			1.00			0.50			0.17			0.50			0.25			0.17			0.50	

Generic Work Process		A11			A12			A14			A15			A16			A17			A18			A19			A20			A21			A22			A23		
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Pre Build Sections,switch nose crossing plain line		3.00			5.00			9.00			9.00			5.00			5			5			3			9			5			5			9	
A2	Disconnect & remove S&T equip		0.33			0.50			1.00			1.00			0.33			0.33			0.33			0.33			1			0.33			0.33			2	
A3	Undo & remove fishplates		0.14			0.25			0.33			0.33			0.20			0.2			0.2			0.14			0..33			0.2			0.2			1	
A5	Position spoil train		1.00			1.00			1.00			1.00			1.00			1			1			0.33			1			1			1			2	
A6	Excavate to 300mm load spoil train		1.00			2.00			3.00			3.00			2.00			2			2			1			3			2			2			6	
A7	Dozer & profile bottom of excavation		0.33			0.50			1.00			1.00			2.00			0.33			0.33			0.33			1			0.33			0.33			2	
A8	Expose &repair failed drain		0.14			1.00			2.00			2.00			1.00			1			1			0.33			2			1			1			4	
A9	Upload bottom ballast		1.00			2.00			3.00			3.00			2.00			2			2			1			3			2			2			6	
A10	Dozer profile & compact ballast		0.33			0.33			1.00			1.00			0.33			0.33			0.33			0.33			1			0.33			0..33			2	
A11	Set up lifting equipment		1.00			2.00			3.00			3.00			2.00			2			2			1			3			2			2			6	
A12	Move layout to site layout tempoarty track		0.50			1.00			2.00			2.00			1.00			1			1			0.33			2			1			1			4	
A14	Remove tempoarty track if applicable		0.33			0.50			1.00			1.00			5.00			0.33			0.33			0.33			1			0.33			0..33			2	
A15	Move lifting equip clear of positioned layout		0.33			0.50			1.00			1.00			5.00			0.33			0.33			0.33			1			0.33			0.33			2	
A16	Relay Adjoining plain line		0.50			1.00			0.20			0.20			1.00			1			1			0.33			2			1			1			4	
A17	Cut in closures do up fish plates		0.50			1.00			3.00			3.00			1.00			1.00			1			0.33			2			1			1			4	
A18	S&T, Fit cabling		0.50			1.00			3.00			3.00			1.00			1.00			1.00			0.33			2			1			1			4	
A19	Upload top ballast		1.00			3.00			3.00			3.00			3.00			3.00			3.00			1.00			3			2			2			6	
A20	Tamp S&C		0.33			0.50			1.00			1.00			0.50			0.50			0.50			0.33			1.00			0.33			0.33			2	
A21	S&T test & commission layout		0.50			1.00			3.00			3.00			1.00			1.00			1.00			0.50			3.00			1.00			1			4	
A22	Box in tidy		0.50			1.00			2.00			3.00			1.00			1.00			1.00			0.50			3.00			1.00			1.00			4	
A23	Give up possession		0.17			0.25			0.50			0.50			0.25			0.25			0.25			0.17			0.50			0.25			0.25			1.00	

Cost	Logistics									
		A1			A2			A2		
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	By Road		1.00			0.50			0.33	
A2	By Rail		2.00			1.00			0.50	
A2	By Rail & Road		3.00			2.00			1.00	

Results of the Pairwise Comparisons Populated by a Switch and Crossing Renewal Expert with Ratio Scores for Gainsbourough Scenario, Case Study One

Cost	Survey																		
			A1			A2			A3			A4			A5			A6	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Remit		1.00			1.00			0.50			0.14			0.20			0.20	
A2	Sponsor Costs		1.00			1.00			1.00			5.00			0.50			0.20	
A3	QRA		2.00			1.00			1.00			1.00			2.00			0.50	
A4	Site Surveys		7.00			0.20			1.00			1.00			2.00			1.00	
A5	Feasibility Surveys		5.00			2.00			0.50			0.50			1.00			0.50	
A6	Specifications		5.00			5.00			2.00			1.00			2.00			1.00	
A7	Testing and Commission																		
A8	Contractors Preliminaries		9.00			9.00			7.00			4.00			7.00			4.00	
A9	Design Costs		9.00			5.00			4.00			4.00			7.00			3.00	
A10	Supplier Costs																		
A11	TSR/PSR Costs																		
A12	Isolation Costs		1.00			1.00			0.20			0.20			0.33			0.33	
A13	TWA Costs																		

Cost	Survey																					
			A7			A8			A9			A10			A11			A12			A13	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Remit					0.11			0.11									1.00				
A2	Sponsor Costs					0.11			0.20									1.00				
A3	QRA					0.14			0.25									5.00				
A4	Site Surveys					0.25			0.25									5.00				
A5	Feasibility Surveys					0.14			0.14									3.00				
A6	Specifications					0.25			0.33									3.00				
A7	Testing and Commission																					
A8	Contractors Preliminaries					1.00			1.00									9.00				
A9	Design Costs					1.00			1.00									9.00				
A10	Supplier Costs																					
A11	TSR/PSR Costs																					
A12	Isolation Costs					0.11			0.11									1.00				
A13	TWA Costs																					

Cost	Access									
			A1			A2			A3	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	**Tempoary Access**		1.00			0.25			0.11	
A2	**Access Rd**		4.00			1.00			0.25	
A3	**Distant Access**		9.00			4.00			1.00	

Cost	Possession												
			A1			A2			A3			A4	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	**Green**		1.00			2.00			0.16			0.50	
A2	**Normal (Weekend)**		0.50			1.00			2.00			0.75	
A3	**Christmas**		6.00			0.50			1.00			2.00	
A4	**Blockade**		2.00			1.00			0.50			1.00	

Cost	Output						
	0-50		A1			A2	
		Min	Mo	Max	Min	Mo	Max
A1	Slow		1.00			0.75	
A2	Line Speed		1.00			1.00	

Cost	Logistics									
			A1			A2			A2	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	By Road		1.00			0.50			0.75	
A2	By Rail		2.00			1.00			0.50	
A2	By Rail & Road		1.00			2.00			1.00	

Cost	Position and Install									
			D1			**D2**			**C3**	
		Min	**Mo**	Max	Min	**Mo**	Max	Min	**Mo**	Max
D1	Position and install layout in one unit		1.00			2.00			4.00	
D2	Position and install layout in sections		0.50			1.00			2.00	
D3	Position and install layout piece meal		0.25			0.50			1.00	

Cost	C1 Lift out old S&C and stack at access in one unit						
			A1			**A2**	
		Min	**Mo**	Max	Min	**Mo**	Max
A1	By Track Lifting Gantry		1.00			1.50	
A2	By Grane road		0.67			1.00	

Cost	C2 lift out old S&C												
			A1			**A2**			**A3**			**A4**	
		Min	**Mo**	Max	Min	**Mo**	Max	Min	**Mo**	Max	Min	**Mo**	Max
A1	One piece road crane		1.00			1.50			1.25			4.00	
A2	One piece KGT or Excavator		0.67			1.00			0.11			3.00	
A3	One piece Rail wheel fitted vehicle		0.80			9.00			1.00			3.00	
A4	Piece Meal Lift ou rail sleeper, components		0.25			0.33			0.33			1.00	

Cost	C3 Lift out S&C Components												
			A1			**A2**			**A3**			**A4**	
		Min	**Mo**	Max	Min	**Mo**	Max	Min	**Mo**	Max	Min	**Mo**	Max
A1	Dismantle existing S&C into components		1.00			0.20			1.00			2.00	
A2	Lift out by true crane		5.00			1.00			0.16			0.11	
A3	Lift out by Rail Road Excavator		6.00			6.00			1.00			0.13	
A4	Lift out by Hyab Unit		0.50			9.00			8.00			1.00	

Onsite Costs

	Generic Work Process	A1			A2			A3			A5			A6			A7			A8		
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Pre Build Sections,switch nose crossing plain line		1.00			8.00			9.00			8.00			3.00			8.00			5.00	
A2	Disconnect & remove S&T equip		0.13			1.00			2.00			1.00			0.33			1.00			0.33	
A3	Undo & remove fishplates		0.11			0.50			1.00			0.33			0.14			0.33			0.25	
A5	Position spoil train		0.13			1.00			3.00			1.00			0.33			1.00			1.00	
A6	Excavate to 300mm load spoil train		0.33			3.00			7.00			3.00			1.00			3.00			2.00	
A7	Dozer & profile bottom of excavation		0.13			1.00			3.00			1.00			0.33			1.00			0.33	
A8	Expose &repair failed drain		0.20			3.00			4.00			1.00			0.50			3.00			1.00	
A9	Upload bottom ballast		0.33			3.00			7.00			3.00			1.00			3.00			7.00	
A10	Dozer profile & compact ballast		0.13			1.00			3.00			1.00			0.33			1.00			0.50	
A11	Set up lifting equipment		0.33			3.00			7.00			1.00			1.00			3.00			7.00	
A12	Move layout to site layout tempoarty track		0.20			2.00			4.00			1.00			0.50			2.00			1.00	
A14	Remove tempoarty track if applicable		0.11			1.00			3.00			1.00			0.33			1.00			0.50	
A15	Move lifting equip clear of positioned layout		0.11			1.00			3.00			1.00			0.33			1.00			0.50	
A16	Relay Adjoining plain line		0.20			3.00			5.00			1.00			0.50			0.50			1.00	
A17	Cut in closures do up fish plates		0.20			3.00			5.00			1.00			0.50			3.00			1.00	
A18	S&T , Fit cabling		0.20			3.00			5.00			1.00			0.50			3.00			1.00	
A19	Upload top ballast		0.33			3.00			7.00			3.00			1.00			3.00			3.00	
A20	Tamp S&C		0.11			1.00			2.00			1.00			0.33			1.00			0.50	
A21	S&T test & commission layout		0.20			3.00			5.00			1.00			0.50			3.00			1.00	
A22	Box in tidy		0.20			3.00			5.00			1.00			0.50			3.00			1.00	
A23	Give up possession		0.11			0.50			1.00			0.50			0.17			0.50			0.25	

	Generic Work Process	A9			A10			A11			A12			A14			A15			A16		
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Pre Build Sections,switch nose crossing plain line		3.00			8.00			3.00			5.00			9.00			9.00			5.00	
A2	Disconnect & remove S&T equip		0.33			1.00			0.33			0.50			1.00			1.00			0.33	
A3	Undo & remove fishplates		0.14			0.33			0.14			0.25			0.33			0.33			0.20	
A5	Position spoil train		0.33			1.00			1.00			1.00			1.00			1.00			1.00	
A6	Excavate to 300mm load spoil train		1.00			3.00			1.00			2.00			3.00			3.00			2.00	
A7	Dozer & profile bottom of excavation		0.33			1.00			0.33			0.50			1.00			1.00			2.00	
A8	Expose &repair failed drain		0.14			2.00			0.14			1.00			2.00			2.00			1.00	
A9	Upload bottom ballast		1.00			3.00			1.00			2.00			3.00			3.00			2.00	
A10	Dozer profile & compact ballast		0.33			1.00			0.33			0.33			1.00			1.00			0.33	
A11	Set up lifting equipment		1.00			3.00			1.00			2.00			3.00			3.00			2.00	
A12	Move layout to site layout tempoarty track		0.50			3.00			0.50			1.00			2.00			2.00			1.00	
A14	Remove tempoarty track if applicable		0.33			1.00			0.33			0.50			1.00			1.00			5.00	
A15	Move lifting equip clear of positioned layout		0.33			1.00			0.33			0.50			1.00			1.00			5.00	
A16	Relay Adjoining plain line		0.50			3.00			0.50			1.00			0.20			0.20			1.00	
A17	Cut in closures do up fish plates		0.50			3.00			0.50			1.00			3.00			3.00			1.00	
A18	S&T , Fit cabling		0.50			3.00			0.50			1.00			3.00			3.00			1.00	
A19	Upload top ballast		1.00			3.00			1.00			3.00			3.00			3.00			3.00	
A20	Tamp S&C		0.33			1.00			0.33			0.50			1.00			1.00			0.50	
A21	S&T test & commission layout		0.50			3.00			0.50			1.00			3.00			3.00			1.00	
A22	Box in tidy		0.50			2.00			0.50			1.00			2.00			3.00			1.00	
A23	Give up possession		0.17			0.50			0.17			0.25			0.50			0.50			0.25	

	Generic Work Process	A17			A18			A19			A20			A21			A22			A23		
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Pre Build Sections,switch nose crossing plain line		5			5			3			9			5			5			9	
A2	Disconnect & remove S&T equip		0.33			0.33			0.33			1			0.33			0.33			2	
A3	Undo & remove fishplates		0.2			0.2			0.14			0..33			0.2			0.2			1	
A5	Position spoil train		1			1			0.33			1			1			1			2	
A6	Excavate to 300mm load spoil train		2			2			1			3			2			2			6	
A7	Dozer & profile bottom of excavation		0.33			0.33			0.33			1			0.33			0.33			2	
A8	Expose &repair failed drain		1			1			0.33			2			1			1			4	
A9	Upload bottom ballast		2			2			1			3			2			2			6	
A10	Dozer profile & compact ballast		0.33			0.33			0.33			1			0.33			0..33			2	
A11	Set up lifting equipment		2			2			1			3			2			2			6	
A12	Move layout to site layout tempoarty track		1			1			0.33			2			1			1			4	
A14	Remove tempoarty track if applicable		0.33			0.33			0.33			1			0.33			0..33			2	
A15	Move lifting equip clear of positioned layout		0.33			0.33			0.33			1			0.33			0.33			2	
A16	Relay Adjoining plain line		1			1			0.33			2			1			1			4	
A17	Cut in closures do up fish plates		1.00			1			0.33			2			1			1			4	
A18	S&T , Fit cabling		1.00			1.00			0.33			2			1			1			4	
A19	Upload top ballast		3.00			3.00			1.00			3			2			2			6	
A20	Tamp S&C		0.50			0.50			0.33			1.00			0.33			0.33			2	
A21	S&T test & commission layout		1.00			1.00			0.50			3.00			1.00			1			4	
A22	Box in tidy		1.00			1.00			0.50			3.00			1.00			1.00			4	
A23	Give up possession		0.25			0.25			0.17			0.50			0.25			0.25			1.00	

Results of the Pairwise Comparisons Populated by a Switch and Crossing Renewal Expert with Ratio Scores for Hatfield South, Case Study One

Cost	Detailed Design																																							
			A1			A2			A3			A4			A5			A6			A7			A8			A9			A10			A11			A12			A13	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Remit		1.00			1.00			0.50			0.14			0.20			0.20						0.05			0.10									1.00				
A2	Sponsor Costs		1.00			1.00			1.00			5.00			0.50			0.20						0.10			0.20									1.00				
A3	QRA		2.00			1.00			1.00			1.00			2.00			0.50						0.16			0.25									5.00				
A4	Site Surveys		7.00			0.20			1.00			1.00			2.00			1.00						0.25			0.25									5.00				
A5	Feasibility Surveys		5.00			2.00			0.50			0.50			1.00			0.50						0.16			0.13									3.00				
A6	Specifications		5.00			5.00			2.00			1.00			2.00			1.00						0.25			0.33									3.00				
A7	Testing and Commission																																							
A8	Contractors Preliminaries		20.00			10.00			6.00			4.00			6.00			4.00						1.00			1.00									0.20				
A9	Design Costs		10.00			5.00			4.00			4.00			8.00			3.00						1.00			1.00									9.00				
A10	Supplier Costs																																							
A11	TSR/PSR Costs																																							
A12	Isolation Costs		1.00			1.00			0.20			0.20			0.33			0.33						5.00			0.11													
A13	TWA Costs																																							

Cost	Access									
			A1			A2			A3	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	**Tempoary Access**		1.00			0.25			0.11	
A2	**Access Rd**		4.00			1.00			0.25	
A3	**Distant Access**		9.00			4.00			1.00	

Cost	Possession												
			A1			A2			A3			A4	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	**Green**		1.00			2.00			0.16			0.50	
A2	**Normal (Weekend)**		0.50			1.00			2.00			0.75	
A3	**Christmas**		6.00			0.50			1.00			2.00	
A4	**Blockade**		2.00			1.00			0.50			1.00	

Cost	Site Restrictions									
			A1			A2			A3	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	**OHL**					0.50			1.25	
A2	**Third Rail**		2.00						1.50	
A3	**OHL + Third Rail**		0.80			0.67				

Cost	Output									
	50-100		A1			A2			A3	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	**Slow TSP**		1.00			2.00			3.00	
A2	**High TSP**		0.50			1.00			0.75	
A3	**Line Speed**		0.33			1.00			1.00	

Onsite Costs

Generic Work Process		A1			A2			A3			A5			A6			A7			A8			A9			A10			A11		
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Pre Build Sections,switch nose crossing plain line		1.00			8.00			9.00			8.00			3.00			8.00			5.00			3.00			8.00			3.00	
A2	Disconnect & remove S&T equip		0.13			1.00			2.00			1.00			0.33			1.00			0.33			0.33			1.00			0.33	
A3	Undo & remove fishplates		0.11			0.50			1.00			0.33			0.14			0.33			0.25			0.14			0.33			0.14	
A5	Position spoil train		0.13			1.00			3.00			1.00			0.33			1.00			1.00			0.33			1.00			1.00	
A6	Excavate to 300mm load spoil train		0.33			3.00			7.00			3.00			1.00			3.00			2.00			1.00			3.00			1.00	
A7	Dozer & profile bottom of excavation		0.13			1.00			3.00			1.00			0.33			1.00			0.33			0.33			1.00			0.33	
A8	Expose &repair failed drain		0.20			3.00			4.00			1.00			0.50			3.00			1.00			0.14			2.00			0.14	
A9	Upload bottom ballast		0.33			3.00			7.00			3.00			1.00			3.00			7.00			1.00			3.00			1.00	
A10	Dozer profile & compact ballast		0.13			1.00			3.00			1.00			0.33			1.00			0.50			0.33			1.00			0.33	
A11	Set up lifting equipment		0.33			3.00			7.00			1.00			1.00			3.00			7.00			1.00			3.00			1.00	
A12	Move layout to site layout tempoarty track		0.20			2.00			4.00			1.00			0.50			2.00			1.00			0.50			3.00			0.50	
A14	Remove tempoarty track if applicable		0.11			1.00			3.00			1.00			0.33			1.00			0.50			0.33			1.00			0.33	
A15	Move lifting equip clear of positioned layout		0.11			1.00			3.00			1.00			0.33			1.00			0.50			0.33			1.00			0.33	
A16	Relay Adjoining plain line		0.20			3.00			5.00			1.00			0.50			0.50			1.00			0.50			3.00			0.50	
A17	Cut in closures do up fish plates		0.20			3.00			5.00			1.00			0.50			3.00			1.00			0.50			3.00			0.50	
A18	S&T , Fit cabling		0.20			3.00			5.00			1.00			0.50			3.00			1.00			0.50			3.00			0.50	
A19	Upload top ballast		0.33			3.00			7.00			3.00			1.00			3.00			3.00			1.00			3.00			1.00	
A20	Tamp S&C		0.11			1.00			2.00			1.00			0.33			1.00			0.50			0.33			1.00			0.33	
A21	S&T test & commission layout		0.20			3.00			5.00			1.00			0.50			3.00			1.00			0.50			3.00			0.50	
A22	Box in tidy		0.20			3.00			5.00			1.00			0.50			3.00			1.00			0.50			2.00			0.50	
A23	Give up possession		0.11			0.50			1.00			0.50			0.17			0.50			0.25			0.17			0.50			0.17	

Generic Work Process		A12			A14			A15			A16			A17			A18			A19			A20			A21			A22			A23		
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Pre Build Sections,switch nose crossing plain line		5.00			9.00			9.00			5.00			5			5			3			9			5			5			9	
A2	Disconnect & remove S&T equip		0.50			1.00			1.00			0.33			0.33			0.33			0.33			1			0.33			0.33			2	
A3	Undo & remove fishplates		0.25			0.33			0.33			0.20			0.2			0.2			0.14			0..33			0.2			0.2			1	
A5	Position spoil train		1.00			1.00			1.00			1.00			1			1			0.33			1			1			1			2	
A6	Excavate to 300mm load spoil train		2.00			3.00			3.00			2.00			2			2			1			3			2			2			6	
A7	Dozer & profile bottom of excavation		0.50			1.00			1.00			2.00			0.33			0.33			0.33			1			0.33			0.33			2	
A8	Expose &repair failed drain		1.00			2.00			2.00			1.00			1			1			0.33			2			1			1			4	
A9	Upload bottom ballast		2.00			3.00			3.00			2.00			2			2			1			3			2			2			6	
A10	Dozer profile & compact ballast		0.33			1.00			1.00			0.33			0.33			0.33			0.33			1			0.33			0..33			2	
A11	Set up lifting equipment		2.00			3.00			3.00			2.00			2			2			1			3			2			2			6	
A12	Move layout to site layout tempoarty track		1.00			2.00			2.00			1.00			1			1			0.33			2			1			1			4	
A14	Remove tempoarty track if applicable		0.50			1.00			1.00			5.00			0.33			0.33			0.33			1			0.33			0..33			2	
A15	Move lifting equip clear of positioned layout		0.50			1.00			1.00			5.00			0.33			0.33			0.33			1			0.33			0.33			2	
A16	Relay Adjoining plain line		1.00			0.20			0.20			1.00			1			1			0.33			2			1			1			4	
A17	Cut in closures do up fish plates		1.00			3.00			3.00			1.00			1.00			1			0.33			2			1			1			4	
A18	S&T , Fit cabling		1.00			3.00			3.00			1.00			1.00			1.00			0.33			2			1			1			4	
A19	Upload top ballast		3.00			3.00			3.00			3.00			3.00			3.00			1.00			3			2			2			6	
A20	Tamp S&C		0.50			1.00			1.00			0.50			0.50			0.50			0.33			1.00			0.33			0.33			2	
A21	S&T test & commission layout		1.00			3.00			3.00			1.00			1.00			1.00			0.50			3.00			1.00			1			4	
A22	Box in tidy		1.00			2.00			3.00			1.00			1.00			1.00			0.50			3.00			1.00			1.00			4	
A23	Give up possession		0.25			0.50			0.50			0.25			0.25			0.25			0.17			0.50			0.25			0.25			1.00	

Cost	B13 Position and Install									
		D1			D2			C3		
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
D1	Position and install layout in one unit		1.00			2.00			4.00	
D2	Position and install layout in sections		0.50			1.00			2.00	
D3	Position and install layout piece meal		0.25			0.50			1.00	

Cost	C1 Lift out old S&C and stack at access in one unit						
		A1			A2		
		Min	**Mo**	Max	Min	**Mo**	Max
A1	By Track Lifting Gantry		1.00			1.50	
A2	By Grane road		0.67			1.00	

Cost	C2 lift out old S&C												
		A1			A2			A3			A4		
		Min	**Mo**	Max	Min	**Mo**	Max	Min	**Mo**	Max	Min	**Mo**	Max
A1	One piece road crane		1.00			1.50			1.25			4.00	
A2	One piece KGT or Excavator		0.67			1.00			0.11			3.00	
A3	One piece Rail wheel fitted vehicle		0.80			9.00			1.00			3.00	
A4	Piece Meal Lift ou rail sleeper, components		0.25			0.33			0.33			1.00	

Cost	C3 Lift out S&C Components												
		A1			A2			A3			A4		
		Min	**Mo**	Max	Min	**Mo**	Max	Min	**Mo**	Max	Min	**Mo**	Max
A1	Dismantle existing S&C into components		1.00			0.20			1.00			2.00	
A2	Lift out by true crane		5.00			1.00			0.16			0.11	
A3	Lift out by Rail Road Excavator		6.00			6.00			1.00			0.13	
A4	Lift out by Hyab Unit		0.50			9.00			8.00			1.00	

Cost	Logistics									
		A1			A2			A2		
		Min	**Mo**	Max	Min	**Mo**	Max	Min	**Mo**	Max
A1	By Road		1.00			0.50			0.33	
A2	By Rail		2.00			1.00			0.50	
A2	By Rail & Road		3.00			2.00			1.00	

Results of the Pairwise Comparisons Populated by a Switch and Crossing Renewal Expert with Ratio Scores for Stoke Summit, Case Study One

Cost	Detailed Design																		
			A1			A2			A3			A4			A5			A6	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Remit		1.00			1.00			0.50			0.14			0.20			0.20	
A2	Sponsor Costs		1.00			1.00			1.00			5.00			0.50			0.20	
A3	QRA		2.00			1.00			1.00			1.00			2.00			0.50	
A4	Site Surveys		7.00			0.20			1.00			1.00			2.00			1.00	
A5	Feasibility Surveys		5.00			2.00			0.50			0.50			1.00			0.50	
A6	Specifications		5.00			5.00			2.00			1.00			2.00			1.00	
A7	Testing and Commission																		
A8	Contractors Preliminaries		20.00			10.00			6.00			4.00			6.00			4.00	
A9	Design Costs		10.00			5.00			4.00			4.00			8.00			3.00	
A10	Supplier Costs																		
A11	TSR/PSR Costs																		
A12	Isolation Costs		1.00			1.00			0.20			0.20			0.33			0.33	
A13	TWA Costs																		

Cost	Detailed Design																					
			A7			A8			A9			A10			A11			A12			A13	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Remit					0.05			0.10									1.00				
A2	Sponsor Costs					0.10			0.20									1.00				
A3	QRA					0.16			0.25									5.00				
A4	Site Surveys					0.25			0.25									5.00				
A5	Feasibility Surveys					0.16			0.13									3.00				
A6	Specifications					0.25			0.33									3.00				
A7	Testing and Commission																					
A8	Contractors Preliminaries					1.00			1.00									0.20				
A9	Design Costs					1.00			1.00									9.00				
A10	Supplier Costs																					
A11	TSR/PSR Costs																					
A12	Isolation Costs					5.00			0.11													
A13	TWA Costs																					

Cost	Access									
			A1			A2			A3	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Tempoary Access		1.00			9.00			20.00	
A2	Access Rd		0.11			1.00			5.00	
A3	Distant Access		9.00			0.20			1.00	

Cost	Possession												
			A1			A2			A3			A4	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Green		1.00			2.00			0.16			0.50	
A2	Normal (Weekend)		0.50			1.00			2.00			0.75	
A3	Christmas		6.00			0.50			1.00			2.00	
A4	Blockade		2.00			1.00			0.50			1.00	

Cost	Site Restrictions									
			A1			A2			A3	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	OHL					0.50			1.25	
A2	Third Rail		2.00						1.50	
A3	OHL + Third Rail		0.80			0.67				

Cost	Output 50-100									
			A1			A2			A3	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Slow TSP		1.00			2.00			3.00	
A2	High TSP		0.50			1.00			0.75	
A3	Line Speed		0.33			1.00			1.00	

Cost	B13 Position and Install									
			D1			D2			C3	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
D1	Position and install layout in one unit		1.00			2.00			4.00	
D2	Position and install layout in sections		0.50			1.00			2.00	
D3	Position and install layout piece meal		0.25			0.50			1.00	

Onsite Costs																																
Generic Work Process		A1			A2			A3			A5			A6			A7			A8			A9			A10			A11			
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	
A1	Pre Build Sections,switch nose crossing plain line		1.00			8.00			9.00			8.00			3.00			8.00			5.00			3.00			8.00			3.00		
A2	Disconnect & remove S&T equip		0.13			1.00			2.00			1.00			0.33			1.00			0.33			0.33			1.00			0.33		
A3	Undo & remove fishplates		0.11			0.50			1.00			0.33			0.14			0.33			0.25			0.14			0.33			0.14		
A5	Position spoil train		0.13			1.00			3.00			1.00			0.33			1.00			1.00			0.33			1.00			1.00		
A6	Excavate to 300mm load spoil train		0.33			3.00			7.00			3.00			1.00			3.00			2.00			1.00			3.00			1.00		
A7	Dozer & profile bottom of excavation		0.13			1.00			3.00			1.00			0.33			1.00			0.33			0.33			1.00			0.33		
A8	Expose &repair failed drain		0.20			3.00			4.00			1.00			0.50			3.00			1.00			0.14			2.00			0.14		
A9	Upload bottom ballast		0.33			3.00			7.00			3.00			1.00			3.00			7.00			1.00			3.00			1.00		
A10	Dozer profile & compact ballast		0.13			1.00			3.00			1.00			0.33			1.00			0.50			0.33			1.00			0.33		
A11	Set up lifting equipment		0.33			3.00			7.00			1.00			1.00			3.00			7.00			1.00			3.00			1.00		
A12	Move layout to site layout tempoarty track		0.20			2.00			4.00			1.00			0.50			2.00			1.00			0.50			3.00			0.50		
A14	Remove tempoarty track if applicable		0.11			1.00			3.00			1.00			0.33			1.00			0.50			0.33			1.00			0.33		
A15	Move lifting equip clear of positioned layout		0.11			1.00			3.00			1.00			0.33			1.00			0.50			0.33			1.00			0.33		
A16	Relay Adjoining plain line		0.20			3.00			5.00			1.00			0.50			0.50			1.00			0.50			3.00			0.50		
A17	Cut in closures do up fish plates		0.20			3.00			5.00			1.00			0.50			3.00			1.00			0.50			3.00			0.50		
A18	S&T, Fit cabling		0.20			3.00			5.00			1.00			0.50			3.00			1.00			0.50			3.00			0.50		
A19	Upload top ballast		0.33			3.00			7.00			3.00			1.00			3.00			3.00			1.00			3.00			1.00		
A20	Tamp S&C		0.11			1.00			2.00			1.00			0.33			1.00			0.50			0.33			1.00			0.33		
A21	S&T test & commission layout		0.20			3.00			5.00			1.00			0.50			3.00			1.00			0.50			3.00			0.50		
A22	Box in tidy		0.20			3.00			5.00			1.00			0.50			3.00			1.00			0.50			2.00			0.50		
A23	Give up possession		0.11			0.50			1.00			0.50			0.17			0.50			0.25			0.17			0.50			0.17		

Onsite Costs																																		
Generic Work Process		A12			A14			A15			A16			A17			A18			A19			A20			A21			A22			A23		
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Pre Build Sections,switch nose crossing plain line		5.00			9.00			9.00			5.00			5			5			3			9			5			5			9	
A2	Disconnect & remove S&T equip		0.50			1.00			1.00			0.33			0.33			0.33			0.33			1			0.33			0.33			2	
A3	Undo & remove fishplates		0.25			0.33			0.33			0.20			0.2			0.2			0.14			0..33			0.2			0.2			1	
A5	Position spoil train		1.00			1.00			1.00			1.00			1			1			0.33			1			1			1			2	
A6	Excavate to 300mm load spoil train		2.00			3.00			3.00			2.00			2			2			1			3			2			2			6	
A7	Dozer & profile bottom of excavation		0.50			1.00			1.00			2.00			0.33			0.33			0.33			1			0.33			0.33			2	
A8	Expose &repair failed drain		1.00			2.00			2.00			1.00			1			1			0.33			2			1			1			4	
A9	Upload bottom ballast		2.00			3.00			3.00			2.00			2			2			1			3			2			2			6	
A10	Dozer profile & compact ballast		0.33			1.00			1.00			0.33			0.33			0.33			0.33			1			0.33			0..33			2	
A11	Set up lifting equipment		2.00			3.00			3.00			2.00			2			2			1			3			2			2			6	
A12	Move layout to site layout tempoarty track		1.00			2.00			2.00			1.00			1			1			0.33			2			1			1			4	
A14	Remove tempoarty track if applicable		0.50			1.00			1.00			5.00			0.33			0.33			0.33			1			0.33			0..33			2	
A15	Move lifting equip clear of positioned layout		0.50			1.00			1.00			5.00			0.33			0.33			0.33			1			0.33			0.33			2	
A16	Relay Adjoining plain line		1.00			0.20			0.20			1.00			1			1			0.33			2			1			1			4	
A17	Cut in closures do up fish plates		1.00			3.00			3.00			1.00			1.00			1			0.33			2			1			1			4	
A18	S&T, Fit cabling		1.00			3.00			3.00			1.00			1.00			1.00			0.33			2			1			1			4	
A19	Upload top ballast		3.00			3.00			3.00			3.00			3.00			3.00			1.00			3			2			2			6	
A20	Tamp S&C		0.50			1.00			1.00			0.50			0.50			0.50			0.33			1.00			0.33			0.33			2	
A21	S&T test & commission layout		1.00			3.00			3.00			1.00			1.00			1.00			0.50			3.00			1.00			1			4	
A22	Box in tidy		1.00			2.00			3.00			1.00			1.00			1.00			0.50			3.00			1.00			1.00			4	
A23	Give up possession		0.25			0.50			0.50			0.25			0.25			0.25			0.17			0.50			0.25			0.25			1.00	

Cost	C1 Lift out old S&C and stack at access in one unit						
		A1			A2		
		Min	Mo	Max	Min	Mo	Max
A1	By Track Lifting Gantry		1.00			1.50	
A2	By Grane road		0.67			1.00	

Cost	C2 lift out old S&C												
		A1			A2			A3			A4		
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	One piece road crane		1.00			1.50			1.25			4.00	
A2	One piece KGT or Excavator		0.67			1.00			0.11			3.00	
A3	One piece Rail wheel fitted vehicle		0.80			9.00			1.00			3.00	
A4	Piece Meal Lift ou rail sleeper, components		0.25			0.33			0.33			1.00	

Cost	Logistics								
		A1			A2			A2	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	By Road		1.00			0.50			0.33	
A2	By Rail		2.00			1.00			0.50	
A2	By Rail & Road		3.00			2.00			1.00	

Results of the Pairwise Comparisons Populated by a Switch and Crossing Renewal Expert with Ratio Scores for Welwyn Garden City, Case Study One

Cost	Detailed Design																		
			A1			A2			A3			A4			A5			A6	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Remit		1.00			1.00			0.50			0.14			0.20			0.20	
A2	Sponsor Costs		1.00			1.00			1.00			5.00			0.50			0.20	
A3	QRA		2.00			1.00			1.00			1.00			2.00			0.50	
A4	Site Surveys		7.00			0.20			1.00			1.00			2.00			1.00	
A5	Feasibility Surveys		5.00			2.00			0.50			0.50			1.00			0.50	
A6	Specifications		5.00			5.00			2.00			1.00			2.00			1.00	
A7	Testing and Commission																		
A8	Contractors Preliminaries		20.00			10.00			6.00			4.00			6.00			4.00	
A9	Design Costs		10.00			5.00			4.00			4.00			8.00			3.00	
A10	Supplier Costs																		
A11	TSR/PSR Costs																		
A12	Isolation Costs		1.00			1.00			0.20			0.20			0.33			0.33	
A13	TWA Costs																		

Cost	Detailed Design																					
			A7			A8			A9			A10			A11			A12			A13	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Remit					0.05			0.10									1.00				
A2	Sponsor Costs					0.10			0.20									1.00				
A3	QRA					0.16			0.25									5.00				
A4	Site Surveys					0.25			0.25									5.00				
A5	Feasibility Surveys					0.16			0.13									3.00				
A6	Specifications					0.25			0.33									3.00				
A7	Testing and Commission																					
A8	Contractors Preliminaries					1.00			1.00									0.20				
A9	Design Costs					1.00			1.00									9.00				
A10	Supplier Costs																					
A11	TSR/PSR Costs																					
A12	Isolation Costs					5.00			0.11													
A13	TWA Costs																					

Cost	Access									
			A1			A2			A3	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Tempoary Access		1.00			0.25			0.11	
A2	Access Rd		4.00			1.00			0.25	
A3	Distant Access		9.00			4.00			1.00	

Cost	Possession												
			A1			A2			A3			A4	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Green		1.00			2.00			0.16			0.50	
A2	Normal (Weekend)		0.50			1.00			2.00			0.75	
A3	Christmas		6.00			0.50			1.00			2.00	
A4	Blockade		2.00			1.00			0.50			1.00	

Cost	Site Restrictions									
			A1			A2			A3	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	OHL					0.50			1.25	
A2	Third Rail		2.00						1.50	
A3	OHL + Third Rail		0.80			0.67				

Cost	Output									
	50-100		A1			A2			A3	
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Slow TSP		1.00			2.00			4.00	
A2	High TSP		0.50			1.00			2.00	
A3	Line Speed		0.25			0.50			1.00	

Onsite Costs																												
Generic Work Process		A1			A2			A3			A5			A6			A7			A8			A9			A10		
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Pre Build Sections,switch nose crossing plain line		1.00			8.00			9.00			8.00			3.00			8.00			5.00			3.00			8.00	
A2	Disconnect & remove S&T equip		0.13			1.00			2.00			1.00			0.33			1.00			0.33			0.33			1.00	
A3	Undo & remove fishplates		0.11			0.50			1.00			0.33			0.14			0.33			0.25			0.14			0.33	
A5	Position spoil train		0.13			1.00			3.00			1.00			0.33			1.00			1.00			0.33			1.00	
A6	Excavate to 300mm load spoil train		0.33			3.00			7.00			3.00			1.00			3.00			2.00			1.00			3.00	
A7	Dozer & profile bottom of excavation		0.13			1.00			3.00			1.00			0.33			1.00			0.33			0.33			1.00	
A8	Expose &repair failed drain		0.20			3.00			4.00			1.00			0.50			3.00			1.00			0.14			2.00	
A9	Upload bottom ballast		0.33			3.00			7.00			3.00			1.00			3.00			7.00			1.00			3.00	
A10	Dozer profile & compact ballast		0.13			1.00			3.00			1.00			0.33			1.00			0.50			0.33			1.00	
A11	Set up lifting equipment		0.33			3.00			7.00			1.00			1.00			3.00			7.00			1.00			3.00	
A12	Move layout to site layout tempoarty track		0.20			2.00			4.00			1.00			0.50			2.00			1.00			0.50			3.00	
A14	Remove tempoarty track if applicable		0.11			1.00			3.00			1.00			0.33			1.00			0.50			0.33			1.00	
A15	Move lifting equip clear of positioned layout		0.11			1.00			3.00			1.00			0.33			1.00			0.50			0.33			1.00	
A16	Relay Adjoining plain line		0.20			3.00			5.00			1.00			0.50			0.50			1.00			0.50			3.00	
A17	Cut in closures do up fish plates		0.20			3.00			5.00			1.00			0.50			3.00			1.00			0.50			3.00	
A18	S&T , Fit cabling		0.20			3.00			5.00			1.00			0.50			3.00			1.00			0.50			3.00	
A19	Upload top ballast		0.33			3.00			7.00			3.00			1.00			3.00			3.00			1.00			3.00	
A20	Tamp S&C		0.11			1.00			2.00			1.00			0.33			1.00			0.50			0.33			1.00	
A21	S&T test & commission layout		0.20			3.00			5.00			1.00			0.50			3.00			1.00			0.50			3.00	
A22	Box in tidy		0.20			3.00			5.00			1.00			0.50			3.00			1.00			0.50			2.00	
A23	Give up possession		0.11			0.50			1.00			0.50			0.17			0.50			0.25			0.17			0.50	

Generic Work Process		A11			A12			A14			A15			A16			A17			A18			A19			A20			A21			A22			A23		
		Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Pre Build Sections,switch nose crossing plain line		3.00			5.00			9.00			9.00			5.00			5			5			3			9			5			5			9	
A2	Disconnect & remove S&T equip		0.33			0.50			1.00			1.00			0.33			0.33			0.33			0.33			1			0.33			0.33			2	
A3	Undo & remove fishplates		0.14			0.25			0.33			0.33			0.20			0.2			0.2			0.14			0..33			0.2			0.2			1	
A5	Position spoil train		1.00			1.00			1.00			1.00			1.00			1			1			0.33			1			1			1			2	
A6	Excavate to 300mm load spoil train		1.00			2.00			3.00			3.00			2.00			2			2			1			3			2			2			6	
A7	Dozer & profile bottom of excavation		0.33			0.50			1.00			1.00			2.00			0.33			0.33			0.33			1			0.33			0.33			2	
A8	Expose &repair failed drain		0.14			1.00			2.00			2.00			1.00			1			1			0.33			2			1			1			4	
A9	Upload bottom ballast		1.00			2.00			3.00			3.00			2.00			2			2			1			3			2			2			6	
A10	Dozer profile & compact ballast		0.33			0.33			1.00			1.00			0.33			0.33			0.33			0.33			1			0.33			0..33			2	
A11	Set up lifting equipment		1.00			2.00			3.00			3.00			2.00			2			2			1			3			2			2			6	
A12	Move layout to site layout tempoarty track		0.50			1.00			2.00			2.00			1.00			1			1			0.33			2			1			1			4	
A14	Remove tempoarty track if applicable		0.33			0.50			1.00			1.00			5.00			0.33			0.33			0.33			1			0.33			0..33			2	
A15	Move lifting equip clear of positioned layout		0.33			0.50			1.00			1.00			5.00			0.33			0.33			0.33			1			0.33			0.33			2	
A16	Relay Adjoining plain line		0.50			1.00			0.20			0.20			1.00			1			1			0.33			2			1			1			4	
A17	Cut in closures do up fish plates		0.50			1.00			3.00			3.00			1.00			1.00			1			0.33			2			1			1			4	
A18	S&T , Fit cabling		0.50			1.00			3.00			3.00			1.00			1.00			1.00			0.33			2			1			1			4	
A19	Upload top ballast		1.00			3.00			3.00			3.00			3.00			3.00			3.00			1.00			3			2			2			6	
A20	Tamp S&C		0.33			0.50			1.00			1.00			0.50			0.50			0.50			0.33			1.00			0.33			0.33			2	
A21	S&T test & commission layout		0.50			1.00			3.00			3.00			1.00			1.00			1.00			0.50			3.00			1.00			1			4	
A22	Box in tidy		0.50			1.00			2.00			3.00			1.00			1.00			1.00			0.50			3.00			1.00			1.00			4	
A23	Give up possession		0.17			0.25			0.50			0.50			0.25			0.25			0.25			0.17			0.50			0.25			0.25			1.00	

Cost	B13 Position and Install									
		D1			D2			C3		
		Min	**Mo**	Max	Min	**Mo**	Max	Min	**Mo**	Max
D1	Position and install layout in one unit		1.00			2.00			4.00	
D2	Position and install layout in sections		0.50			1.00			2.00	
D3	Position and install layout piece meal		0.25			0.50			1.00	

Cost	C1 Lift out old S&C and stack at access in one unit						
		A1			A2		
		Min	**Mo**	Max	Min	**Mo**	Ma
A1	By Track Lifting Gantry		1.00			1.50	
A2	By Grane road		0.67			1.00	

Cost	C2 lift out old S&C						
		A1			A2		
		Min	**Mo**	Max	Min	**Mo**	Ma
A1	One piece road crane		1.00			1.50	
A2	One piece KGT or Excavator		0.67			1.00	
A3	One piece Rail wheel fitted vehicle		0.80			9.00	
A4	Piece Meal Lift ou rail sleeper, components		0.25			0.33	

Cost	C3 Lift out S&C Components						
		A1			A2		
		Min	**Mo**	Max	Min	**Mo**	Ma
A1	Dismantle existing S&C into components		1.00			0.20	
A2	Lift out by true crane		5.00			1.00	
A3	Lift out by Rail Road Excavator		6.00			6.00	
A4	Lift out by Hyab Unit		0.50			9.00	

Cost	Logistics										
		A1			A2			A2			
		Min	**Mo**	Max	Min	**Mo**	Max	Min	**Mo**	Max	
A1	By Road		1.00			0.50			0.33		
A2	By Rail		2.00			1.00			0.50		
A2	By Rail & Road		3.00			2.00			1.00		

Results of the Pairwise Comparisons Populated by a Switch and Crossing Renewal Expert with Ratio Scores for Lo2 Switch Body Maintenance, Case Study Two

Cost		A1			A2			A3			A4			A5			A6			A7		
	2 Monthly Spring Return Points Inspec	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Point Box - operation, fixing etc 1200	1.00	1.00	1.00		3.00			0.14			1.20			2.50			4.00				
A2	Turbuckle - Pins, Nuts, Grease 300				1.00	1.00	1.00		0.33			1.50			0.50			0.50				
A3	switch body 9000							1.00	1.00	1.00		9.00			9.00			9.00				
A4	thermit joints 200					0.67			0.11		1.00	1.00	1.00		0.50			0.50				
A5	concrete repairs 500					2.00			0.11			2.00		1.00	1.00	1.00		1.00				
A6	detection 500					2.00			0.11			2.00			1.00		1.00	1.00	1.00			
A7																				1.00	1.00	1.00
A8	Check Rail 1000					3.00			0.11			4.00			2.00			2.00				
A9																						
A10																						
A11																						
A12	Throw Points 200					0.67			0.11			1.00			0.50			0.40				
A13	Blades side wear 100					0.33			0.11			0.50			0.20			0.20				

Cost		A8						A10			A11			A12			A13		
	2 Monthly Spring Return Points Inspec	Min	Mo	Max	Min		Max												
A1	Point Box - operation, fixing etc 1200		1.50												5.00			1.00	
A2	Turbuckle - Pins, Nuts, Grease 300		0.33												1.50			3.00	
A3	switch body 9000		9.00												9.00			9.00	
A4	thermit joints 200		0.25												1.00			2.00	
A5	concrete repairs 500		0.50												2.00			5.00	
A6	detection 500		0.50												2.50			5.00	
A7																			
A8	Check Rail 1000	1.00	1.00	1.00											5.00			9.00	
A9					1.00	1.00	1.00												
A10								1.00	1.00	1.00									
A11											1.00	1.00	1.00						
A12	Throw Points 200		0.20											1.00	1.00	1.00		2.00	
A13	Blades side wear 100		0.11												0.50		1.00	1.00	1.00

Cost		A1			A2			A3			A4	
	2 Monthly Spring Return Points Inspec	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo
A1	forklift		1.00			1.00			3.00			0.50
A2	transport		1.00			1.00			3.00			0.50
A3	80 general tooling compresser + attachments		0.33			0.33			1.00			0.25
A4	trafic management		1.00			2.00			4.00			1.00

Results of the Pairwise Comparisons Populated by a Switch and Crossing Renewal Expert with Ratio Scores for Lo2 Switch Body Maintenance, Case Study Two

Cost		A1			A2			A3			A4			A5			A6			A7		
	2 Monthly Spring Return Points Inspec	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	Rail		1.00			1.00			9.00			9.00			9.00			9.00			9.00	
A2	labour		1.00			1.00			9.00			9.00			9.00			9.00			9.00	
A3	plant hire forklift		0.11			0.11			1.00			1.00			1.50			0.50			1.50	
A4	scrap skip		0.11			0.11			1.00			1.00			1.50			0.50			2.00	
A5	extra lighting		0.11			0.11			0.67			0.67			1.00			0.33			1.50	
A6	pandrol clips		0.11			0.11			2.00			2.00			3.00			1.00			4.00	
A7	rail saws x2		0.11			0.11			0.67			0.50			0.67			0.25			1.00	

Results of the Pairwise Comparisons Populated by a Switch and Crossing Renewal Expert with Ratio Scores for Cathedral Switch Body Maintenance, Case Study Two

Cost		A1			A2			A3			A4			A5			A6			A7		
	rail replacement	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max
A1	contractor		1.00			2.00			0.33			8.00			4.00			3.00			3.00	
A2	polymer charge		0.50			1.00			0.25			5.00			2.50			2.00			1.50	
A3	switch body		3.00			4.00			1.00			9.00			9.00			9.00			9.00	
A4	transport		0.13			0.20			0.11			1.00			0.50			0.33			1.40	
A5	other plant hire		0.25			0.40			0.11			2.00			1.00			1.00			1.00	
A6	concrete		0.33			0.50			0.11			3.00			1.00			1.00			1.00	
A7	switch blades		0.33			0.67			0.11			0.71			1.00			1.00			1.00	

Results of the Pairwise Comparisons Populated by a Switch and Crossing Renewal Expert with Ratio Scores for Rail Reclamation by Welding, Case Study Two

Cost		A1			A2			A3			A4			A5			A6	
	2 Montly Hand Point Inspection	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo
A1	labour		1.00			3.00			4.00			9.00			9.00			9.00
A2	materials (weilding)		0.33			1.00			1.00			4.00			2.00			4.00
A3	prework surveys		0.25			1.00			1.00			3.00			1.50			3.00
A4	feul gas & deseil		0.11			0.25			0.33			1.00			0.50			0.20
A5	ultrasonic testing work pre-post		0.11			0.50			0.67			2.00			1.00			2.00
A6	grinding works		0.11			0.25			0.33			5.00			0.50			1.00

Results of the Pairwise Comparisons Populated by a Switch and Crossing Renewal Expert with Ratio Scores for Rail Reclamation by Welding, Case Study Two

Cost		A1			A2			A3			A4			A5			A6			A7			A8						A10	
	2 Montly Power Point Inspection	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min	Mo	Max	Min		Max		
A1	labour		1.00			1.00			2.00			5.00			4.00			2.00			5.00			2.50			8.00			9.00
A2	polymer		1.00			1.00			2.00			4.00			3.00			1.50			5.00			8.00			7.00			6.00
A3	rail		0.50						1.00			2.50			2.00			1.00			2.20			1.20			4.00			4.00
A4	concrete		0.20			0.25			0.40			1.00			0.50			3.00			1.00			2.00			2.50			1.50
A5	road transport		0.25			0.33			0.50			2.00			1.00			0.50			1.50			1.00			3.00			2.00
A6	plant hire		0.50			0.67			1.00			0.33			2.00			1.00			3.00			1.50			6.00			5.00
A7	trafiic management		0.20			0.20			0.45			1.00			0.67			0.33			1.00			0.50			2.00			1.50
A8	weilding		0.45			0.13			0.83			0.50			1.00			0.67			2.00			1.00			4.00			3.00
A9	surveys		0.13			0.14			0.25			0.40			0.33			0.17			0.50			0.25			1.00			1.00
A10	isolations		0.11			0.17			0.25			0.67			0.50			0.20			0.67			0.33			1.00			1.00

Results of the Pairwise Comparisons Populated by a Switch and Crossing Renewal Expert with Ratio Scores for Bristol, Case Study Three

	Removal of Old sidings, Site Clearance, Relaying of new sidings and stoning of Depots	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**	**A11**	**A12**	**A13**	**A14**	**A15**	**A16**	**A17**
		Mo	**Mo**	**Mo**	**Mo**	**Mo**	**Mo**	**Mo**	**Mo**	**Mo**	**Mo**	**Mo**	**Mo**	**Mo**	**Mo**	**Mo**	**Mo**
A2	Make up ballast levels, supply and lay in new sidings with servicable rail on Inc serviceable concrete sleepers(F23) and all associated fittings. Siding 1 Q324	1.00	1.00	1.00	7.00	0.20	0.11	3.00	0.11	7.00	1.00	0.25	1.00	7.00	0.50	0.25	0.33
A3	Prepartory Works, Make up ballast levels, supply and lay in new sidings with servicable rail on Inc serviceable concrete sleepers(F23) and all associated fittings. Siding 2 Q332	1.00	1.00	1.00	7.00	0.17	0.13	3.00	0.11	7.00	1.00	0.25	1.00	7.00	0.25	0.25	0.14
A4	Prepartory Works, Make up ballast levels, supply and lay in new sidings with servicable rail on Inc serviceable concrete sleepers(F23) and all associated fittings. Siding 3, Q360	1.00	1.00	1.00	7.00	0.15	0.13	3.00	0.11	7.00	0.20	0.25	1.00	7.00	1.00	0.25	0.33
A5	Prepartory Works, Make up ballast levels, supply and lay in new sidings with servicable rail on Inc serviceable concrete sleepers(F23) and all associated fittings. Headshunt, Q45	0.14	0.14	0.14	1.00	3.00	2.00	1.00	0.11	1.00	2.00	0.11	0.20	1.00	1.00	0.11	1.00
A6	Install CV8 Turnouts and inc rail bearers, & all ass Fitiings. Q2	5.00	6.00	7.00	0.33	1.00	0.50	1.00	1.00	9.00	1.00	1.00	1.00	0.50	0.50	0.50	0.33
A7	Install Tandom Turnouts and inc rail bearers , & all ass fittings, Q1	9.00	8.00	8.00	0.50	2.00	1.00	9.00	0.11	9.00	9.00	2.00	5.00	9.00	9.00	1.00	0.66
A8	Install Sliding buffer stop Q2	0.33	0.33	0.33	1.00	1.00	0.11	1.00	0.11	6.00	1.00	0.11	1.00	3.00	3.00	0.50	1.00
A9	Stone up area, Q1	9.00	9.00	9.00	9.00	1.00	9.00	9.00	1.00	9.00	9.00	2.00	9.00	9.00	9.00	6.00	0.33
A10	Walkways, Q75	0.14	0.14	0.14	1.00	0.11	0.11	0.17	0.11	1.00	0.11	0.11	0.11	1.00	1.00	0.11	1.00
A11	Attendance on other works, Q1	1.00	1.00	5.00	0.50	1.00	0.11	1.00	0.11	9.00	1.00	1.00	5.00	9.00	9.00	1.00	0.66
A12	Preliminaries, Q1	4.00	4.00	4.00	9.00	1.00	0.50	9.00	0.50	9.00	1.00	1.00	1.00	5.00	0.50	0.50	0.33
A13	Miscellaneous Repairs, Bridge, Q1	1.00	1.00	1.00	5.00	1.00	0.20	1.00	0.11	9.00	0.20	1.00	1.00	6.00	6.00	0.20	0.33
A14	Mobilisation/Demobilisation, Q1	0.14	0.14	0.14	1.00	2.00	0.11	0.33	0.11	1.00	0.11	0.20	0.17	1.00	1.00	0.20	0.66
A15	Return visit for lifting and fettling, Q1	2.00	4.00	1.00	1.00	2.00	0.11	0.33	0.11	1.00	0.11	2.00	0.17	1.00	1.00	0.11	0.66
A16	Compiliance with CDM regs, Q1	4.00	4.00	4.00	9.00	2.00	1.00	2.00	0.17	9.00	1.00	2.00	5.00	5.00	9.00	1.00	0.66
A17	Prepartory Works Q1061	3.00	7.00	3.00	1.00	3.00	2.00	1.00	3.00	1.00	2.00	3.00	3.00	2.00	2.00	2.00	1.00

Results of the Pairwise Comparisons Populated by a Switch and Crossing Renewal Expert with Ratio Scores for L London, Case Study Three

	Pway Works for Purley Sidings		A1	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	A21	A22
		Min	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo
A1	**Site Accomidation -** office provision: removing from site making good site on completion Q1		1.00	4.00	9.00	9.00	9.00	9.00	4.00	9.00	9.00	9.00	1.00	1.00	5.00	4.00	1.00	9.00	9.00	2.00	4.00	5.00	9
A3	**Management -** Project Management Q1		0.25	1.00	1.00	1.00	1.00	0.30	0.50	0.11	2.00	0.20	0.20	1.00	1.00	0.20	0.20	1.00	1.00	0.20	1.00	1.00	1
A4	Commercial Management Q1		0.11	1.00	1.00	1.00	1.00	0.30	0.50	0.11	2.00	9.09	0.20	1.00	1.00	0.20	0.20	1.00	1.00	0.20	1.00	1.00	1
A5	Planning Management Q1		0.11	1.00	1.00	1.00	1.00	0.30	0.50	0.11	2.00	0.20	0.20	1.00	1.00	0.20	0.20	1.00	1.00	0.20	1.00	1.00	1
A6	Heath and saftly management Q1		0.11	1.00	1.00	1.00	1.00	0.30	0.50	0.11	2.00	0.20	0.20	1.00	1.00	0.20	0.20	1.00	1.00	0.20	1.00	1.00	1
A7	Possession Management - attending meetings 1wk		0.11	3.00	3.00	3.00	3.00	1.00	0.50	0.11	2.00	0.20	0.20	1.00	1.00	0.20	0.20	1.00	1.00	0.20	1.00	1.00	1
A8	**Plant -** Road Railers Q1		0.25	2.00	2.00	2.00	2.00	2.00	1.00	9.00	4.50	9.00	0.50	1.00	1.00	0.50	0.11	3.00	1.00	0.50	2.00	3.00	1
A9	Trolleys 2wk		0.11	9.00	9.00	9.00	9.00	9.00	0.11	1.00	0.11	1.00	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
A10	General attendant plant 2Wk		0.11	0.50	0.50	0.50	0.50	0.50	0.22	9.00	1.00	1.00	0.11	0.50	0.20	0.20	0.11	1.00	1.00	0.11	1.00	1.00	0.11
A11	**Security Site** - Progress Photographs Q1		0.11	5.00	0.11	5.00	5.00	5.00	0.11	1.00	1.00	1.00	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
A12	Position and install		1.00	5.00	5.00	5.00	5.00	5.00	2.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	0.50	1.00	1.00	1.00	1.00	1
A13	**Temp Works** - Lighting of the work sites and the like 2wk		1.00	1.00	1.00	1.00	1.00	1.00	1.00	9.00	2.00		1.00	1.00	1.00	1.00	1.00	0.50	1.00	1.00	1.00	1.00	1
A14	Waste Disposal Survey Q1		0.20	1.00	1.00	1.00	1.00	1.00	1.00	9.00	5.00	9.00	1.00	1.00	1.00	0.50	0.50	0.50	1.00	0.50	0.50	1.00	0.11
A15	**Prep works** - Delivery of IBJs to site inc mobilisation Q1		0.25	5.00	5.00	5.00	5.00	5.00	2.00	9.00	5.00	9.00	1.00	1.00	2.00	1.00	1.00	0.50	0.50	1.00	0.50	0.50	1
A16	Installation work - IBJ installation: BS113A FB rail Q1		1.00	5.00	5.00	5.00	5.00	5.00	9.00	9.00	9.00	9.00	1.00	1.00	2.00	1.00	1.00	2.00	2.00	1.00	2.00	2.00	1
A17	Thermit welding of rail joints (2 welds) Q1		0.11	1.00	1.00	1.00	1.00	1.00	0.33	9.00	1.00	9.00	2.00	2.00	2.00	2.00	0.50	1.00	1.00	0.20	1.00	1.00	0.11
A18	Indpection of Thermit welding rail joints Q1		0.11	1.00	1.00	1.00	1.00	1.00	1.00	9.00	1.00	9.00	1.00	1.00	1.00	2.00	0.50	1.00	1.00	0.20	1.00	1.00	0.11
A19	**IBJ recovery Works -** Remove existing redundant BS113A FB rail IBJs in CWR track in installing new closure rail		0.50	5.00	5.00	5.00	5.00	5.00	2.00	9.00	9.00	9.00	1.00	1.00	2.00	1.00	1.00	5.00	5.00	1.00	2.00	2.00	1
A20	Thermit welding of rail joints (Q1		0.25	1.00	1.00	1.00	1.00	1.00	0.50	9.00	1.00	9.00	1.00	1.00	2.00	2.00	0.50	1.00	1.00	0.50	1.00	1.00	0.5
A21	Inspection of Thermit welding rail joints		0.20	1.00	1.00	1.00	1.00	1.00	0.33	9.00	1.00	9.00	1.00	1.00	1.00	2.00	0.50	1.00	1.00	0.50	1.00	1.00	0.5
A22	Removal of scrap materials on completion of the works																						1.00

Results of the Pairwise Comparisons Populated by a Switch and Crossing Renewal Expert with Ratio Scores for Purley, Case Study Three

	Pway Works for Purley Sidings		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14
		Min	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo
A1	Remove existing track store on site Sidings 2&3 Q310		1.00	1.00	2.00	1.00	0.11	0.11	1.00	2.00	0.11	1.00	1.00	2.00	1.00	1.00
A2	Remove existing Buffers, store and renovate for re use Q2		1.00	1.00	1.00	0.20	0.11	0.11	1.00	0.50	0.20	1.00	1.00	1.00	0.50	1.00
A3	Erect fence between sidings 1 and adj running rail Q200		0.50	1.00	1.00	0.11	0.11	0.11	0.20	0.30	0.11	0.20	0.11	0.50	0.15	0.20
A4	Refurbish Siding 1 Q1		1.00	5.00	9.00	1.00	0.11	0.11	1.00	0.50	0.50	2.00	1.00	1.00	1.00	1.00
A5	Make up ballast levels & supply and lay in new sidings with servicable rail on &inc serv F23 concrete and all associated fittings Q345		9.00	9.00	9.00	9.00	1.00	2.00	0.11	9.00	9.00	9.00	9.00	9.00	9.00	9.00
A6	Supply and install bv 8 contra Flexture turnout and inc rail bearers & and all ass fittings Q1		9.00	9.00	9.00	9.00	0.50	1.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00	9.00
A7	Top ballast Q75		1.00	1.00	5.00	1.00	9.00	0.11	1.00	1.00	0.20	1.00	0.50	1.00	0.50	1.00
A8	Refit sliding buffer stop QQ2		0.50	2.00	3.00	2.00	0.11	0.11	1.00	1.00	0.11	0.50	0.11	1.00	0.11	1.00
A9	Tamp/follow up tamp Q375		9.00	5.00	9.00	2.00	0.11	0.11	5.00	9.00	1.00	4.00	1.00	8.00	2.00	8.00
A10	Pedestrain walkways Q2		1.00	1.00	5.00	0.50	0.11	0.11	1.00	2.00	0.25	1.00	1.00	1.00	0.50	1.00
A11	Position and install Q1		1.00	1.00	9.00	1.00	0.11	0.11	2.00	9.00	1.00	1.00	1.00	2.00	1.00	2.00
A12	Repair Buffer sidings 1 Q1		0.50	1.00	2.00	1.00	0.11	0.11	1.00	1.00	0.13	1.00	0.50	1.00	4.00	0.50
A13	New lever boxes, rods & anti slip boards to 3 T/O's Q1		1.00	2.00	7.00	1.00	0.11	0.11	2.00	9.00	0.50	2.00		0.25	1.00	2.00
A14	700mm wide graded stone working areas(walkways) Q1		1.00	1.00	5.00	1.00	0.11	0.11	1.00	1.00	0.13	1.00	0.50	2.00	0.50	1.00

Results of the Pairwise Comparisons Populated by a Switch and Crossing Renewal Expert with Ratio Scores for Toten New Bank, Case Study Three

	Toton New Bank Sidings Opion A	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17
		Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo
A2	Take up recovery 7 loading of track materialson to road vechcles	1.00	1.00	1.00	7.00	0.20	0.11	3.00	0.11	7.00	1.00	0.25	1.00	7.00	0.50	0.25	0.33
A3	Dismantle and stack materials as necessary	1.00	1.00	1.00	7.00	0.17	0.13	3.00	0.11	7.00	1.00	0.25	1.00	7.00	0.25	0.25	0.17
A4	To handle and load all accumulated spoil into road vechiles	1.00	1.00	1.00	7.00	0.15	0.13	3.00	0.11	7.00	0.20	0.25	1.00	7.00	1.00	0.25	0.33
A5	Excavate and prepare formation sub grade, handle and lay bottom ballast	0.14	0.14	0.14	1.00	3.00	2.00	1.00	0.11	1.00	2.00	0.11	0.20	1.00	1.00	0.11	1.00
A6	Provide and lay geotextile	5.00	6.00	7.00	0.33	1.00	0.50	1.00	1.00	9.00	1.00	1.00	1.00	0.50	0.50	0.50	0.33
A7	Road 4 intall approx 144mof plain line track	9.00	8.00	8.00	0.50	2.00	1.00	9.00	0.11	9.00	9.00	2.00	5.00	9.00	9.00	1.00	0.66
A8	Road 4 intall approx 144mof top ballast	0.33	0.33	0.33	1.00	1.00	0.11	1.00	0.11	6.00	1.00	0.11	1.00	3.00	3.00	0.50	1.00
A9	Road 9 install approx 230 m of plain line track	9.00	9.00	9.00	9.00	1.00	9.00	9.00	1.00	9.00	9.00	2.00	9.00	9.00	10.00	6.00	0.33
A10	Road 9 install approx 230 m of top ballast	0.14	0.14	0.14	1.00	0.11	0.11	0.17	0.11	1.00	0.11	0.11	0.15	1.00	1.00	0.11	1.00
A11	Road 10 install approx 128.3m of plain line track	1.00	1.00	5.00	0.50	1.00	0.11	1.00	0.11	9.00	1.00	1.00	5.00	9.00	9.00	1.00	0.66
A12	Road 10 install approx 128.3m of op ballast	4.00	4.00	4.00	9.00	1.00	0.50	9.00	0.50	9.00	1.00	1.00	1.00	5.00	0.50	0.50	0.33
A13	S&C No 6 partial renewal	1.00	1.00	1.00	5.00	1.00	0.20	1.00	0.11	7.00		1.00	1.00	6.00	6.00	0.20	0.33
A14	Supply and aggregates for construction of all walkways	0.14	0.14	0.14	1.00	2.00	0.11	0.33	0.11	1.00	0.11	0.20	0.17	1.00	1.00	0.20	0.66
A15	Allowance for a return visit to siteie manual lifting a packing fettling	2.00	4.00	1.00	1.00	2.00	0.11	0.33	0.10	1.00	0.11	2.00	0.17	1.00	1.00	0.11	0.66
A16	Planning Supervsior	4.00	4.00	4.00	9.00	2.00	1.00	2.00	0.17	9.00	1.00	2.00	5.00	5.00	9.00	1.00	0.66
A17	Possessions	3.00	6.00	3.00	1.00	3.00	2.00	1.00	3.00	1.00	2.00	3.00	3.00	2.00	2.00	2.00	1.00

Results of the Pairwise Comparisons Populated by a Switch and Crossing Renewal Expert with Ratio Scores for Westbrooks, Case Study Three

	Westbrooks		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14
		Min	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo	Mo
A1	**Survey** Site prior to commencement of works		1.00	9.00	4.00	9.00	9.00	9.00	9.00	4.00	9.00	9.00	9.00	1.00	1.00	5.00
A2	**Prep Works**Delivery of IBJs to site		0.11	1.00	1.00	0.11	0.11	0.11	0.11	0.11	0.50	0.11	1.00	0.11	0.11	0.11
A3	**Installation Works** IBJ Installation BS113A FB rail (16)		0.25	1.00	1.00	1.00	1.00	1.00	0.30	0.50	0.11	2.00	0.20	0.20	1.00	1.00
A4	**Survey** Site prior to commencement of works		0.11	9.00	1.00	1.00	1.00	1.00	0.30	0.50	0.11	2.00	9.09	0.20	1.00	1.00
A5	**Prep Works**Delivery of IBJs to site		0.11	9.00	1.00	1.00	1.00	1.00	0.30	0.50	0.11	2.00	0.20	0.20	1.00	1.00
A6	**Installation Works** IBJ Installation BS113A FB rail (16)		0.11	9.00	1.00	1.00	1.00	1.00	0.30	0.50	0.11	2.00	0.20	0.20	1.00	1.00
A7	IBJ Installation BS951 FB rail (4)		0.11	9.00	3.00	3.00	3.00	3.00	1.00	0.50	0.11	2.00	0.20	0.20	1.00	1.00
A8	Thermit weilding of Rail joints(32)		0.25	9.00	2.00	2.00	2.00	2.00	2.00	1.00	9.00	4.50	9.00	0.50	1.00	1.00
A9	Inspection of Thermit welding rail joints		0.11	2.00	9.00	9.00	9.00	9.00	9.00	0.11	1.00	0.10	1.00	0.11	0.11	0.11
A10	**Exit over** Remove existing Bomac Level Crossing panals to allow access and reinstate on completion		0.11	9.00	0.50	0.50	0.50	0.50	0.50	0.22	10.00	1.00	1.00	0.11	0.50	0.20
A11	**IBJ Recovery Works** Remove existing redundant BS113a FB rail IBJ in CWR track and install new closurer ail		0.11	1.00	5.00	0.11	5.00	5.00	5.00	0.11	1.00	1.00	1.00	0.10	0.11	0.11
A12	Thermit welding of rail joints		1.00	9.00	5.00	5.00	5.00	5.00	5.00	2.00	9.00	9.00	10.00	1.00	1.00	1.00
A13	Inspection of Thermit welding rail joints		1.00	9.00	1.00	1.00	1.00	1.00	1.00	1.00	9.00	2.00		1.00	1.00	1.00
A14	Removal of scrap materials on completion of the work		0.20	9.00	1.00	1.00	1.00	1.00	1.00	1.00	9.00	5.00	9.00	1.00	1.00	1.00