CRANFIELD UNIVERSITY

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IMPROVING WATER ASSET MANAGEMENT WHEN DATA ARE SPARSE

SCHOOL OF APPLIED SCIENCES

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Improving Water Asset Management When Data are Sparse

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ABSTRACT

Ensuring the high of assets in water utilities is critically important and requires continuous improvement. This is due to the need to minimise risk of harm to human health and the environment from contaminated drinking water. Continuous improvement and innovation in water asset management are therefore, necessary and are driven by (i) increased regulatory requirements on serviceability; (ii) high maintenance costs, (iii) higher customer expectations, and (iv) enhanced environmental and health/safety requirements.

High quality data on asset failures, maintenance, and operations are key requirements for developing reliability models. However, a literature search revealed that, in practice, there is sometimes limited data in water utilities - particularly for over-ground assets. Perhaps surprisingly, there is often a mismatch between the ambitions of sophisticated reliability tools and the availability of asset data water utilities are able to draw upon to implement them in practice.

This research provides models to support decision-making in water utility asset management when there is limited data. Three approaches for assessing asset condition, maintenance effectiveness and selecting maintenance regimes for specific asset groups were developed. Expert elicitation was used to test and apply the developed decision-support tools. A major regional water utility in England was used as a case study to investigate and test the developed approaches.

The new approach achieved improved precision in asset condition assessment (Figure 3–3a) - supporting the requirements of the UK Capital Maintenance Planning Common Framework. Critically, the thesis demonstrated that, on occasion, assets were sometimes misallocated by more than 50% between condition grades when using current approaches. Expert opinions were also sought for assessing maintenance effectiveness, and a new approach was tested with over-ground assets. The new approach's value was demonstrated by the capability to account for finer measurements (as low as 10%) of maintenance effectiveness (Table 4-4). An asset maintenance regime selection approach was developed to support decision-making when data are sparse. The value of the approach is its versatility in selecting different regimes for different asset groups, and specifically accounting for the assets unique performance variables.

Published work

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOTATION

Abbreviation	**Meaning**
CG	Condition grade
EE	Expert elicitation
EO	Expert opinions
PAS	Publicly accepted standards
BSI	British standards institute
Ofwat	UK water service regulation authority
OPEX	Operating expenditure
ME	Maintenance effectiveness

PM	Preventative maintenance
CM	Corrective maintenance
CBM	Condition based maintenance
AHP	Analytical hierarchy process
MCDM	Multi-criteria decision making
RCM	Reliability centred maintenance
CA	Condition assessment
MMT	Maintenance management tool
CR	Consistency ratio
CI	Consistency index
RI	Random index
Ofgem	UK gas and electricity regulation authority
IWA	International water association
NUREG	Nuclear regulatory authority
USEPA	United States regulatory authority
AWWARF	American water works association research foundation
WERF	Water environment research foundation
CMPCF	Capital maintenance planning common framework
UKWIR	UK water companies, research company
DWI	The drinking water Inspectorate
EA	Environment Agency
BSC	Balance score-card
QFD	Quality function deployment
MPM	Maintenance performance measurement
VBM	Vibration-based maintenance
CMMS	Computerized maintenance management system
PdM	Predictive maintenance
PI's	Performance indicators
OSA-CBM	Open system architecture for condition-based maintenance
PDF	Probability density function
FMECA	Mode effect and criticality analysis
MAUT	Multi-attribute utility theory
SMART	Simple multi-attribute rating technique

NUSAP	Numeral, Unit, Spread, Assessment, and Pedigree
IIMM	International Infrastructure Management Manual
CEN	European committee for standardisation
ELECTRE	Elimination and choice expressing the reality
PROMETHEE	Preference ranking organization method for enrichment evaluation
STS	Socio-technical system analysis
DEA	Data envelopment analysis
ELL	Economic level of leakage
DMAs	District Metering Areas
UFW	Unaccounted for water
MLD	Million litres per day
IPWEA	Institute of public works engineering Australia
NAMS	New Zealand asset management support
CARE-W	EU fifth framework program for research and development project to develop a framework for water network rehabilitation
SAMPs	System Asset Management Plans
SMPs	Shoreline Management Plans
CFMPs	Catchment Flood Management Plans
VBM	Vibration Based Maintenance
MCMHF	Multi-criteria multi-hierarchical framework
QFDT	Quality function deployment technique
CMMS	Computerized maintenance management system
VBPM	Value-based performance measurement

1 INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Asset management is the art and science of making the right multi-disciplinary decisions in optimising the management of (primarily) physical assets (their selection, maintenance, inspection and renewal). Asset management is important for water utility companies to stay competitive in a continuously growing and competitive market. Improved customer service can be achieved through increased water production and distribution assets availability of assets. Maintenance of these assets is a prerequisite to ensuring high availability. Maintenance costs have increased rapidly during recent years and the United States alone had an estimated maintenance cost of 200 billion dollars in 1979 (Wireman, 1990a) with expected increases of 10-15 % per year to follow. Wireman (1990) also reported that as much as one-third of the total maintenance cost was unnecessarily incurred due to asset failure (reactive maintenance). These circumstances included bad planning, overtime costs, poor usage of work order systems, poor quality preventative maintenance and others. Good maintenance has been defined as when very few corrective maintenance actions are undertaken and when as little preventative maintenance as possible is performed (Emery, 2002a). This calls for planning optimal preventative maintenance intervals and preventative maintenance tasks monitoring and scheduling. Preventative maintenance would lead to increased availability and reduced direct maintenance costs, such as labour and spare parts. The preventative maintenance should, for the most effective execution, be planned to minimise its costs and achieve high asset availability in order to attain optimal maintenance (Al-Najjar and Alsyouf, 2002).

Condition assessment and the use of condition-based maintenance systems in industry is one way of reducing maintenance budgets. Good asset condition assessment programmes lead to less corrective maintenance actions (decreases in spare parts and labour costs), better planned preventative maintenance (increases in the availability of items and assets), and reduced maintenance costs. Research on condition assessment, maintenance costs, budgets, and potential maintenance savings has been performed by Alsyouf (2006), Davis *et al (*2013), Gaewski and Blaha (2007) and Klutke (2003) Tahir (2008) and Wireman (1990b).

The word asset in this research refers to any item or component of an installation, with most reference to the water distribution industry. The terms item and component are used interchangeably and refer to a whole or part of an asset, respectively.

1.1.1 Problem statement

The water industry in England and Wales is regulated by the Office of water services (Ofwat). The five year asset plan requirement by the United Kingdom (UK) Office of water services (Ofwat), demands innovation in asset management and investment planning from water utilities. The aim is to optimise water distribution assets operation and minimise maintenance costs and hence, minimise costs to customers. Operators are required to continuously improve their approaches to managing assets, whereas the water industry has generally lagged behind compared to other critical infrastructure industries, such as oil and gas (Parsons, 2006a). Other sectors, such as UK flood defence asset management have also made strides in their management strategies (Environment Agency, 2010a). This research therefore, aims to improve asset management in the water utility sector by developing new and improved approaches in order to address compliance standards and support operators' decision making.

Some of the UK water companies, such as the case study water utility face the following challenges;

- Maintenance policy is sometimes designed based on a rule-of–thumb, but little research has been done to justify the choice and cost of maintenance regimes. These key factors impact on maintenance policy design and decisions.
- Expert elicitation is the method of gathering data or information from experts regarding any uncertain quantity or information. It is widely used when

assessing assets condition. There is a large scope for further developing the condition assessment measures process where there is limited data.

- Maintenance effectiveness assessments are not carried out, particularly when data are sparse.

Alsyouf (2004) reports on research within the water industry indicating that preventative maintenance (use-based or time-based) was the most frequently used. Item condition assessment and failure-based maintenance (corrective maintenance) were second, total productive maintenance was third, and reliability-centred maintenance was fourth. There is no reported research-based and validated approach used to support decision-making in choosing these maintenance regimes. The most common technique for condition assessment was manual visual inspection, where data were limited (Bengtsson, 2004a).

In the literature, little comprehensive research on condition assessment has been published to meet the needs when data are sparse. Most of the published literature focuses on cases where data exists and mainly on underground assets. Expert opinions are widely sought in water utility and yet, very few studies have been published on expert elicitation in asset condition assessment, particularly for over-ground assets. Whang and Zhang (2008a) only mention expert opinions in passing when assessing asset remaining life. Maintenance effectiveness was not found to be assessed where there are sparse data in the literature. Maintenance regime selection with limited data at the maintenance stage of the asset life was also not identified in the literature.

1.1.2 Research question

In order to fulfil the aim of the research, three research questions (RQ) were formulated through careful literature studies to identify ways in which asset management can be improved. Discussions with professionals from academia and the water industry were vital in guiding and framing objectives for the research, which were based on the following research questions;

RQ1) What improvements can be made to assess condition of water utility assets where limited historical asset data are available?

In developing condition assessment systems, historical asset performance data are required and such data are not always available. Condition assessment is important because it supports asset maintenance plans and helps managers to prioritise asset maintenance resources. The question sets out to investigate if current asset condition assessment methods are effective and to develop improved approaches.

RQ2) Given existing maintenance approaches, what methods and techniques can be used for assessing maintenance effectiveness, particularly where limited historical asset performance data are available?

The complexity and automation level of a maintenance effectiveness assessment process is sometimes not justifiable for an organisation. Sometimes the data to assess maintenance effectiveness are sparse and yet the assessment is always crucial for establishing and/or reviewing a maintenance regime or strategy within a water utility. The research sought to develop an effective maintenance approach to cope where data are limited.

RQ3) What aspects and approaches does a water utility need to consider when deciding what maintenance regime to implement for its different asset groups where there is limited historical asset data available?

Work methods in an organisation can be deeply rooted in the ordinary day-to-day implementation of a maintenance regime. Following an accepted implementation strategy, the choice of the maintenance regime such as condition based maintenance, can be difficult to justify and select. The question sets out to examine if there are any approaches a utility could consider when deciding to choose and implement a maintenance strategy. This research question focuses on selecting a particular maintenance regime strategy that is suitable for each asset group within a water utility.

Delimitations

Even though asset condition assessment and maintenance could refer virtually to any process component or asset, in this research it only refers to physical assets such as motors, machines, pumps, and others. These are assets that can be found within the ordinary water processing and distribution industry. Software assets and services were excluded. Case studies that have been performed within the research focused on companies in the water industry. Comparisons between the water and other industries have been made in the literature.

Asset condition assessment and maintenance effectiveness processes were analysed and presented within the diagnosis and prognosis framework for purposes of this research. Maintenance regimes were in the policy framework for purposes of the research. The research was formulated to approach the problem statement in a more specific manner, focusing solely on water utilities.

1.1.3 Research aim and objectives

The aim of the research was to develop novel models to support the management of assets and their associated risks in a water utility when there are sparse, disparate, or limited data. From the aim of the research, the objectives formulated were;

1. Develop improved expert elicitation approaches to assessing asset conditions when limited data are available.
2. Develop approaches to selecting optimal maintenance regimes for different asset groups where there are limited data.
3. Develop approaches to assess maintenance effectiveness when data are limited.

The objectives aimed to achieve results that would enrich and support consultation, dialogue and decision-making for managers in managing assets and their associated risks.

1.1.4 Research rationale and industry relevance

The Capital Maintenance Planning Common Framework (CMPCF) was developed as a joint research programme between UK water companies, research company

UKWIR and the UK Water Services Regulation Authority (Ofwat) to provide guidance for the estimation of the economic level of capital maintenance (Emery, 2002b). The steering group for the research included representatives from the Environment Agency (EA), the Drinking Water Inspectorate (DWI) and the Department for Environment and Rural Affairs (DEFRA), as well as water companies and Ofwat.

A number of key concepts form the basis of the CMPCF and are as follows [Lumbers and Hewood (2005) and Ofwat (2004a)];

- capital maintenance should normally be justified on the basis of current and forecast probability and consequence of asset failure, with and without investment,
- consequences are expressed as direct or indirect impacts on service and company costs,
- service is defined as service to customers and the environment (including all relevant third parties and regulatory requirements),
- service is assessed using suitable indicators, such as interruptions to supply and effluent quality,
- opportunities for trade-offs between operating costs and capital costs should be evaluated, and

All the above requirements involve asset management activities and particularly to ensure that assets are kept in good condition, which requires effective condition assessment. Condition assessment should be supported by effective maintenance processes and ensuring that good overall maintenance regimes are adopted by organisations. Currently, only various discrete drivers for asset condition assessments arise from time to time, requiring water companies to undertake asset condition assessments. For example, some water utilities only carry out asset condition assessment when they need to produce report to the water regulator, Ofwat. Such reliance on discrete investigations is disjointed practice and does not support good asset condition assessment needs (Marlow and Burn, 2008a).

Currently the case study water utility requires improvement in condition assessment in order to support expenditure budgets and asset life analysis. The case study water utility currently has no approach for determining the type of maintenance regime to adopt in managing their assets. Maintenance effectiveness is not formally assessed by the case study water utility. Expert elicitation is not conducted formally and as a result, the results are of lesser quality (O'Hagan, 2005a). The elicitation protocol is not followed well to support the best outcome from experts, and only group consensus agreements are used to aggregate experts' opinions.

In summary, Ofwat requirements for water utilities form the basis for the industrial rationale of the research. The requirements form part of the basis through which Ofwat evaluates water utilities' asset capital planning, and regulates water prices that utilities can charge customers, as well as the amount of financial resources they can utilise for asset management. The requirements include linkages between service and serviceability objectives and customer value (Parsons, 2006b; Ofwat, 2004b);

This research mainly addressed the following Ofwat requirements (see Table 1-1);

Table 1-1: Water sector requirements and research contributions

Ofwat requirement	**Contributions to industry**	**Academic contribution**
Asset performance	*An asset condition assessment* approach (mainly for over-ground assets) that would help mainstream condition assessment in organisations is developed with limited data situation.	Current research has mainly focused developing approaches for pipe condition assessment in water utility, with advanced technologies and methodologies and ignored over-ground assets (Masiunas, 2008; Masuinus, 2005; UKWIR, 2002)
'Best value' implicit through implementation of optimal least cost capital maintenance strategy	A systematic, quantifiable and verifiable maintenance regime section approach is developed to select optimal maintenance regime.	
Improvements in data quality and analytical approaches.	An improved condition assessment using expert	A probability based approach is developed,

	elicitation approach is developed.	which builds on the condition grade method already used when there is no data, but only using fixed full number scales (Wang and Zhang, 2008b).
Reduce error bands in model and value of loss of service results	A penalty costs assessment approach is developed for inadequate condition assessment, which would result in asset failure and loss of service. Maintenance effectiveness approach is developed, which helps determine error in the quality of maintenance and reduce them.	A purely expert elicitation-based approach for assessing maintenance effectiveness. Only a cost effectiveness preventative maintenance assessment approach has been found in the literature (Briand *et al*, 2000).
Service to customers and the environment	*Condition assessment* ensures reliable assets and hence, high customer satisfaction and environmental protection from pollution and flooding in case of failed assets dispersing poisonous chemicals.	

The research objectives can be said to address asset risk management or managing the risk of asset failure. Figure 1-1 summarises the risk management rationale of the research areas explored in the research.

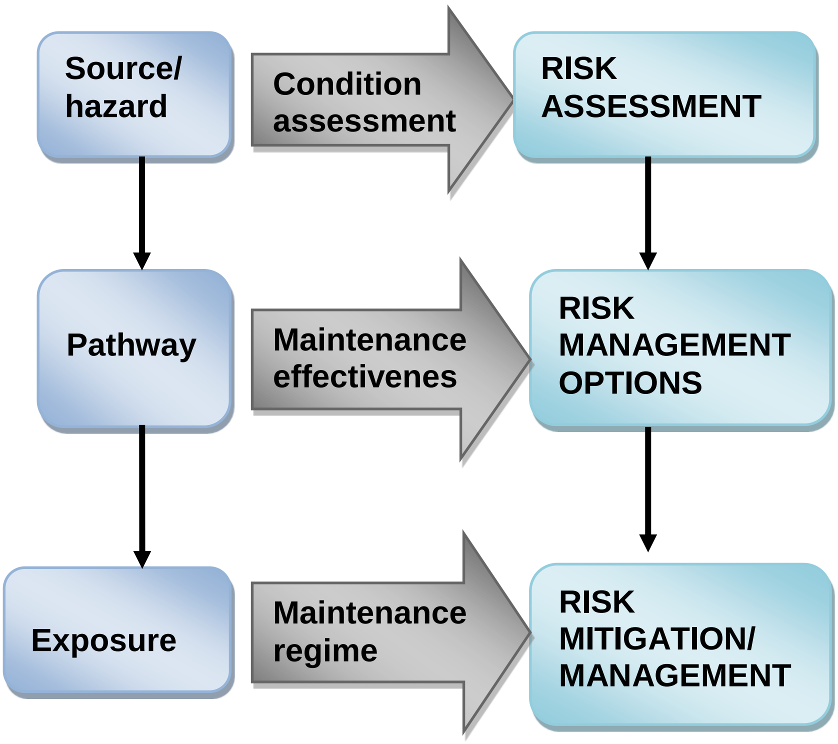

Figure 1-1: Asset risk management research rationale

Each of the research objectives and their risk management framework are discussed in Chapter 6.

Scope of asset management addressed in the research

Water utilities have constantly endeavoured to balance their capital and operating expenditure between providing good customer service and protecting the environment, whilst making profit for shareholders. Figure 1-2 summarises the effort to align this balance with asset management activities addressed in this research (condition assessment, maintenance effectiveness and maintenance regime).

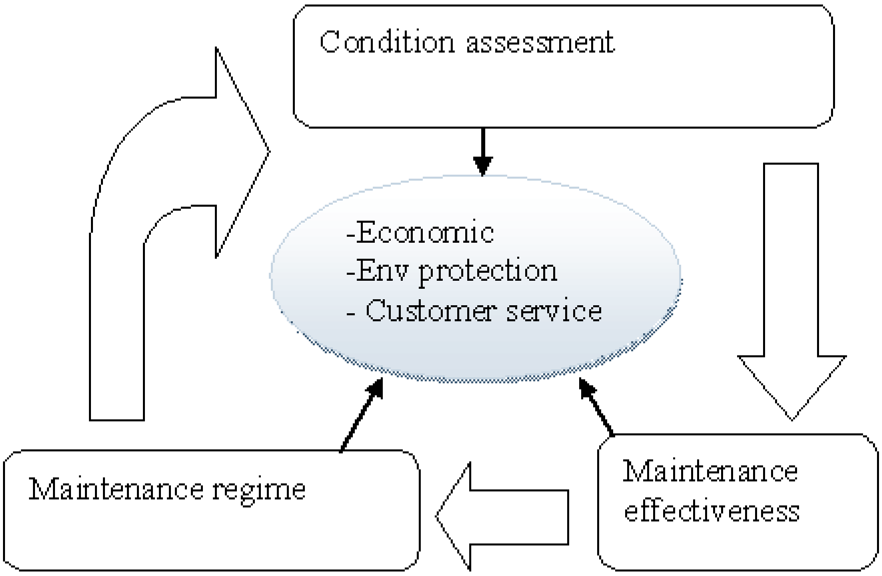

Figure 1-2: Asset management scope of the research

Sustainability is another important factor in asset management. Sustainable development means making the necessary decisions now to realise our vision of stimulating economic growth and tackling the deficit, maximising wellbeing and protecting our environment, without negatively impacting on the ability of future generations to do the same (Defra, 2013a). According to Defra (2013b), the founding principle of sustainable development is that the three pillars of the economy, society and the environment are all interconnected. In the context of the water sector, this makes sustainable development equally central to the work of the economic regulator. Ofwat is committed to delivering sustainable outcomes as efficiently as possible, but states that action is needed to carry this through into regulatory policies and decisions. Ofwat encourages water companies to take responsibility for the wider social, economic and environmental impacts of their activities. Water utilities must meet today's consumer needs, without compromising quality of life for future generations. The companies set out their long-term plans including their approach to climate change and sustainability in their strategic direction statements (Ofwat, 2012).

This research mainly focuses on economic aspects of sustainability, although the environmental and social aspects of sustainability indirectly benefit from the economic aspect. For example, assets kept in good condition through effective management are less likely to fail and cause environmental pollution. The same assets also deliver water to customers effectively and ensure high customer satisfaction, which can be a social aspect of sustainability. The reason for focusing on the economic aspect of sustainability was the fact that asset management is mainly concerns the economic aspects of water utilities. The cost of installing, maintaining and replacing assets being a major issue in utilities' performance as it impacts on customer service and profitability. The research specifically focused on the maintenance stage of asset management. The other factors of sustainability were deemed to be outside the scope of this research.

Industrial aims of the research

The research was aimed at contributing to water asset management, including effective asset management processes that would help water utilities to;

- Follow best practice, as required by the asset planning common framework.
- Identify critical assets as condition assessment is mainstreamed.
- Identify and manage the risk of asset failure through condition assessment programmes.
- Identify indicators of failure to monitor the critical items as supported by variable selection approaches in the research.
- Identify priorities for addressing and cost effective maintenance solutions as presented by the maintenance regime selection method, whilst providing consistency to decision-making.
- Identifying assets that are not used and may need decommissioning. This could include water pumps and reservoirs no longer in use

The research could be beneficial for other regulated industries such as gas and electricity which face similar challenges, as the water sector, in managing their assets. Similar challenges include regulation on how much they can spend on expenditures and having to choose between getting (Stern, 2005a);

• a lower capital expenditure (CAPEX) allowance, but with a high incentive that allows them to retain significant benefits if they can deliver the required outputs more efficiently, and

• a higher CAPEX allowance, but with a lower incentive that gives a relatively smaller reward for under spending a higher allowance.

Typically, regulation director of the office of gas and electricity distribution regulation (Ofgem) stated that the uncertainty in assets condition assessment and forecasting is a challenge faced by electricity and gas companies as well (Stern, 2005b).

Academic aims of the research

Condition assessment (risk assessment) **-** The condition assessment was assessed in the framework of risk assessment as the condition of the asset reflects the risk of failure. A probability based approach was developed for assessing assets condition. It builds on the condition grade method already used when limited or sparse data are available (Wang and Zhang, 2008c).

Maintenance effectiveness measures (risk alternatives) – Maintenance effectiveness provides options for the identified risk in condition assessment. A purely expert elicitation-based approach for assessing maintenance effectiveness was developed. Only a cost effect preventative maintenance assessment approach that employs experts' knowledge has been found in the literature (Briand *et al*, 2000).

Maintenance regimes (risk mitigation and management) – The maintenance regime selection provides a risk elimination of management option for the asset management decision maker. An approach that provides a systematic, quantifiable and verifiable procedure for selecting a maintenance regime where there is limited data was developed. It adopted an existing method that has not been applied in maintenance selection at the operation stage, except in combination with a goal programming approach (Bertolini and Bevilacqua, 2006).

In meeting both organisational and regulatory requirements in water utility, quantifiable and verifiable tools are necessary to support decision-making. This would contribute towards ensuring the balance between high levels of service, environmental protection, social well-being, and economic viability for water utilities are ensured without compromising any.

1.1.5 Thesis outline

The thesis is structured in chapters. Chapter 1 is an introduction of the research and literature review in line with the three objectives of the research. Chapter 2 presents the rationale and processes followed in the development of the methodology used to meet the three objectives of the research. Chapter 3 presents the results of the asset condition assessment research, in accordance with objective or research question one. Chapter 4 presents the results of the maintenance effectiveness assessment research, in accordance with objective or research question two. Chapter 5 presents the results of the maintenance regime selection research, in accordance with objective or research question three. Chapter 6 is a summary discussion of the results from Chapters 3, 4, and 5. The conclusions and recommendations are presented in Chapter 7.

1.1.6 Research methodology

A methodology was developed to meet each of the three research objectives (asset condition assessment, maintenance effectiveness, and maintenance regime selection). A detailed research methodology is presented in Chapter 2 of the thesis.

Figure 1-3 summarises the expert elicitation methodology theme used in the three sections of the research.

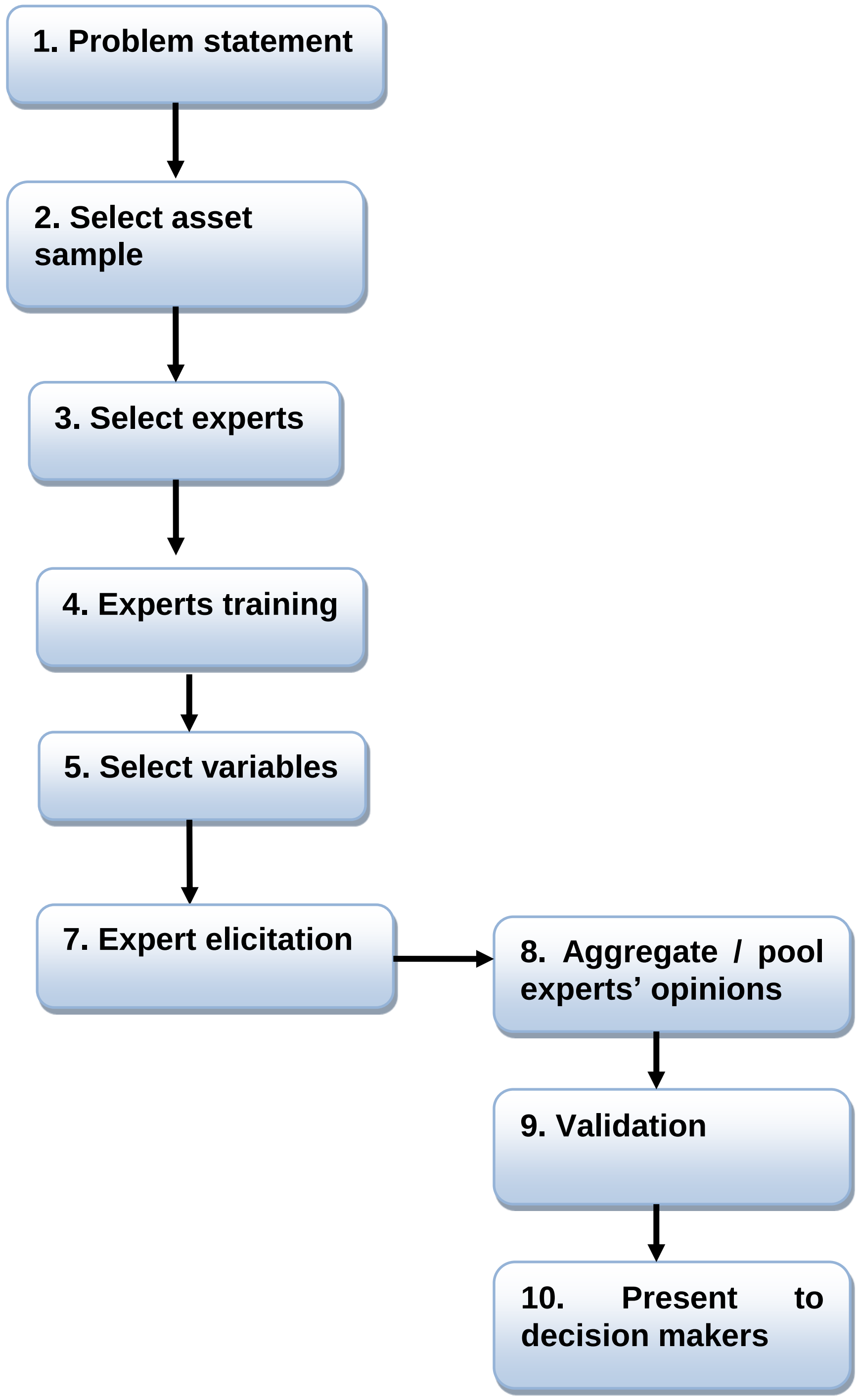

Figure 1-3: General overall elicitation methodology

The following section explores literature on asset management, focussing on the research objectives; asset condition assessment, maintenance effectiveness assessment and maintenance regime selection.

1.2 Literature review

Asset condition assessment

This section discusses some of the asset management literature reviewed on asset condition assessment, maintenance effectiveness and maintenance regime selection.

The literature review undertaken for this research was based on the aims and objectives as well as the methodology for achieving the objectives. The results of the literature search were based on a balanced analysis of the available selected literature in each of the areas of the research (asset condition assessment, asset maintenance effectiveness and asset maintenance regime selection).

1.2.1 Research background

The primary aim of managing assets is to ensure that the function or service that the assets provide is always available and at high standards. It is to also to ensure that the asset usage is maintained in a high capacity. In water utility, the primary asset management objective is to deliver clean water in accordance with the demand and in the most cost effective way. Customer satisfaction and regulation are the major drivers for asset reliability initiatives in water. Incidents particularly of loss of supply and water discolouration are largely caused by asset failure and maintenance policy failures (Bradshaw, 2008a).

According to Bradshaw (2008b), The role of asset management in ensuring high quality risk management in order to avoid health hazards to the public and minimise economic loss to water utilities has not been the focus of risk management until recently. The focus has tended to be in the role of organisational culture and incidents (Pollard *et al,* 2004). MacGillivray *et al*, (2007) and Pollard *et al,* (2007) also state that none of the water sector risk management strategies focuses only on asset management.

A focus on asset management can be justified by some of the asset failure related incidence in water supply. According to Bradshaw (2008c), some of these incidents are caused by human reliability failures, a considerable amount has been shown to have been caused by assets failures (12.9%) and asset maintenance (11.8%). A total of 24.7% of water quality incidents were attributable to asset failures in UK water utilities between 1997 and 2006 (Bradshaw, 2008d). The percentage for water discolouration due to corrective maintenance and asset failure was even higher in the same period (56.5%). Out of 369 incidents in water utilities between 1997 and 2006, 187 were caused by maintenance related problems. 57 were caused by operations related issues and the rest were shared between design and construction problems within the same period. This also indicates the importance of asset maintenance

This research therefore, focuses on the development of asset management approaches in order to enhance asset management in water utility. Providing good quality information in support of decision-making through better asset condition assessment, maintenance effectiveness and maintenance policy choice when there is no quality data was the specific overall focus of the research. Experts' opinions were sought and incorporated in this research to provide quality data as a strategy to support asset maintenance decision making where data are sparse.

1.2.1.1 Asset management and strategy

Different drivers have influenced the development of asset management in many water utilities from different countries. Levels of development vary from basic to advanced asset management strategies. The key asset management principles remain broadly the same in all the water utilities and they include; asset condition and performance assessment, asset performance data capture, serviceability assessment, and maintenance quality assessments.

An asset management strategy provides details of how the assets will be managed for the long-term and to deliver the organisational strategic plan. It needs to be carefully considered initially and reviewed from time to time, to ensure that it meets the needs of the business. It is important to consult with individuals and teams with an interest in the performance of the assets, including internal departments and external stakeholders such as regulators, owners (where asset management is sub-contracted), investors and customers. The asset management strategy will need to balance the views of stakeholders, but should seek to account for these views to ensure it is aligned with business objectives and is advocating the correct actions to meet stakeholder needs.

From just-in-time delivery to higher quality and increased technical support, customers are requiring more from their suppliers. Not only must the product be of high quality, and at the lowest possible price, but deliveries must be on time. Often severe financial penalties are imposed by an industrial partner consumer or regulators when a supplier fails to deliver on-time or at required quality thresholds. Consequently, the financial impact of unexpectedly stopping a production line or can be costly.

Because of the need to ensure that customer service commitments are achieved, companies increasingly are turning to plant asset management as an optimization strategy to improve their process efficiency and reduce maintenance, thus enhancing their return on assets. According to Sun *et al* (2013), companies are reporting as much as a 30 percent reduction in maintenance budgets and up to a 20 percent reduction in production downtime as a result of implementing plant asset management strategy. Since as much as 40 percent of manufacturing revenues are budgeted for maintenance, these savings contribute significantly to a company's bottom line.

Maintenance strategies that once were "run-to-failure" now are "condition-based." Enterprise asset management (EAM) systems and computerized maintenance management systems (CMMS) are implemented to support maintenance scheduling, workflow management, inventory management and purchasing. They are also used to integrate these functions with automation, production scheduling, and manufacturing systems. Leading corporations now have direct connections from their EAM system to electronic-commerce maintenance, repair, and operations procurement systems, which offer considerable time and cost savings compared to traditional maintenance methods.

a) Plant asset management strategies (PAM)

Since a critical factor in both maintenance and operational scheduling is the ability to constantly monitor the health of assets, companies are implementing complete plant asset management (PAM) systems. A PAM system allows asset personnel to assess the risk of failure and the ability to schedule and plan future maintenance activities (Lefton, 2011a). The purpose of a PAM system is to provide timely information to operations and maintenance (O&M) personnel in order to ensure minimum cost per unit of output. These benefits occur as the company makes optimum operating and maintenance decisions through the application of a PAM system's information solution. O&M personnel are constantly faced with decision-making based on limited information. PAM systems make the decision-making easier by providing information about the current and future condition of assets.

Maintenance support - PAM systems assist maintenance personnel in answering the following questions:

- What equipment may fail if it does not receive maintenance intervention?
- What intervention should be taken and how soon?
- What parts should be ordered and how soon?
- What is the optimal blend of condition-based (CBM), calendar-based (prevent maintenance), usage-based (prevent maintenance), and run-to-failure maintenance for a given piece of equipment?

Operations support

The first module of a PAM system is the asset information register. This module provides the rest of the PAM modules with information about the location of the asset and its criticality to the process, as well as asset-specific model data and nameplate information. Registers also need to store measurement location information, such as the type of transducer being used, the post-processing to perform on a measurement location, and the spatial orientation of orientation-sensitive measurements such as vibration locations. Some registers also keep information from a reliability study such as reliability centred maintenance (RCM) audit, as well as financial metrics that could influence decisions regarding the asset. Others include the dates of future maintenance tasks, such as planned overhauls, and can track work and failure history on the asset through gateways to external systems.

The PAM system turns asset measurement data into actionable information and issues advisories to both maintenance and operation systems by synthesizing the asset measurements it has obtained (Lefton, 2011a). In this regard, PAM can be said to be similar to SAP asset management system that several water utilities employ in managing their assets. SAP achieves the same as PAM, although the level of automation currently designed into it is less than PAM. A lot of the data capture into SAP is not automatic, but has to be logged in by engineers or logged in after an incident by another staff member. This limited automation in data capture could be a factor in water utilities having sparse data. Where data capture automation is limited, systems should be in place to encourage a culture of effective data collection in the organisation.

b) Asset management strategies/ frameworks in the water industry

The water industry carries out a range of approaches for implementing asset maintenance. Many companies keep day-to-day operational maintenance in-house and contract out major work. Some companies outsource almost all their work. It is important for the company to maintain maintenance expertise, in such cases, in order to carry out asset management planning and manage the maintenance contracts. It is also important to ensure the quality of asset data.

Water companies in England and Wales publish their water resource management plans. The last planning was in 2009, looking ahead 25 years from 2010. The plans are required by government legislation and guidelines set by the Environment Agency to ensure companies maintain adequate water in the environment and have sufficient water to supply the public (WaterUK, 2012a).

Water utilities are regulated by Ofwat in England and Wales. Under Ofwat regulation, Water utilities have to elaborate their resource management five yearly plans, which include their asset management strategies in these plans. The five yearly plans required by government legislation and guidelines set by Ofwat to ensure companies' water charges to customers are fair also require asset management plans and strategies (Ofwat, 2012b).

Water utilities asset management strategies tend to follow the standard general asset management framework. The major exception is the tendency to emphasize risk assessment. The nature of the product demands the risk emphasis, as water pollution poses a high risk to human life. Risk to environmental pollution is high where toxic chemicals are used (such as in waste water treatment), but clean water distribution carries less risk to the environment. On the other hand, other asset intensive industries (such as oil and gas) emphasise environmental risk in their asset management (Davis *et al,* 2013).

As indicated earlier, one of Ofwat's major concern is that water is delivered at affordable prices to consumers (Ofwat, 2010a). Water utilities therefore, have to balance their asset management strategy against the financial constraints that may be imposed by Ofwat. This is unique in that most private companies' pricing of their product and profits are determined by the supply and demand in the market. Such companies may afford to invest extravagantly in their asset management from time to time – but water utilities have to deliver the best service at the price negotiated with Ofwat. Asset strategy design and implementation in water utilities can therefore, be constrained by these limits.

Water utilities sometimes mix their asset management strategies to meet their needs. They use risk-based strategies such as those employed by Defra as well as other formal non-risk based strategies. Asset risk and criticality is mainly used to prioritise resource-allocation in the short-term. Long-term asset maintenance strategies such as corrective or planned maintenance are also used (Alegre *et al,* 2012a). The maintenance intervals are then set to meet that water utility needs and to suit asset types. For example, corrective maintenance may not be carried out for some assets due to their low value or high cost of repair (Alegre *et al,* 2012b). When the asset fails, it is deemed to be at the end of its life and replaced. Section 1.2.4 explores some of the maintenance regimes used by water utilities and other sectors to employ maintenance strategies. As Ofwat is one of the major drivers in water utilities asset management strategies, innovation is priced by the regulator. This introduces a large scope for improvement by water utilities to bring asset strategies to state-of-the art leading industries level, such as aviation and oil and gas. The risk of damage to human health in cases of incidences in water utility also calls for such asset strategy improvements.

c) Systems, Applications and Products for data processing (SAP)

One particular strategy employed by water utilities is the Systems, Applications and Products for data processing (SAP) business management system. SAP brings together different disciplines in managing assets. It is reported by some water utilities to cuts costs, with total asset management solutions. The SAP system ultimately covers all business operations. The components of SAP include financials, controlling, procurement, asset management, employee self-service, manager self-service and human capital management.

SAP benefits - The combination of the asset management and human resources capabilities provided by the SAP applications allows water utilities to integrate information sources. This helps it to predict, plan and schedule maintenance and allocate correctly skilled work crews with the right spare parts for each specific task. This approach increases first-time resolution rates, which results in lower operational costs and increased service availability. Use of SAP resource and portfolio Management is estimated to improve capital efficiency by 20 per cent (Severn Trend Water, 2010a). On-site updates of asset condition and work completed enables automated replenishment of parts used. Remote working allows staff to update hours worked and confirm days off, which in turn feeds the work planning system, determining work allocations. Large capital programs can be managed with greater visibility and control, enabling water utilities to deliver planned infrastructure changes and maintenance at a lower cost, with end-to-end asset management. This helps to reduce the total cost of ownership of assets and ultimately, ensures delivery of improved services to customer base (Anglian Water, 2005).

Key Solution Components - SAP application include financials, controlling, procurement, supply chain management, asset life-cycle management, project management, planned maintenance, human capital management, employee self-service, manager self-service, business warehouse, supplier relationship management, customer relationship management, resource and portfolio management and scheduler workforce management (Severn Trend Water, 2010b).

The SAP information management system can be an effective strategy, particularly because it can be a platform for applying PAM as it is comprehensive, catering for all the different aspects of asset maintenance. Since PAM determines what asset maintenance regime is suitable for asset groups based on the asset performance data, SAP is an effective data collection tool. The major current limitation of SAP is that most water utilities have installed it in recent years and there is limited data collected to effectively use to support asset maintenance decisions. Some of the data are sparse due to limited data collection consistency. Therefore, tools for supporting decision-making where there is limited data are still required in some cases.

d) Environment Agency asset management strategies

The management of flood defence assets by the Environment Agency (EA) is carried out within the framework of optimum management and efficiency through its protocol for the maintenance of flood and coastal risk management assets (Environment Agency, 2012). The Agency has powers to do works and to regulate the actions of others on main rivers and the coast for the function of flood and coastal risk management. All references to Environment Agency assets relate to main river and sea defences.

The Agency's asset management approach involves;

i) Management strategies and plans **-** The UK National Strategy builds on existing approaches to flood and coastal erosion risk management. It encourages the use of a wider range of measures such as: sustainable urban drainage systems, individual property protection and resilience, and managing flooding and erosion in a co-ordinated way are implemented. The measures balance the needs of communities, the economy and the environment.

In addition to the National Strategy, the Environment Agency employs the following strategies (Environment Agency, 2010c):

- catchment flood management plans (CFMPs), which establish long-term future plans for the management of the river network;
- shoreline management plans (SMPs), which set out strategic options for managing coastal assets;
- change project plans that set out in more detail the proposals in a CFMP or SMP for some specific geographical locations.

ii) Consultation - After carrying out initial assessment, the EA consults those who would be affected by permanent changes to our maintenance activities. This is to ensure that the evaluation and prioritisation of maintenance activities consider other views. Decisions on the future management of the assets are then taken.

iii) Assessment and categorisation **-** Catchment Flood Management Plans (CFMPs) are used to identify where maintenance activities can be reduced.

System asset management plans (SAMPs) are used to identify systems and assets which are candidates for stopping or reducing maintenance due to being uneconomic.

iv) The four categories strategy - The maintenance of asset systems is carried out using a risk-based approach. This is to ensure that investment is made where activities contribute most towards reducing the potential for damage, and where it is environmentally and economically justified.

Four categories are considered in the range of factors considered relevant when the required level of maintenance for an asset is reviewed (Environment Agency, 2010);

Category 1- assets for which there is an economic case for maintenance to reduce the risk from flooding to people and property.

Category 2- assets that are required to protect internationally designated environmental features from the damaging effect of flooding

Category 3- where work is justified due to legal commitments but assets do not fit categories one and two above.

Category 4- assets that do not fit the above three categories.

v) Economic appraisal – asset management decisions are based on economic appraisal of impacts. The appraisal compares the whole life costs of an option with the whole life benefits. This is used to decide where maintenance work is done and where works should stop. If the costs are higher than the benefits, then the work considered to be not economic, and vice versa. Where the benefits of maintaining an asset are only slightly higher than the costs, we might reduce maintenance rather than stop it entirely.

The environment Agency's asset maintenance strategy is effective in prioritising the allocation of resources. It also effectively brings information together from consultations with different stakeholders for informed decision-making. The limitation is the lack of integrated co-ordination between other management disciplines – compared to water utilities PAM management strategies. The agency's strategy also lack mechanism for assessing the effectiveness of maintenance regimes based on te asset performance data. There is, instead, main reliance on economic viability in the decision-making.

Summary diagram of the Environment Agency asset management strategy is presented (Figure 1-4).

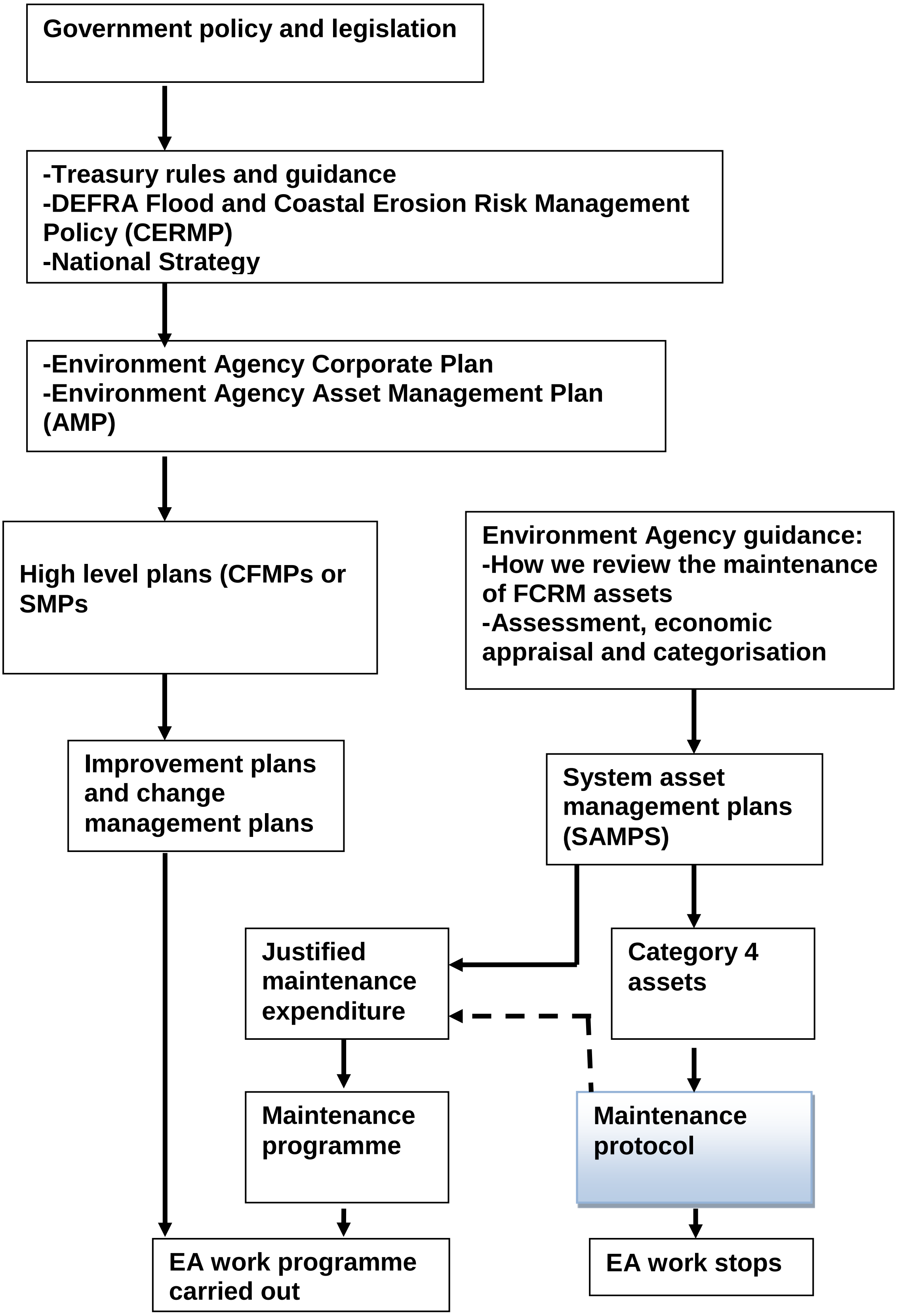

Figure 1-4: Environment Agency summary asset management strategy

In summary, the Agency's asset management strategy ensures that more properties are better protected from flooding from all sources. Properties in disadvantaged communities are better protected from flooding, assets meet their target condition, and there is a right balance between constructing new and maintaining existing assets.

The asset management strategy for the environment agency is good in that asset condition assessment is carried out and maintenance work is prioritised as informed by the condition assessment. The limitation is the lack of formal maintenance effectiveness assessment. Maintenance effectiveness assessment is necessary for informing and reviewing the choice of maintenance regime used. On the other hand, water utilities do assess maintenance effectiveness where data are available – although have not been known to assess the same when there is limited data.

e) Defra strategy for managing assets at risk of flooding

The national flood and coastal erosion risk management (FCERM) strategy for England and Wales emphasizes the need for risk to be managed in a co-ordinated way across river catchments and along the coast. A range of practical options are considered in helping local decision-making. The government and the authorities who are responsible for managing these risks are brought together with the organisations, communities, and people who are at risk of flooding. The strategy encourages asset managers to work together to (Defra, 2011a):

- know when and where flooding and coastal erosion is likely to happen. Risk managers have to understand the risks of flooding and coastal erosion. This understanding can be said to be similar to this research asset managers' need to understand the condition of their assets. Asset condition knowledge then acts as a basis for most of the asset management planning as it informs other asset management decisions and activities. The maintenance strategy does not formally define asset management activities, but it incorporates them in a more practical sense.
- make sure that any flood and coastal risk management plans use the most up-to-date information and raise awareness of these risks among affected communities. Data and information capture is always necessary to inform

decision-making in asset management. Limited data is the major basis of the methodology employed in this research, as is the experience of some water utilities. Defra's strategy to capture and use data and all information available indicates that decision-making is generally informed as supported by data and consultation.

- reduce the chance of harm to people and damage to the economy, environment and society by building, maintaining and improving flood and coastal erosion management infrastructure and systems.

Defra strategy indicates awareness of using optimal maintenance regime, although it does not state what those maintenance regimes are. Appropriate maintenances regimes are critical for maintaining assets in good condition, as indicated in section 1.4 and many water utilities employ these maintenance regime strategies (Alegre, 2012b). As indicated in Figure 1-5, Defra employs formal asset management strategies, though they are not very formal in stating asset management terms. This could be due to that they take a particularly more risk-based approach than the standard asset management approach. The emphasis on the risk-based approach is necessary for the nature of the hazards their assets face and asset type they manage. The mandate is mainly to help manage and minimise flood damage to the assets and floods can be unpredictable. Figure 1-5 illustrated Defra's risk-based asset management strategy.

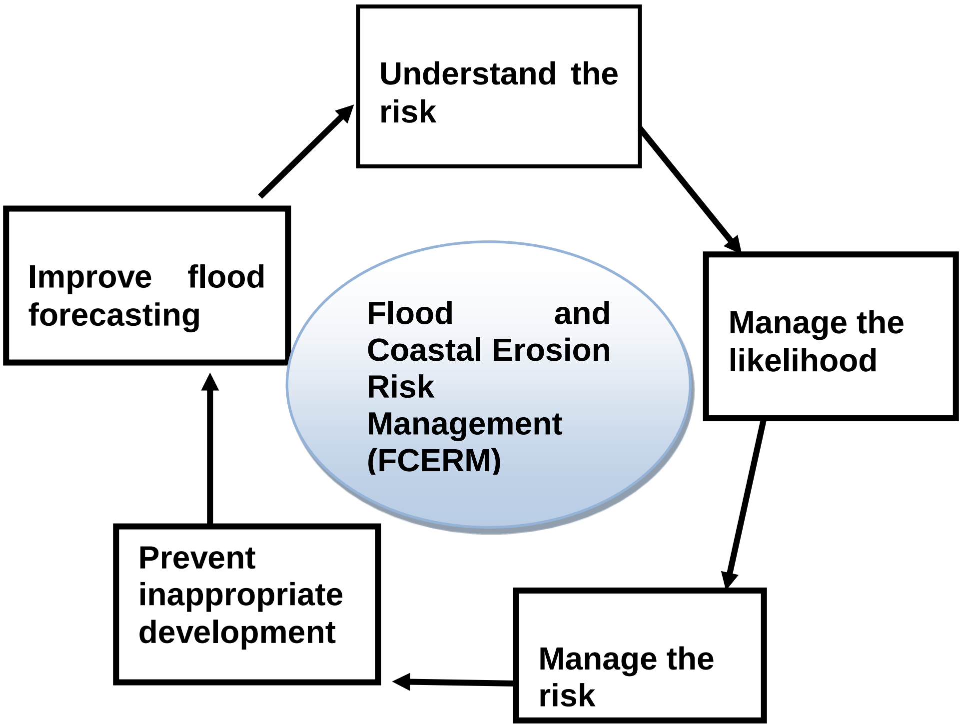

Figure 1-5: Management strategy for assets at risk of flooding (after Defra, 2011b)

f) Ofwat asset management strategy

Ofwat is interested in water asset management in England and Wales as the economic regulator of water utilities. Ofwat's basic principle is to encourage innovation, continuous improvement and best practice in customer service and fair pricing of water.

Table 1-2 summarises the guiding and driving force for asset planning strategy for water utilities in England and Wales.

Table 1-2: Asset capital planning framework for water utilities in England and Wales (after; Ofwat, 2004)

A	**<u>Historical analysis</u>** ***Identify historical levels of maintenance expenditure and serviceability indicator trends.***	Expenditure review.	- Identify asset categories. - Identify historical expenditure. - Identify typical expenditure.
		Service and asset performance review.	- Select indicators. - Historical and current values. - Reveal underlying tariffs. - Draw conclusions.
B	**<u>Forward-looking analysis</u>** ***Identify future maintenance expenditure to meet regulatory objectives.***	Preparations	- Focus the analysis. - Select the planning objective. - Monitor service and failures. - Design and initiate customer surveys (optional).
		Service and cost forecasting	- Identify failure modes. - Obtain asset observations. - Develop estimation methods for; • Probability of failure • Consequences of failure • Cost of failure - Validate estimation methods. - Forecast service.
		Intervention analysis	- Identify intervention methods. - Estimate impact of interventions. - Estimate intervention costs. - Value service changes (optional). - Select optimal interventions. - Collate and categorise costs.
C	**<u>Conclusions</u>** ***Compare and explain results of historical and forward-looking analyses. Make the case for the required level of future maintenance.***	Compare and explain.	
		Explain scope for further inefficiencies.	
		Present the case	

Ofwat is very interested in that water utilities employ optimal asset management strategies because it regulates the economic side of water utilities. This is particularly in ensuring that utilities deliver water to consumers at affordable prices. Therefore, investment in asset management activities is of major interest to Ofwat, in carrying out the mandate of regulating water utilities. Unlike the risk-based strategy by Defra and EA, Ofwat asset management strategy tend to have a major financial theme to it, which in turn is incorporated by water utilities in their asset strategies. Although Ofwat asset strategy is not formal, the regulator has strategic themes that water utilities must adopt (Table 1-2). For example, they must show a balance between good customer service and the price of water they charge – whilst justifying their asset capital and maintenance costs (Ofwat, 2010). The challenge for water utilities and Ofwat is the balance between fair water pricing and the need for large asset maintenance and replacement investments the water distribution requires.

1.2.1.2 Assets performance information

It is necessary to capture asset performance data in water utilities. The data could include; what assets are owned by the water utility, their value, their location and their condition (Vanier, 2001). The primary information for underground network are the physical attributes of the network i.e. the diameter, the material from which the pipe is made, the age and the spatial location of the pipe. Other information relates to the environmental factors which affect the underground asset condition. These could include type of soil, ambient soil temperature, groundwater properties and information related to the climatic conditions. The information regarding type of traffic flow and the depth of soil cover above the underground asset, are also relevant (Hu and Hubble, 2005).

The manual of British engineering practices recommends recording data on leakage relative to various types of mains bursts. It further recommends recording of data regarding the details of mains, joints, fittings where appropriate, the causes of fracture, and the impact of pressure. It also mentions that the most valuable records are the drawings of the network of the distribution system. However, there are still many water utilities in England which do not have this level of data about all of their assets (Carriço 2012). Similarly, the availability of information about assets within the American and Canadian water utilities varies (Wood *et al,* 2007a). On the other hand, most of the Australian water utilities have improved their data capture. Asset management practices substantially improved over the years and they believe they have a reliable database (Moglia *et al,* 2006).

1.2.2 Condition and performance assessment

The renewal decisions regarding the underground assets of a water utility are dependent on the information about the condition and performance of the assets. The condition of an asset is an indicator of the probability of failure. Condition and performance assessment, in combination with assessment of failure consequences, contribute to the assessment of risk. With an understanding of the asset risk level, utilities are able to determine appropriate operational, capital maintenance and other asset management requirements (Urquhart, 2006a).

The term ‘condition’ in asset management refers to some measure of asset state (Marlow and Burn, 2008b). According to Grigg (2006a), the condition of an asset is ‘readiness of a component to serve its function’ which includes physical integrity and the operational readiness. Grigg’s definition of condition refers to a combination of two terms defining ‘condition’ (structural integrity) and ‘performance’ (functional capability) of an asset. Marlow and Burn (2008c) interpreted condition and performance of an asset as complementary. From this point onwards the researcher has used the word ‘condition’ to imply both structural integrity and functional capability, which has an element of performance.

Assessing the condition of a water supply system can be complex and expensive. This is because water distribution systems are composed of many different asset types with different material, ages and are subjected to different loading and soil conditions (Ellison, 2001a). Many assets can continue to perform their function satisfactorily even when their condition has significantly deteriorated. Hence, the definition of condition adopted in the research includes the asset’s performance and structural integrity. According to Urquhart (2006b), expenditure priorities should effectively be determined by assessment of both asset performance and structural condition.

1.2.2.1 General asset condition

It is difficult to make any physical observation on the condition of each of the components of the assets which are part of an underground network because of the sheer volume of the underground assets, on account of their inaccessibility and the costs involved (Knudson *et al,* 2006). The observation process is a disruptive and costly process which adds to the degree of difficulty in executing such a procedure (Ellison, 2001b). Harlow and Stewart (2006) recommended that, since condition assessments are costly, and they should only be undertaken if the risk outweigh the costs.

For many types of water utility assets, there is a general relationship between age, condition and the asset’s propensity to fail (Marlow and Burn, 2008d). Failure mechanisms include corrosion, fatigue and mechanical wear. The rate of deterioration (worsening of condition) is highly asset and context (environmental and operational) specific. The inherent variability of these factors make it is very complex to establish any time dependent relationship between asset condition and failure probability (Rajani and Kleiner, 2004a).

Many studies and reports have considered the impact of factors such as environment (type of soil, temperatures), operational (pressures, water quality), and pipe material on the condition of pipes (Kleiner and Rajani, 1999). However no two systems are similar in terms of a combination of these factors. Hence, no single model can be suitable for all the systems. The methods that are commonly used for a structural integrity assessment of the pipes are direct inspection, coupon sampling, controlled destructive evaluation, remote field eddy current (RFEC) and acoustics (Ellison, 2001c; Grigg, 2006b). Coupon sampling is one of the destructive methods used for old cast iron pipes that measures remaining wall thickness, encrustation, corrosion or other physical indicators of the pipe. Grigg (2006c) advocates the coupon sampling method only for those pipe materials where loss of wall thickness or corrosion might be related to conditions that can be generalised.

Severn Trent Water, UK has used coupon and opportunistic sampling to develop a model for the assessment of the remaining useful life of the pipes by estimating corrosion rates taking into consideration all the factors affecting the process of corrosion (Kane, 1997a). Opportunistic sampling refers to collecting samples of the underground assets when these assets are exposed because of reasons such as repair work and new connections being made. Severn Trent's model specifies the need for coupon sampling over and above opportunistic sampling, stating that the latter has no additional cost but has a bias in that samples are collected only from failure sites. The process of coupon sampling is more expensive, however this method is necessary to neutralise the bias in the opportunistic sampling. Alternatively, if opportunistic sampling is adopted then it is recommended to collect significant proportions of random samples also (Kane, 1997b).

Non-destructive evaluation (NDE) techniques have been developed for the evaluation of the condition of metallic and pre-stressed pipes. A majority of the underground infrastructure in the developed world is metallic (UK- 80%, Australia-70%, Sweden-58%, Germany-75%, Russia-71%) (Savic and Walters,1999). Practical NDE techniques have not been used for non-metallic /polymer pipes. Remote Field Eddy Current (RFEC) method is the most common and effective NDE method for the condition evaluation available for iron pipes (Ellison, 2001). Grigg also drew attention to the importance of the 'hidden' potential for evaluation of the condition of underground assets, suggesting the value of making use of existing records and the knowledge and experience of employees.

Canning (2002), Ellison, (2001d) and Grigg, (2004d) advocate analytical methods which do not directly measure asset condition but only infer it from other measurements and data. Such data could be hydraulic evaluation involving pressure measurements of the water supply and water quality evaluation of the underground pipe network for condition assessment of water distribution networks. They suggested other method such as water audit, flow gauging, pressure measurement and fire flow tests have also been recommended to assess the condition of the water system. They also suggested the C-factor (Hazen Williams's factor) test, which determines the roughness coefficient (indicating the smoothness of the inside of a pipe) in assessing the physical integrity/structural condition of a pipe. According to Wood (2007b), the number of annual water main breaks is typically used as a surrogate for the condition of the network. However, it does not always reflect the pipe condition because breaks can result from causes other than lack of strength. Ellison (2001e) reports that the simplest method to assess the condition of an underground pipe network is to use statistical analysis with age as a dependent variable and material type and diameter of the pipe as independent variables. However, condition assessment through statistical modelling may be a very complicated process (DeSilva *et al*, 2005). It requires extrapolation from the condition of inspected samples to a relevant asset population or pipe length. Statistical sampling is, however, widely used for the condition assessment undertaken for financial or regulatory reporting (Urquhart, 2006c).

The condition of the assets is affected by many other factors such as water quality, operational practices, environmental factors and age – which also determine the probability of failure (Hu and Hubble, 2005b). Rajani and Kleiner (2004b) provided an approach to estimate the probability of failure due to deterioration or poor condition of the asset by taking into consideration other factors affecting the condition of an asset based on physical or statistical models. They also noted that these empirical models typically oversimplify a complex reality. Substantial historic data relating to the condition of the asset and factors affecting the condition of asset are critical for assessing its condition. However, lack of appropriate data means other models should be developed to accommodate such cases (Moglia *et al,* 2006b).

No single method can be fully sufficient for assessment of the condition of the water distribution network assets. An appropriate decision has to be made regarding selection of appropriate methods for condition assessment of the network assets. The decision could be based on the knowledge of factors affecting the condition of the assets. This could include the experience of water utility staff that have a working knowledge about the condition and functioning of the assets. Particular attention should be paid to the possible influence of specific factors that affect the condition of particular asset groups than the current use generic factors across water networks.

1.2.2.2 Asset performance assessment

Performance, that is the functional capability of assets, can also be viewed in terms of either the failures of assets or failure of the network to deliver the required levels of service. Marlow and Burn (2008d) emphasised that service provision is an appropriate focus for asset management and recommended a comprehensive service level performance monitoring system as the more relevant guide to decision making. Service levels are a measure of both the effectiveness of asset management and general water utility's performance. Cause of failure is important for assessing the performance of an asset or group of assets. Failure of an asset or poor performance could be a result of poor operational practice or 'condition' of the assets.

Asset failure records are kept by companies in order to create model to predict the future performance of the assets to estimate capital maintenance investment. Assets can be considered when the failure had been due to poor condition. Where the cause of failure is incompetence in operational practices or third party interference may not be considered for condition assessment. Models based on asset performance do not take the variation in construction methods, ground conditions, consumption pattern and climate. However, these variations depend on historical performance data of the assets (D'Agata, 2003a). He also noted that the knowledge of the historical performance of asset is best to assess the condition.

Performance indicators of the assets are considered to be management tools fundamental to monitoring the actions of the assets (Alegre *et al, 2008*). Selection of performance indicators/measures is very crucial to asset management. Performance indicators can be influenced by a range of factors such as capital maintenance or operational practices. An ideal performance indicator would allow assessing the scope for improvement in system efficiencies and align it with the organisation's strategic policy and plan (UKWIR, 2002b). There are costs and efforts involved to gather inputs and maintain each performance measure. Therefore, the selection of performance measures regarding asset management should be carefully evaluated in terms of their strategic value against maintenance costs and stakeholders' expectations. It should also be strongly justified on a cost benefit basis. Performance measures should provide objective quality evidence to assist in decision making or the preparation of action plans (Matichich *et al,* 2006a).

Each year water and sewerage companies in England and Wales are required to thesis information on their performance against various aspects of service as shown in Table 1-3.

Table 1–3: OFWAT Serviceability indicators (OFWAT, 2008a)

DG2	Inadequate pressure
DG3	Supply interruptions (unplanned)
DG4	Restriction on water use (Hosepipe restrictions or drought orders)
DG5	Flooding from sewers
DG6	Billing contacts
DG7	Written complaints
DG8	Bills for metered customers
DG9	Ease of telephone contacts

These are known as serviceability indicators, which are focussed on the service to the customers. These serviceability indicators measure the performance of the system instead of performance of a particular asset or asset category. It is serviceability to customer and not serviceability of the assets (Parsons, 2006a). DG2 to DG5 can be directly related to capital maintenance however DG6 to DG9 clearly have little direct connection with pipe network operation or capital maintenance issues. Serviceability as defined by Ofwat is a long-run approach, which considers the ability of the appointed water companies to maintain the existing standard of service to customers. Serviceability indicators are defined as set of outputs or outcomes that are considered to indicate the capability of the fixed assets to provide service to customers now and in the future (Ofwat, 2007). According to Parsons (2006b), serviceability is considered at company level and the aim is to ensure that the trend in serviceability remains stable or improves. Serviceability indicators, with respect to capital maintenance, can be impacted by the deterioration of a number of assets. It may not be possible to isolate the impact of a particular asset or class of assets (UKWIR, 2002c).

Asset performance indicators and serviceability indicators are sometimes used interchangeably. Service defines performance of the asset and service to customer. ‘Service to customer’ includes both customer service and water service. Indicators can be a set of service indicators and the other set is the asset performance indicators and the intersection of the two sets is the serviceability indicators (UKWIR, 2002d).

There is an obvious lack of distinction is drawn between customer service and water supply service. A combination of asset performance indicators and water service indicators could be referred to as serviceability indicators. Indicators such as telephone contact are customer service indicators and independent of the physical asset performance.

An AWWA research utilised seven performance measures to gain insight into asset condition and renewal requirements from the data gathered from eleven water utilities in the United States of America (USA). These were number of unplanned service interruptions, number of main breaks/mile, number of water quality violations, renewal and replacement status, maintenance activity, preventative maintenance and age vs. service life (Matichich *et al,* 2006b). In Australia, water supply interruptions are regulated and used as key performance indicators (Moglia *et al,* 2006c).

1.2.2.3 Service performance indicators

a) Asset serviceability indicators

These include ease of telephone contact, properties subject to flooding incidents, and bursts of pipes.

Alegre (2006a) reported that in the European CARE-W programme, performance indicators were classified into five categories for the rehabilitation manager tool, specifically directed at pipe network renewal. Alegre (2006b) have also reported that in the pilot research of application of these performance indicators, economic and financial indicators had the lowest rate of success because of unavailability of data at subsystem level.

b) Operational indicators

These include mains rehabilitation, mains renovation, valve replacement, valve failures, active leakage control repairs, water losses, power failures, and other failures and repairs

c) Financial indicators

These include annual costs, unit total costs, unit running costs, investment for asset replacement, water colour test compliance, and critical interruptions per connection

d) Quality of service indicators

Quality of service include pressure of supply adequacy, water interruptions, customer complaints, interruptions per connection, days with restrictions to water service, and service complaints per connection

1.2.2.4 Strategic objectives of performance indicator

Strategic objectives related indicators include (Alegre, 2007);

- Invest in measures to reduce discoloured water complaints
- Reduce number of customer complaints
- Improve water quality compliance at treatment facility, turbidity at treatment facility, water quality compliance at tap, coli form compliance (treatment facility, service reservoir), and iron pick up in system
- Reduce interruption to supply
- Reduce unplanned interruptions, interruption duration, interruption frequency, water pumping station failures, bursts per unit length.

The indicators recommended by Ofwat to be reported for assessment of capital maintenance requirement through asset management planning by water utilities in England and Wales have a specific focus on service to customer. Other performance indicators are for internal asset management planning of water utilities, encompassing financial and operational aspects, and resource availability besides customer service.

Studies undertaken in the UK, Australia and the United States (US) have shown that the state of existing water infrastructure is deteriorating. Significant level of renewal/replacement resources are required to ensure that water utilities can continue to deliver their services. The trend is the same worldwide. A lot of resources are invested on underground asset management, but utilities need to maintain aboveground assets as well. The challenge for water utilities is how best to manage their assets with limited financial resources. Since the long-term cost implications for poor asset management can be large, formal asset management strategies that includes a condition assessment and maintenance quality assessments can help utilities to;

- Understand asset condition and remaining life, allowing for proactive budgeting for high-risk assets
- Quantify the benefits of different management/operational strategies
- Meet customer service expectations as well as legislative requirements

Water utilities tend to use all the above indicators in assessing their overall organisational performance. However, asset condition as based on performance requires a focus on asset condition specific indicators. Where utilities use specific asset performance indicators, they tend to apply them across all asset groups and yet each asset group has its unique performance indicators. This minimises the quality of asset condition assessments. This research develops an asset condition assessment approach that utilises specific performance indicators for each asset group. The method is based on a case where there is sparse or limited data to assess the assets condition.

1.2.2.5 Condition assessment process

The condition assessment process is based on grading of the condition of variable or parameters, and an overall condition grading is given. The assessment of asset conditions is carried out before maintenance activities and maintenance costs estimate are made. The condition parameters: importance, intensity and extent of defects are assessed and a condition rating score is given per asset.

Condition assessment follows a hierarchical clearly defined method of classification of components condition. The condition rating follows, for example, the classification in Table 1-4.

Table 1-4: Six-point scale standard for condition assessment of assets

Condition rating	General condition description
1	Excellent
2	Good
3	Fair
4	Poor
5	Bad
6	Very bad

1.2.2.6 Importance of assets maintenance based on performance

Condition assessment reveals defects that affect the functioning of an asset or components. Defects can be minor, serious or critical. The functioning of the asset or component is significantly affected by critical defects. Materially intrinsic defects such as corrosion affect the asset's functioning and are rated as critical defects. The condition of assets is determined by the intensity of defects. Defects caused by ageing such as wear, develop over time in different intensities. Defects caused by accidents happen at once.

Knowledge about the extent of defects is needed to assess the condition of the asset. General ageing defects covering the whole asset can be differentiated from specific functional defects. In the case of general ageing defects, the intensity of a defect corresponds to the condition. The asset condition of ageing defects is then rated according to the extent and the intensity of a defect. Assets can have more than one defect, with similar of differing intensities (Makar *et al,* 2001; Straub, 2003a).

1.2.2.7 Maintenance performance levels

Formulating performance levels in maintenance involves setting performance standards, planning maintenance activities, and investing the necessary resources to maintain those performance levels. Maintenance activities can be distinguished according to type (planned, corrective or predictive maintenance). Different condition targets for an asset of asset group can then be set; 2%, 2%-10%, 10%-30%, 30%-70% and 70% (Figure 1-6).

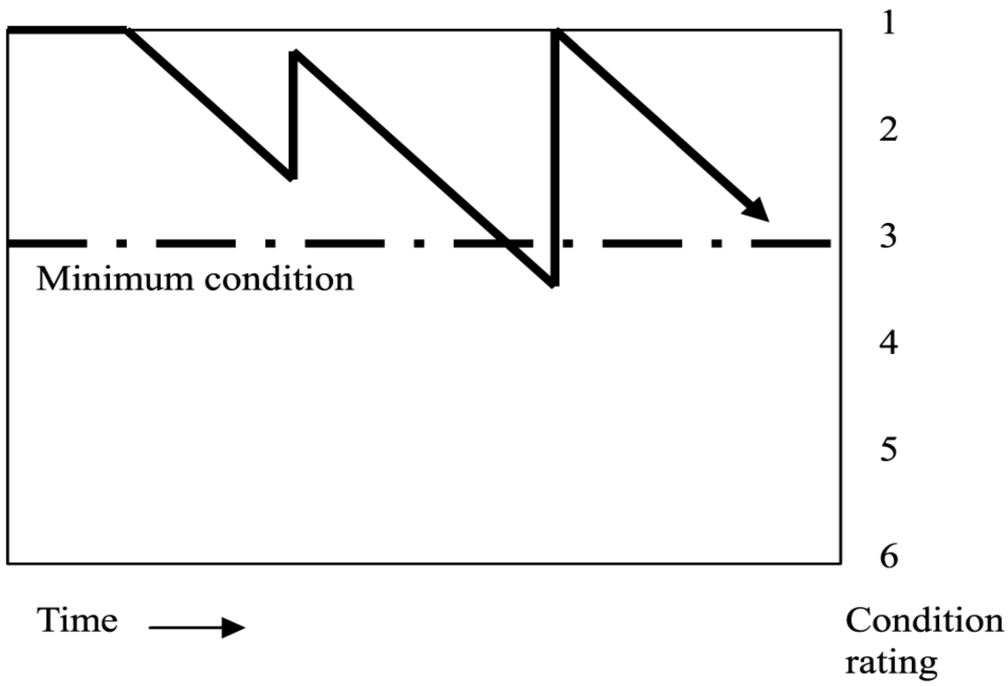

Figure 1-6: Maintenance performance levels

1.2.2.8 Other utilities of condition assessment

Coleman (2006a) describes different models for priority-setting of maintenance that are based on assessment of the condition of assets. The functional operation of assets is determined by the condition of the asset. He links risk consequence grading criteria to asset condition rating. Cigolini *et al* (2009) outline a decision diagram using similar risk categories and the significance of assets. Significant assets are those whose failure would affect customers' health and safety, the environment, and overall business operation efficiency.

Asset condition assessment can also be used to assess the effectiveness of maintenance. The performance of a component after carrying out maintenance work should be clear, in order to record the effectiveness of maintenance. However, information about maintenance activities is sometimes sparse. The condition of components after replacements and repairs may not be assessed in most organisations (Straub, 2003b). The condition of an asset can be ‘as new’ after a major replacement work (condition rating 1). The condition gap before and after partial replacements and repairs can be subjective. Repainting of surfaces does not influence the technical performance of components. The technical defects remain the same, whilst the surface appearance improves. The maintenance effectiveness assessment may be difficult to assess in such cases. On the other hand, functional material repairs lead to performance improvements, with the maintenance effectiveness easier to assess.

Condition assessment can also help improve or select an optimal maintenance regime. It can help prioritising maintenance work. Determining maintenance performance levels and prioritising maintenance work from condition assessment help to determine suitable maintenance regimes for different asset groups (Kleiner, 2001).

1.2.2.9 Condition assessment summary and literature gap

Studies, literature, and discussions with water utility experts served as a basis for identifying gaps where more research and advancement is needed. The objective was to evaluate asset condition assessment state in water utility and obtain direction for the research. The literature review and discussions with industry experts focussed on data needs for conducting condition assessment and making asset management decisions; use of flow monitoring for asset management; systematic approaches to condition assessment; the importance of understanding the mechanisms of assets degradation; and tools and models available for conducting condition assessments decision-making related to water distribution assets.

Critical gaps in our knowledge of asset condition assessment were identified and summarized below;

1. Research is needed to further define optimal levels of costs and benefits of asset condition assessment. Methods for determining the impact of failures associated with asset condition are needed in order to support water utility regulation and internal decision making.
2. Condition assessment technologies are available for underground assets for inspecting pipes below the waterline and for inspecting mains that are in service. There is limited advancement in research for above-ground assets regarding condition assessment approaches and technologies in water utility (xxx.
3. Where limited data exist for assets condition assessment, there is wide scope for improvement in efficiency and precision of current approaches. The data was found to be very sparse, particularly for over-ground assets.
4. Data management methods and models are available, but a lack of consistency in collected data makes it difficult to collate quality data for asset maintenance assessments needs.
5. Research is needed to improve how asset condition is monitored over time. Practitioners need training on topics such as infrastructure failure mechanisms; using historical inspection data for condition assessment applications; developing condition assessment programmes as part of the organisations' value chain; and preparing accurate record drawings for new and rehabilitated assets.
6. Data collection efforts need to be improved in order to have quality data for monitoring asset conditions over time and use in other asset management modelling needs.

1.2.3 Maintenance effectiveness assessment

This section explores the literature and developments in maintenance effectiveness.

1.2.3.1 Introduction

Maintenance effectiveness can be defined as the quality of maintenance actions in meeting an organisation needs and set levels of asset performance. Maintenance effectiveness, as used in this research, is the net effect of a maintenance action as reflected by condition of the asset. An important aspect of maintenance performance (maintenance effectiveness) measurement is to formulate maintenance performance indicators, such that the maintenance strategies are linked with the overall organisational strategy (Simões, 2011). Literature reviews reveals that a large number of attempts have been made in the past for classifying maintenance performance measures as a means to develop effective and efficient maintenance performance measurement systems. Tsang (2002a) classifies performance measures into three different categories based on: 1) equipment performance measure, 2) cost measures and 3) process performance measures. Kutucuoglu *et al* (2001a) suggest another general classification of maintenance effectiveness assessment. They proposed a balanced performance measure by listing them into five categories: equipment related performance measures, task related performance measures, cost related performance measures, immediate customer impact related performance, and learning and growth related measures

1.2.3.2 Maintenance effectiveness measurement approaches

Maintenance effectiveness addresses various issues related to maintenance quality assessments. This includes providing accurate and timely maintenance data, efficient handling of large amounts of maintenance information, and measuring maintenance performance. Pintelon and Puyvelde (1997a) present different performance maintenance measurement systems. These include indicators (global performance indicators [PI's], set of PI's, Structured PI's), reference numbers and graphs. Pintelon and Puyvelde (1997b) also present some models, such as the MMT (maintenance management tool). The MMT is considered to be the most efficient in terms of diagnosis and performance assessment. However, the tools incorporate performance indicators which are too aggregate, rely on single measures for assessing performance, concentrate on immediate goals rather than long term goals and are based on measuring the financial impacts - without measuring the actual quality of maintenance (Tsang, 1999c). Maintenance effectiveness assessment can be classified as follows;

a) Value-based performance measurement (VBPM)

Tsang *et al* (1999b) presents an improved performance measurement technique. It takes into account the impact of maintenance activities on the future value of the organisation. The limitation of this technique is that it focuses only on the financial aspects of maintenance performance. It is also complex to implement. Current methods in water utility use the future value of the assets. The approach does not specifically focus on maintenance related activities in evaluating maintenance effectiveness. The quality values do not directly reflect the quality of maintenance to support decision-making about, for example, planned maintenance intervals.

b) The balance scorecard technique (BSC)

First developed by Kaplan and Norton (1992), the balance scorecard links the maintenance strategy with the overall business strategy. It also develops performance measures for maintenance on four perspectives; financial, learning, growth and customers. Long and short-term means to achieve financial objectives are considered (Tsang, 2002b). The approach is not widely used by water utilities to assess maintenance quality but to assess overall organisation performance of the network. It would be very difficult to implement at individual asset level. Although the current use of the approach can be aggregated at unit asset level, it is a poor measure of maintenance quality because an agregate does not take into account the unique asset condition, size and operating conditions.

c) Systems audit (SA)

Tsang *et al* (1999c) also developed a systems audit technique that is based on socio-technical system analysis. It is used for predicting future maintenance performance. He also developed a DEA (Data Envelopment Analysis) technique. It is a non-parametric quantitative approach for benchmarking the organisational maintenance performance with the competitors’ maintenance. This method is used by water utilities, but it does not cater for maintenance quality assessments of each asset group and individual assets. This is because it involves a lot of generalisations about indirect aspects of maintenance, such as customer service levels.

d) Extended balance scorecard (EBSC)

The extended balance scorecard (EBSC) was developed by Alsyouf (2006a) from balance scorecard (BSC). It incorporates performance measures based on seven perspectives; 1) corporate business (financial), 2) society, 3) production, 4) consumers, 5) support functions, 6) human resources and 7) supplier perspectives. Alsyouf (2006a) argued that the performance measures in the BSC only focus on top-down performance measurement. He argued that the measurement does not take into account the extended value chain - ignoring the suppliers, employees and competitors. Some water utilities adopt a simplified approach to using the EBSC by using some, but not all of the seven perspectives (Alegre, 2000). The approach does not account for specific asset performance variables and operating conditions and hence, too general for effective asset maintenance quality assessment.

e) Quality function deployment technique (QFDT)

The quality function deployment technique developed an effective performance measurement system for the maintenance function (Kutucuoglu *et al.* (2001a). Its advantages include; ease of implementation, alignment of performance indicators with the corporate strategy and ability to hold both subjective and objective measures. The technique helps to incorporate all the key features necessary for effective maintenance performance measurement. It caters for all maintenance systems across all functional structures and vertically aligned performance indicators. This technique is comprehensive in nature, but it has similar limitations as the balance score card (BSC). It would be difficult to implement at individual asset level, but suitable for general assessment of overall network assets.

f) Maintenance management information system (MMIS)

According to Shareghi and Faiezam (2011), a maintenance effectiveness system using the maintenance management information system (MMIS) was developed in 1998. Using the operational view of the maintenance function, it defines a number of indices for performance measurement. However, these indices do not take into account the tactical and strategic aspects related to maintenance performance (Labib, 2001). MMIS is used by water utilities, but does not define unique asset operating conditions. Water utilities mainly use it as a data collection tool than a data analysis tool.

1.2.3.3 Frameworks and quality contribution of maintenance effectiveness assessment

The previous section considered some of the performance indicators that could be used in assessing maintenance effectiveness. This section focuses on how these performance indicators can support a maintenance system. The purpose of maintenance effectiveness measure and the value it creates for the organisations are also explored.

A major concern in the field of maintenance is measuring the maintenance performance in a feasible and cost effective way. Improper implementation of maintenance performance (maintenance effectiveness) measurement systems can lead to ineffective results. A maintenance effectiveness assessment system can be helpful in identifying problematic areas, used for benchmarking, measuring maintenance personnel performance, and to achieve organisational goals (Parida, 2006). On the other hand, Kutucuoglu *et al.* (2001b) identifies six key features of an effective performance measurement system for maintenance. According to them, an effective maintenance effectiveness system should: recognizes different hierarchies, integrate objective and subjective measures, align performance indicators with the strategic objectives, balance the different maintenance systems, involve employees, and have a cross-functional structure.

a) Quality creation for organisations (QFD)

Different techniques have been developed to assess maintenance effectiveness. Kutucuoglu *et al,* (2001c) developed a general framework using Quality Function deployment (QFD) technique, which employs a three stage-matrix approach. It involves the; 1) identification of key performance indicators (PI's), 2) assigning weights to the different PI's, and 3) measurement and evaluation. The framework shows the interdependence of different performance indicators. It has a cross-functional structure, which is able to translate strategic goals into performance measures. It also ensures top-down bottom-up communication in the organisation. Therefore, it establishes a balanced maintenance effectiveness assessment system.

Contribution: The QFD model supports benchmarking, assessing impact on customers, identifying areas for improvement, and assessing financial impacts. It also creates direct values (cost savings, profits, production added value) and indirect values such as; increased customer loyalty and employee satisfaction.

b) Maintenance effectiveness link with maintenance strategies

This section explores some of the link factors between maintenance and maintenance strategies.

Vibration based maintenance (VBM)

Al-Najjar and Alsyouf (2004) focused on the economic (financial) and maintenance improvements benefits achieved through maintenance performance measurement. They develop a model based on technical and economic inputs to assess the performance effectiveness of vibration based maintenance. The assets are mainly assessed on their vibration rates. Hi vibrations indicating poor maintenance quality and vice versa. The asset vibration is assessed to determine the quality of maintenance. The approach is limited in that it can be only applied to asset or components that can vibrate (active assets), such as water pumps. Assets that are passive in nature, such as water pipes cannot be assessed.

Al-Najjar (2007a) developed a strategy for evaluating the performance of maintenance strategies (condition-based maintenance and vibration-based maintenance). It also quantifies the cost-effectiveness of VBM and helps identify real and potential savings in maintenance and other functional areas.

Assessment: The model can help organisations track maintenance costs, potential savings, maintenance profits, and justify maintenance budgets.

Water utilities have not widely used this approach, though it would be suitable for some asset groups such as water pumps.

Balance scorecard (BSC)

Alsyouf (2006c) adopts the extended Balance Scorecard techniques for formulating a framework that establishes the effect of using different maintenance strategies. The framework also assesses the impact on a company's competitive advantage. Alsyouf (2006d) shows the quantitative and qualitative impacts of CBM with respect to the perspectives of the extended BSC by applying the method in condition based maintenance.

The seven phase cyclic framework that utilises the balance scorecard technique evaluates the effectiveness of CBM. The framework is cyclic in nature and it allows the evaluation of maintenance performance by identifying different blocks of the framework. It evaluates the maintenance effectiveness, efficiency and maintenance related cost.

Contribution: The model can help organisations gain better customer and stakeholder satisfaction, as well as increase production capacity and product quality. It can also help an organisation to effectively utilise its resources by identifying the cost-effectiveness of maintenance. The framework also enables organisations to benchmark the maintenance strategies with other practices in the industry. This approach is not widely used in water utility. A less complex version is however used by some water utilities to benchmark their maintenance strategies (Alegre *et al,* 2000b).

Computerized maintenance management system (CMMS)

CMMS comprises of the formulation of a database for analysing performance and decision making in maintenance. A computerized maintenance management system (CMMS) gathers performance indicators (PI's) from various areas (Fernandez, 2003). The CMMS is used as a tool for monitoring and assessing performance for condition-based maintenance. Technical and financial impacts are assessed.

Contribution: The framework provides early detection and correction of defects by using a database and information technology infrastructure. It provides for improvements in maintenance planning by using data from different areas, such as production and logistics. Overall, the framework provide for proactive decision making by linking a maintenance strategy to a particular asset based on its criticality. It also allows for the analysis of risks and life cycle cost associated with a particular maintenance strategy. Water utilities use a version of CMMS referred to as SCADA, which performs some of the functions of CMMS. For example SCADA analysis the risk of failure level of the assets (Boyes, 2009).

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Multi-criteria multi-hierarchical framework (MCMHF)

The multi-criteria multi-hierarchical framework (MCMHF) is used to analyse long-term stakeholder value, customer satisfaction, cost savings, and justify maintenance investment to offer control at different organisational levels. Parida and Chattopadhyay (2007) proposed a method for evaluating the effectiveness of e-maintenance systems. The framework incorporates value-based aspects that include assessing cost savings, profits, production added value, increased customer loyalty, employee satisfaction. Al-Najjar (2007b)'s framework on condition-based maintenance (CBM) focused on real savings, potential savings, and the ability to analyse effects on other functional areas. It also includes effectively utilising resources, identify the cost-effectiveness of a maintenance strategy, identifying and tracing the root cause of failures. It could also include condition based maintenance early detection and correction of defects, analysing maintenance costs, and improving maintenance planning tasks.

The different frameworks, along with the quality they provide were analysed. The finding was that some of the maintenance strategies tended to be independent of the maintenance effectiveness systems or techniques.

1.3.3.4 Maintenance effectiveness features and quality

A large number of attempts have been made to develop maintenance effectiveness assessment systems that can create value for organisations. These include assessing how an organisational strategy can be aligned with the strategies of the maintenance function. They also include developing measures to link the maintenance performance measures to different hierarchies of the organisation. Developments have also been made in how to translate the management plans at operational level to the corporate level so that they create value for the whole organisation and their customers (Parida & Kumar 2006a). While most researchers have developed frameworks based on the financial and tangible measures, others have used non-financial and non-tangible measures to formulate their maintenance effectiveness frameworks. Alsyouf (2006e) proposed some key features for an effective and efficient maintenance effectiveness assessment system. It is able to assess the contribution of maintenance function to the strategic business objectives. It can also identify the weakness and strengths of the implemented maintenance strategy. It can establish sound foundation for a comprehensive maintenance improvement strategy using qualitative and quantitative data. Lastly, it can re-evaluate the criteria that are employed in benchmarking.

This characterization is line with the idea that a maintenance effectiveness system should focus on measuring total maintenance effectiveness. This includes both the internal and external effectiveness Parida & Kumar (2004b). The criteria show that frameworks that focus on measuring maintenance effectiveness based on financial impacts help in improving the internal processes of the maintenance function. They are however, limited in accounting for the impact of maintenance strategies on functions external to the maintenance function. External functions include; production logistics, customers, employees and organisational goals. The criteria also fail to directly assess individual maintenance actions, which is necessary for developing and refining maintenance regimes.

The maintenance effectiveness techniques such as performance indicators (PI's can help in representing maintenance quality assessment in an inclusive manner. On the other hand, the formulation of performance indicators by focusing solely on financial aspects, and does not support maintenance regime development and specific asset maintenance quality assessment.

Literature review of the maintenance effectiveness techniques also reveals that these techniques are not specific to a particular maintenance strategy such as CBM, preventative or predictive. The techniques only provide an insight into how the indicators for measuring the effectiveness of these maintenance strategies must be formulated. They provide methods for deciding what are the relevant indicators for an effective maintenance performance, what kind of indicators should be used to measure maintenance performance and its impacts on the organisation? Based on publications reviewed and it can be concluded that the maintenance effectiveness measurement techniques are independent of the maintenance strategies. Hence, the objectives develop a new approach to assess maintenance effectiveness.

1.3.3.5 Maintenance effectiveness summary and literature gap

Evaluating the performance of maintenance strategies using effective financial and non-financial measures has been a major concern in maintenance operations literature. Different techniques and frameworks have been developed for measuring the performance of maintenance strategies. However, only a limited amount of has been found that applied in a practical environment, hence tested practical setting. This is because most of the techniques require full data and some companies have limited data. Therefore, there is the need to develop maintenance effective techniques that can be applied when there is limited data. Chatpter 4 of this thesis presents a developed maintenance effectiveness technique developed for a case where there are limited data.

Different techniques for measuring the maintenance effectiveness were reviewed. It was found that these techniques are general techniques that help in determining the right set of performance indicators and are independent of the maintenance strategy. They do not determine the most optimal technique for evaluating for example, the effectiveness of a condition based maintenance. Different frameworks and models such as how maintenance effectiveness assessment systems could be implemented or used are evaluated. These include systems on how the models can create value, both financial and non-financial values, for the organisation. The review also showed what value is created when different frameworks are used. The literature revealed how and what value is created by using these maintenance assessment frameworks for the organisations that have condition-based, vibration-based and reliability-centred maintenance. However, it failed to identify how and what value is created when these frameworks are used in an organisation that uses other maintenance regimes.

The Environment Agency and water utilities uses consultation based approaches, however these consultation approached can be further developed for better precision in assessment. The consultation based approaches can also be applied in new areas of asset management. This is particularly the case for water utilities who are creating innovative approaches in their asset management strategies in the face of limited data. Experts could be useful in determining each asset group's major performance indicators and assessing the maintenance quality when there are no data. Expert elicitation based assessment can be useful in focusing only on the specific asset maintenance quality for purposes of maintenance regime development.

Through identifying these gaps in the literature the following research directions were formulated;

- Develop an approach to assess maintenance effectiveness where there are limited data,
- Apply expert elicitation approaches in assessing the maintenance effectiveness, and
- test the approach on a specific case study.

Maintenance effectiveness was assessed with a variety of methods in the literature. The approaches employed were found to be lacking in precision range uncertainty value where no data existed. Other approaches in the literature assumed full availability of data and were found to be lacking application in practice. Chapter 4 presents the developed approach for assessing maintenance effectiveness where data are sparse or not available by employing experts.

1.2.4 Maintenance regime selection and development

This section explores the literature in maintenance regime selection when data are sparse.

1.2.4.1 Introduction

This section aims to describe and analyse the existing theories that can be found within maintenance regimes, in order to place the research into a context as well as give an overview of other related research. This is because it is necessary to build research results on both theories and empirical data, in order to reach reliable conclusions.

1.2.4.2 Maintenance regime types

Maintenance refers to all activities and resources that are employed to ensure assets specified performance and condition within a given time frame (BSI, 2004). Over the years, maintenance has moved away from the traditional definition of repair failed items to condition and predictive based maintenance (Tsang *et al,* 1999d). In this research, the maintenance terminology standard SS-EN 13306:2001a, a European terminology standard approved by CEN (European Committee for Standardisation), and the BSI (British Standard Institute) has been mainly used. In other areas of the research, the British standard of definitions of terms in maintenance was used. The terminology standard (SS-EN 13306, 2001b) defines maintenance as a combination of all technical, administrative, and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function.

Retain it in or ‘restore it to’ indicate that there are two main strategies to perform maintenance (Figure 1-7). The first is a preventative approach (retain it in); where maintenance is carried out to prevent asset failure. The second is a corrective approach (restore it to); where maintenance is carried out after the asset fails. The maintenance approaches are described (Figure 1-7).

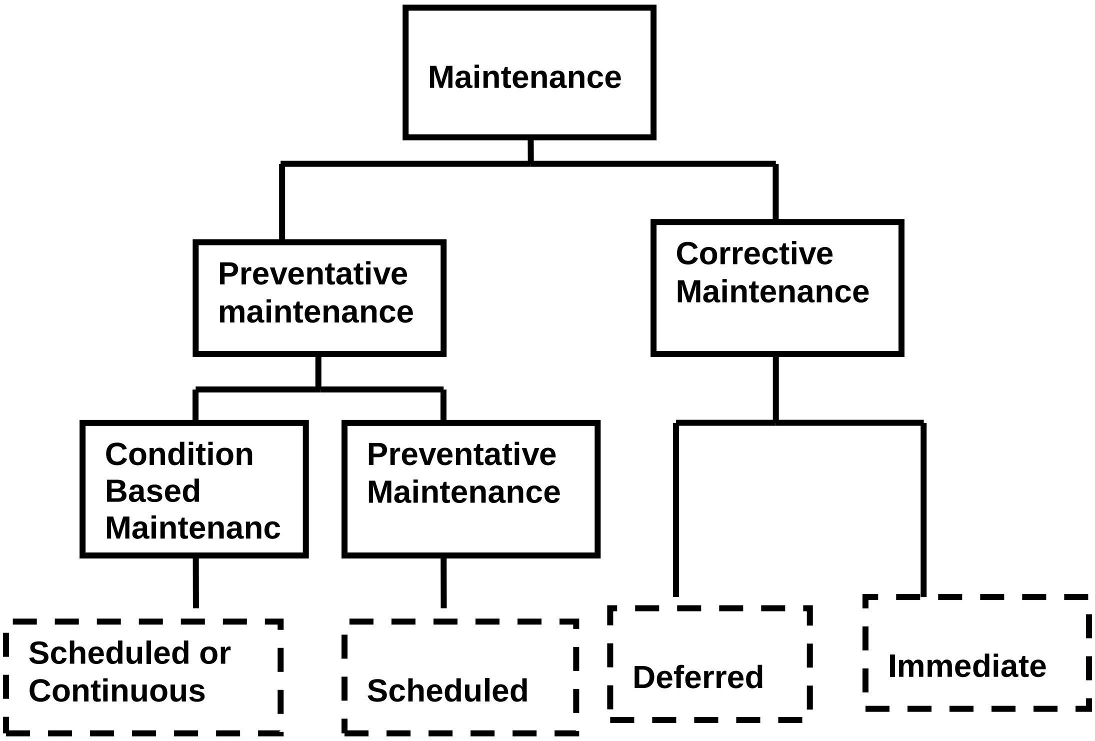


Figure 1-7: Asset maintenance types

a) Corrective Maintenance

Corrective maintenance is approach where maintenance is carried out when an asset fails. The maintenance is carried out after a breakdown and is intended to restore the function of the asset (BSI, 2008a).

Corrective maintenance is not suitable for critical assets where consequences of failure can be fatal. For example, where failure is a safety risk, where the repair work will lead to long unavailability and failure cannot be identified before consequences are evident (BSI, 2008b). Corrective maintenance, under normal circumstance, can be repair work or component replacement. Minimal repair means that the failed asset is restored back its functioning state. The failure rate is said to remain the same as it was immediately before the failure occurred. This assertion is quite subjective because it is not easy to know the exact failure rate before the asset failed. The item can only be said to have been restored to an “as bad as old” state (Høyland and

Rausand, 1994). If the item is restored to “as good as new” state, the failure rate can sometimes be higher than it was before the breakdown. This is referred to as a renewal process or sometimes a maximal repair. This corrective maintenance type is on the high end of repair. Most corrective maintenance actions tend to be in between (imperfect repair) (Wang and Zhang, 2009).

Corrective maintenance regime is widely used by water utilities to maintain their assets. It is mainly applied for assets that have a very short life, such as electrical assets and some very small pumps. Preventative maintenance is not carried out on such assets.

b) Preventative maintenance

Preventative maintenance is maintenance carried out at predetermined, and usually, equal intervals. It is aimed at preventing the degradation of the asset condition (BSI, 2008b). Predetermined intervals means preventative maintenance is carried out in at established intervals of time. The number of hours the asset has been in operation is sometimes used to determine the preventative maintenance intervals. The condition of the asset is not always assessed before the maintenance is carried out.

Preventative maintenance regime is widely used by water utilities to maintain their assets (Wang and Zhang, 2006). It is mainly applied for assets that have a reasonable length of life and of high value. These include pipes, some very large water pumps, and assets that are very expensive to maintain and replace. The limitation is that maintenance intervals are sometimes not reviewed and supported by performance data. Another category of preventative maintenance is condition based maintenance.

b.i) Condition based maintenance (CBM)

Condition based maintenance is defined as maintenance actions based on actual asset condition (Mitchell, 1998). It is a set of maintenance actions based on real-time assessment of asset condition. It is an effort to improve system reliability and availability (Moya and Vera, 2003). For this research, the definition in SS-EN 13306 was adopted, where condition based maintenance is defined as preventative maintenance based on the performance of the asset (SS-EN 13306, 2001d).

The performance and parameter monitoring may be scheduled on ad-hoc basis or continuously. Condition based maintenance utilises condition monitoring tools to analyse the current state of an asset. Maintenance schedules are then set up for the future.

Condition based maintenance is also preventative since maintenance actions prevent future failures. Condition assessment in condition based maintenance can be carried out after a given numbers of operations continuous or at specific time intervals. An assessed item can be a component, whole asset or subsystem (Parida and Kumar, 2009c). The research adopts the same term ‘item’ for the definition of an ‘asset’ and the terms are sometimes used interchangeably in the thesis.

Condition-based maintenance regime is widely used by water utilities to maintain their assets. The asset condition assessments are sometimes limited to strategic planning purposes and limited data is collected on the asset condition. Hence, there is often sparse data for asset condition assessment. It is mainly applied for assets that have a reasonable long life and assets that are very expensive to maintain and replace.

b.ii) Predictive maintenance

Predictive maintenance is based where maintenance is carried out to prevent future failure or bad state of degradation. Degradation levels can be predicted by considering one or more factors; such as, usage intensity or time (BSI, 2008d). According to Parida and Kumar (2009d), predictive maintenance is carried out following an asset condition forecast, which is derived from the evaluation of a possible future condition of the item.

Predictive maintenance regime is used by water utilities to maintain their assets. It is mainly applied for assets that have a reasonable long life and are very expensive to maintain and replace. The limitation is that some of the decisions when applying predictive maintenance are based on standard procedure and not informed by performance data. This is sometimes due to lack of data, but sometimes it is standard practice.

Maintenance costs and asset type usually affect the decisions what asset groups are maintained with the different maintenance strategies. Some components benefit from a preventative maintenance approach, others form corrective strategy. For items that are capital-intense, critical to production and safety, a predictive maintenance approach usually benefits those assets that are critical in terms of safety and productivity.

Methods for deciding on the most appropriate maintenance approach for each asset group were suggested by Al-Najjar and Alsyouf (2003b). The scheduling of the predictive maintenance actions can be carried out per asset group or use of data analysis databases. Advanced maintenance system can be required to capture data in real time and analyse it, giving predicted asset conditions. Maintenance schedules can then be set according to the predicted conditions.

1.2.4.3 Stages in selecting and implementing a maintenance regime

Most maintenance regime selection methods are based on availability of data assumption and multi-criteria analysis, which considers different criteria in selecting the appropriate maintenance regime. Kotter (1996a) indicates that successful implementation of change in organisations has to follow two important patterns; firstly, the change has to follow a multi-step process that motivation for participants. The success of an implementation of an innovation is in relation to the time between the generation of the innovation to the implementation of it, and that success is achieved if this time is kept to a minimum. These implementations are only successful in companies that follow a very strict implementation strategy (Vrakking, 1995a). He also presented the four phases that the innovation process should follow; generation of ideas, initiation, implementation and incorporation.

Vrakking (1995b) presents eleven practical implementation factors including; training, learning process, top-down and bottom-up communication, research approach, support from leaders, prevent “group think”, create support and line management must support the change. Kotter and Cohen (2002) point out that empowerment to remove barriers is one very important aspect when it comes to implementing change.

Spare (2001) states that condition based maintenance programmes should be designed and implemented through: well-defined goals and a cost-effective investment strategy. Reichard *et al.* (2000) give a more technically oriented aspect by stating that the implementation of such systems requires a combination of sensor data fusion, feature extraction, classification, and prediction algorithms. Hardman (2009) point out that the human aspect cannot be forgotten in condition based maintenance technology by stating. Correct analysis and diagnosis based on the collected information is essential for right maintenance decisions. Participation and intervention of the human experts are necessary for all these activities. There is no international standard on managing a predictive maintenance program, little less to say no standard for implementing it either (Carnero, 2003).

A predictive maintenance (PdM) program should be established focusing on: (1) goals, objectives, and benefits; (2) functional requirements; (3) selling predictive maintenance programmes; (4) selecting a predictive maintenance system; (5) database development; and (6) getting started. No model with steps in time is presented though. Steps in predictive maintenance;

- In the first section on goals, objectives, and benefits, focus is on the importance of creating a reference or baseline dataset of the existing maintenance costs and other parameters that will be affected through the introduction of predictive maintenance.
- The second section (functional requirements) focuses on the importance of management support and dedicated personnel, efficient data collection and analysis procedures, and the initial creation of a database.
- The third section (selling predictive maintenance programmes) focuses on keys to success. This involves formulating a program plan, knowing the

audience, creating an implementation plan, taking a holistic view, and getting acceptance by management. The most important part of the establishment is to construct a concise, detailed program plan. The plan must include well-defined goals and objectives that will be achievable within the expected time limit. The plan should also be of a phased approach so that the capital investment can be spread out over a period of time. Also mentioned is the importance of assigning responsibility to specific individuals and that there must be a start date and an end date for all research.

- The fourth section (selecting a predictive maintenance system) focuses on system requirements. These include software, hardware, automated data acquisition, reliability, cost, training and support. The fifth section (database development) focuses on data acquisition frequency, analysis parameters and defining alarm limits and alerts.

1.2.4.4 Literature summary and conclusions

Companies are constantly under pressure to produce and deliver more at lower costs and at less risk to people and the environment by regulatory requirements (regulated companies) and competition (private companies). Asset management cost minimisation in water utilities is mainly due to regulatory requirements. The literature suggests that asset condition assessment for maintenance and replacement is often undertaken in an ad-hoc manner by water utilities (Marlow 200d). This is usually due to lack of data for developing explicit models to support maintenance decision-making. The manner, cost and effort involved in data collection mean that asset-specific data collection could be challenging. It is a matter of further research to develop tools and models that make it easy to assess asset performance using all possible indicators at low costs and with simplicity. The literature also suggests that maintaining and rehabilitating large water infrastructure systems requires continuously improving asset management practices and the development of decision support tools.

Much progress has been made in the understanding of asset deterioration processes and failure modes; however the knowledge gap challenge still remains (Rajani and

Kleiner, 2004c). Most utilities have an inadequate understanding of their assets and have data constraints. The data that is available with the water utilities is often incomplete. There are often poor records about the condition or even location of the underground assets (Hobson, 2005a). Wood (2007c) reported that the data collection challenges mainly consist of missing and conflicting historical data, poor reliability of existing data and non-computerised information. The tacit knowledge and experience regarding assets and asset failure held by utility staff is considered to be important and recommended to be utilised for asset maintenance decision making. The experience of Oakes and Phillips (2006a) was that “better and perfect data will take many years to collect and assimilate, however if the available data is used correctly, it is of a standard to improve asset maintenance decisions”. Mather (2006) reported that in his experience, “many predictive asset maintenance programmes are based on approximately 30% empirical data and 70% expert knowledge. Albee (2005) stated that the quality of the decisions taken by water utility managers or the water policy planners reflects their professional judgment on the basis of experience that they have gained because of working in this sector. However, guesswork and chance too often influence key choice.

This research therefore, emphasizes the use of asset condition assessment within the context of established and emerging asset management principles, one of which is to forecast assets life based on performance - with condition assessment made possible in real-time through efficient performance data management. The results will mean that maintenance must be justified on current and predicted probability of asset failure and the resultant consequences for costs arising. The asset grades will be performance based, which will improve precision in forecasting asset remaining life and associated maintenance costs allocation. The literature also suggests that some water utilities do not adequately follow expert elicitation protocol (Whang and Zhang *et al*, 2008d). The research explores how protocol affects the quality of experts’ assessments.

1.3 Review of approaches considered for research methodology

Different approaches were considered for the research methodology. Only approaches that could be used where limited or no data existed were considered and they are reviewed be

1.3.1 Condition assessment and maintenance effectiveness methodology approaches.

This section provides an analytical overview of the tools for uncertainty assessment that were considered for use in developing the asset condition and maintenance effectiveness approaches. Uncertainty analysis approaches were examined because the research sought to assess asset condition where there is sparse or no data, which are uncertain quantities compared to cases where data are available.
The tools covered were:

- Error propagation equations (Tier 1)
- Sensitivity analysis
- Monte Carlo analysis (Tier 2)
- NUSAP (Numeral Unit Spread Assessment Pedigree)
- Expert elicitation

This section does not analyse an exhaustive list of tools that may be used in assessing uncertain quantities for assets condition assessment, maintenance effective assessment and selecting maintenance regimes. The tools described in this section may exist in many different flavours in practice and this thesis does not cover all of them. The selection discussed covers different sorts and locations of uncertainties presented in asset condition assessment. Practices and research in the fields were also examined.

This chapter provides a tool-by-tool description. For each tool, types of uncertainty addressed, description of the tool, resources required to use the tool, goals and use of the tool, strengths and limitations of each tool and, suitability for use in the research

1.3.1.1 Error propagation equations

The error propagation equation is used to assess how quantified uncertainties in model inputs are propagated in model calculations. This is done in order to produce an uncertainty range in a model. An example of the error propagation equations were used by the Intergovernmental Panel on Climate Change (IPCC), which provides good practice guidance and uncertainty management in national greenhouse gas inventories (IPCC, 2000a). The IPCC distinguishes two levels of comprehension for quantitative uncertainty assessment in emissions monitoring, which they named TIER 1 and TIER 2. TIER 1 uses the error propagation equation (Bevington and Robinson, 1992) to estimate error propagation in calculations whereas TIER 2 consists of a full Monte Carlo analysis. The method using the classic analytical equations for error propagation has now become widely referred to as the TIER 1 approach.

Goals and use of error propagation equations

The goal of the error propagation equations is to assess how quantified uncertainties in model inputs are propagated in model calculations to produce an uncertainty range in a given model outcome of interest. For the most common operations, the error propagation equation can be written as:

$$\sigma E^2 = \sigma A^2 F^2 + \sigma F^2 A^2$$

Where σE^2 is the product of activity variance, σA^2 is the variance of the activity data, and σF^2 is the variance of the product factor. On the other hand, A is the expected value of the activity data, and F is the expected value of the product factor. According to Chave *et al* (2004), the conditions for use of the error propagation equation include that the uncertainties are relatively small (the standard deviation divided by the mean value being less than 0.3). The uncertainties should also have no significant covariance and should have normal distributions.

TIER 1 addresses statistical uncertainty (inexactness) in inputs and parameters and estimates its propagation in simple calculations. It does not treat knowledge uncertainty separately from variability related uncertainty (Mandel, 1984). It provides no insight in the quality of the knowledge base. The error propagation equations can be applied on an ordinary scientific calculator or using a spread sheet.

Assessment for usage in the research

The method requires very little resources and skills. It can be relatively quick, but can be too subjective.

Typical *weaknesses* include that the error propagation equation has a limited domain of applicability (e.g. near-linearity assumption). The basic error propagation equations cannot cope well with distributions of other shapes than normal. It leads to a tendency to assume that all distributions are normal. The method cannot easily be applied in complex calculations.

This method was not adopted for the research because assets' life and condition are not known to have a normal distribution only, but other types of distribution. Assets assume different distributions through their life. Conditions of assets widely differ at these life stages. The method also tends to ignore the model boundaries and structure, which are necessary in assessing assets condition as they are bounded by the number of performance parameters used.

1.3.1.2 Monte Carlo Analysis

Monte Carlo Simulation is a statistical numerical technique for analysing error propagation in model calculations (Morgan and Henrion, 1990). Monte Carlo analysis is used to trace the structure of the distributions of model output resulting from specified uncertainty distributions of model inputs. The distribution is mapped by calculating the results for a large number of random draws from input data and parameters of the model. Monte Carlo analysis requires the specification of probability distributions of all inputs and parameters, as well as the correlations between them.

Uncertainty addressed

Monte Carlo analysis typically addresses statistical uncertainty in inputs and parameters. It can also be used for assessing model structure uncertainty (Vose, 2000). This is accomplished by introducing one or more parameters to switch between different model structures with probabilities attached for each position of the switch. Two-dimensional Monte Carlo Analysis allows for a separate treatment of knowledge and variability related uncertainty. The two-dimensional mode provides some insight into the quality of the knowledge base.

Selecting input data and distributions for use in Monte Carlo analysis

The first step is to conduct preliminary sensitivity analyses or numerical experiments to identify model structures and input assumptions (Saltelli, 2008a). Parameters that make important contributions to the assessment and its overall uncertainty should then be assessed. The data can then be used to inform the choice of input distributions for the model parameters. This could be determining if there is any mechanistic basis for choosing a distributional family of the likely shape of a distribution. The basic methods of sampling should be followed when obtaining empirical data to develop input distributions for model parameters. Areas of uncertainty should be identified and included in the analysis, either quantitatively or qualitatively.

Typical *strengths* of Monte Carlo simulation;

Monte Carlo is capable to cope with any conceivable shape of probability density function and can account for correlations (Cavaliere *et al,* 2003). Secondly, it provides comprehensive insight into how a specific uncertainty in inputs propagates through a model. It also allows different inputs uncertainties and interdependencies to be considered.

Monte Carlo assessment is limited to those uncertainties that can be quantified and expressed as probabilities. Secondly, one may not have any reasonable basis on which to ascribe a parameterised probability distribution to parameters. Lastly, the interpretation of a probability distribution of the model output by decision makers is not always straightforward. There is no single rule arising out of such a distribution that can guide decision-makers concerning the acceptable uncertain quantity.

1.3.1.3 Sensitivity analysis

Sensitivity analysis (SA) is used to determine how a given model depends upon the information fed into it. It assesses how the variation in the output of a model can be apportioned to different sources of variation (Saltelli *et al,* 2004). The variations in the output can be apportioned qualitatively or quantitatively.

Use of sensitivity analysis

The goal of sensitivity analysis is to understand the quantitative sources of uncertainty in model calculations. It is also to identify sources that contribute the largest amount of uncertainty in a given outcome.

Types of sensitivity analysis include;

• *Global SA* – investigate the effects on the outcomes due to variation in the inputs, as all inputs are allowed to vary over their ranges (Saltelli *et al,* 2008b). The Morris algorithm is highly considered and recommended for its computational efficiency: (Morris, 1991). The typical case to apply this tool is if there are many parameters.

• *Local SA* - investigates the effect of the variation in each input factor when the others are kept at some constant level. It assesses the rate of change of the output, relative to the rate of change of the input.

• *Screening SA* - is a general investigation of the effects of variation on the inputs (Oke and Charles-Owaba, 2006). The main purpose of screening methods is to identify a short list of the most important sensitive factors so that resources can be used in the most efficient way.

Advantages and disadvantages

Some identified *strengths* of sensitivity analysis include;

It provides information about potential influences of different changes in inputs. It helps discriminate parameters according to importance for the accuracy of the outcome. Sensitivity analysis is also generally easy to use.

Identified *weaknesses* of sensitivity analysis include;

It does not assess the likelihood of specific values of the parameters occurring. Sensitivity testing does not provide information about dependencies between parameters and probabilities that certain values will occur together. It typically addresses statistical uncertainty in inputs and parameters. It is, however, also possible to use this technique to analyse sensitivity to changes in model structure. It does not treat knowledge uncertainty separately from variability related uncertainty. It provides no insight into the quality of the knowledge base.

The major reason for not using this methodology in the research was because it does not establish quality assurance in its application. This was deemed to weaken the value of the results of the research. Also, directly observed data were not available and the parameter or variable were estimated based on subjective assessments. Parameters or variables determined by such indirect methods have a weaker empirical basis and will generally score lower than those based on direct observations.

1.3.1.4 Numeral, Unit, Spread, Assessment, and Pedigree (NUSAP)

Numeral, Unit, Spread, Assessment, and Pedigree (NUSAP) is a notational system proposed by Costanza *et al* (1992), which provides an analysis and diagnosis of uncertainty in science for policy. It caters for both qualitative and quantitative dimensions of uncertainty. It provides peer review by different stakeholders.

1.3.1.4.1 Goals and use of NUSAP

The goal of Numeral, Unit, Spread, Assessment, and Pedigree (NUSAP) is to discipline and structure the critical appraisal of the knowledge base on quantitative policy relevant scientific information. The basic idea is to qualify quantities using the five qualifiers of the NUSAP acronym: Numeral, Unit, Spread, Assessment, and Pedigree. NUSAP has extended the statistical approach to uncertainty with the methodological and epistemological dimensions. This is due to adding expert judgment on assessment and systematic multi-criteria evaluation. Flexibility is ensured by providing a separate qualification for each dimension of uncertainty

(Boone *et al*, 2010). NUSAP can convey of meaning of quantities concisely and clearly than only statistical methods.

There are five qualifiers used in NUSAP (Numeral, Unit, Spread, Assessment, and Pedigree). The first is numeral; this is usually an ordinary number; but when appropriate it can be a more general quantity. Second is unit, which may also contain extra information, as the date at which the unit is evaluated. The middle category is a spread, which generalises from the variance of statistics to the random error of experiments. The other two qualifiers constitute the qualitative side of the NUSAP expression. Assessments express qualitative judgments about the information. In the case of statistical tests, this could be the significance level. In the case of numerical estimates, the qualifier could be optimistic or pessimistic (Craye *et al,* 2009).

The P for pedigree conveys an evaluation account of the information production process. It also indicates different aspects of the scientific status of the knowledge used and the underpinning numbers. It is expressed by means of a set of pedigree criteria to assess these different aspects. Assessment of pedigree involves qualitative assessments.

1.3.1.4.2 Source of uncertainty

The different qualifiers in the NUSAP system address different types of uncertainties. The Spread qualifier addresses statistical uncertainty in quantities (input data and parameters). The assessment qualifier typically addresses unreliability (van der Sluijs, 2002). The pedigree criterion further qualifies the knowledge base by providing detailed insights in its specific weaknesses or strengths.

1.3.1.4.3 Strengths and weaknesses

Typical *strengths* of NUSAP are:

It identifies the different types of uncertainty in quantitative information and enables them to be displayed in a clear and transparent format. This allows easier assessment of uncertainties. It is also flexible and can be used on different levels of comprehensiveness. It covers each pedigree criterion, combined with a full Monte

Carlo assessment. NUSAP enables a more effective assessment of quantitative information (Craye *et al,* 2005).

Typical *weaknesses* of NUSAP include;
There is not yet a system of quality assurance in its applications and no guidelines for good practice. The scoring of pedigree criteria is to a certain degree subjective. The choice of experts to do the scoring is also a potential source of bias. The method is applicable only to simple calculations with small numbers of parameters.

The major reason for not using this methodology in the research was because directly observed data were not available. The parameters or variables are estimated based on partial measurements or calculated from other quantities. Parameters or variables determined by such indirect methods have a weaker empirical basis.

1.3.1.5 Expert elicitation

Expert elicitation refers to a structured approach to synthesize subjective judgments of experts on a subject where there is uncertainty due to insufficient data (Slottje, 2008a). An expert is a person who has special skills or knowledge in a particular field. A judgement is the forming of an estimate or degree of belief about a subject from information presented to or available to the expert. Expert elicitation is widely used by water utilities in risk analysis to quantify uncertainties in cases where there is no or very little direct empirical data available to infer on uncertainty.

Goals of expert elicitation

Expert elicitation is typically, applied in situations where there is scarce or no empirical data for a direct quantification of uncertainty. It is applied where it is necessary to obtain verifiable and defendable results (Goossens, 2006).

1.3.2 Maintenance regime selection approaches

Maintenance regimes, as outlined and discussed in Chapter 1 have to be implemented in a consistent and planned manner. The selection of a maintenance regime for an asset group is important as it should suit the respective asset group. The following sections discuss some of the methods considered for selecting a maintenance regime where no data exist in an organisation. Single (Section 2.3.1) and multi-criteria (Section 2.3.2) approaches were considered.

1.3.2.1 Single criterion maintenance regime selection approaches

It is very important to make distinction between decision-making processes, whether they involve a single or multiple criteria. A decision problem may have a single criterion or a single aggregate measure, such as cost. The decision can then be made by determining the alternative with the best value of the aggregate measure. The classic form of an optimisation problem has the objective function as the single criterion. The constraints are the requirements on the alternatives. Depending on the form and functional description of the optimisation problem, different optimisation techniques can be used. The technique could be linear programming, nonlinear programming and discrete optimisation (Hermans and Erikson, 2007).

The case when there are a finite number of criteria, but the number of the feasible alternatives are infinite, is referred to as multiple-criteria optimisation. Techniques of multiple criteria optimisation can be used when the number of feasible alternatives is finite but they are given only in implicit form (Tseng and Li, 2006). This research focuses on decision making problems when the number of the criteria and alternatives is finite, and there are several alternatives. Problems of this type are referred to as multi-attribute decision making problems.

1.3.2.2 Multi-criteria approaches

1.3.2.2.1 Multi-attribute Utility Theory (MAUT) methods

In most of the approaches based on the Multi-attribute Utility Theory (MAUT), the weights associated with the criteria can properly reflect the relative importance of the criteria only if the scores are from a common, dimensionless scale. The basis of

MAUT is the use of utility functions. Utility functions can be applied to transform the raw performance values of the alternatives against diverse criteria, both factual (objective, quantitative) and judgmental (subjective, qualitative), to a common, dimensionless scale. In the practice, the intervals [0,1] or [0,100] are used for this purpose. Utility functions play another very important role: they convert the raw performance values so that a more preferred performance obtains a higher utility value. A good example is a criterion reflecting the goal of cost minimization. The associated utility function must result in higher utility values for lower cost values (Marzouk, 2006).

A normalisation is usually performed on a nonnegative row in the matrix of the entries. The normalisation can be achieved by dividing by the sum of the entries in the row, by a desired value greater than any entry in the row, or by the maximal element in the row (Phillips, 2007).

1.3.2.2.2 Simple Multi-attribute Rating Technique (SMART)

Simple multi-attribute rating technique (SMART) is the simplest form of the MAUT methods. The ranking value of alternative is obtained as the weighted algebraic mean of the utility values associated with it (Collins et al, 2006). The weight for each of the criteria should reflect its relative importance to the decision. The criteria are ranked in order of importance and 10 points are assigned to the least important criterion. The next-least-important criterion is chosen, more points are assigned to it, and so on, to reflect their relative importance. The final weights are obtained by normalizing the sum of the points to one.

The attributes must reflect the range of the utility values of the alternatives (Busacca and Padula, 2005). They proposed a variant (SMARTS) that in the course of the comparison of the importance of the criteria also considers the amplitude of the utility values. It considers the changes from the worst utility value level to the best level among the alternatives.

1.3.2.2.3 Generalized means

In a decision problem the vector x = (x1,...,xn) plays a role of aggregation, taking the performance scores for every criterion with the given weight into account. This means that the vector x should fit into the rows of the decision matrix in the best possible way. Mészáros and Rapcsák (1996) introduced an entropy optimisation problem to find the vector x of best fit. The optimal solution is a positive multiple of the vector of the weighted geometric means of the columns. The generalised mean constitute a reasonable and theoretically established system of ranking values.

1.3.2.2.4 Outranking methods

The principal outranking methods assume data availability broadly similar to that required for the MAUT methods. They require the specification of the criteria and alternatives. Vincke (1992) provides an introduction to the best known outranking methods. The two most popular families of the outranking methods, the Elimination and Choice Expressing Reality (ELECTRE) and the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) methods are briefly described.

1.3.2.2.5 The Elimination and Choice Expressing (ELECTRE) methods

The Elimination and Choice Expressing Reality (ELECTRE) methodology is based on the concordance and discordance indices (Mousseau, 1999). Assuming that the sum of the weights of all criteria equals to 1, one can start from the data of the decision matrix. For an ordered pair of alternatives (A*j, Ak)*, the concordance index is the sum of all the weights for those criteria where the performance score of A*j* is at least as high as that of A*k*. The concordance index lies between 0 and 1 (Ngo, 2002).

A ranking that defines the set of alternatives is established. It considers the set of all alternatives that outrank at least one other alternative. The ELECTRE I method is used to construct a partial ranking and choose a set of promising alternatives. ELECTRE II is used for ranking the alternatives. In ELECTRE III an outranking degree is established, representing an outranking creditability between two alternatives. Figueira *et al* (2005a) provides details about further members of the ELECTRE family.

1.3.2.2.6 The Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) methods

The Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) introduces a decision table (Amponsah *et al*, 2012). In this method, the scores are not necessarily normalized into a common dimensionless scale. It is assumed that a higher score value means a better performance. It is also assumed that the weights *wi* of the criteria have been determined by an appropriate method. Figueira *et al* (2005b) gives a review of the PROMETHEE methods.

Some ideas of AHP can also be applied in the PROMEETHE methodology. Macharis *et al* (2004) proposed to use the pair-wise comparison technique of AHP to determine the weights of the criteria in the PROMEETHE method. They used a tree-structure to decompose the decision problem into smaller parts.

1.3.2.2.7 The Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) was proposed by Saaty (1980a). Subjective assessments of relative importance are converted to a set of overall scores or weights in the method. The AHP is one of the widely applied multi-attribute decision making methods. The methodology is based on pair-wise comparisons of how important criterion C*i* relative to criterion C*j*. This is used to establish the weights for the criteria and the alternatives (Cheung and Suen, 2002).

The weights of the criteria are derived by first assuming that the *m* criteria are not arranged in a tree-structure. For each pair of criteria, the decision maker is required to give a pair-wise comparison rating of the relative importance of the two. The ranking of the pair can use the following nine-point scale. The rating expresses the intensity of the preference or importance for one criterion over another;

1= Equal importance.

3= Moderate importance.

5= Strong or essential importance.

7= Very strong importance.

9= Extreme importance.

1.3.2.3 Research method summary

The research methods of interest were those that use multi-criteria approaches and those that can be applied where limited data exists. Chapter 2 presents the methods applied in this research in detail – detailing the rationale for selecting the methods. Expert elicitation was used to develop models for decision support where there was limited data. The Analytical Hierarchy Process was also used in selecting a maintenance regime where there was limited data.

2 RESEARCH METHODOLOGY

2.1 Introduction

Maintenance research is traditionally viewed from an operations research perspective. Such operations are usually in manufacturing industries where assets or components' performance data are captured in large databases. Some of the operations data are captured in real-time, such as in the aerospace industry (Dermici, 2008). The methodology in this research is aimed at designing new approaches for asset condition assessment, maintenance effectiveness assessment and maintenance policy selection when there is uncertainty due to lack of data in order to support asset maintenance decision making.

Decision making is the process of identifying and choosing alternatives based on the values and preferences of the decision maker. Reliable information is important for effective decision making. Where there are alternative choices, choosing the one that best supports organisational aims, values, goals and objectives is key (Vreeker, *et al*, 2002). Decision making should start with the identification of the decision maker(s) and stakeholder(s) in the decision, reducing the possible disagreement about problem definition, requirements, goals, and criteria (Bouyssou *et al,* 2000). This chapter outlines the research methodology that was used within this research. Section 2.1 gives the introduction if the research methodology. Section 2.2 discusses the research methodology developed for assessing asset condition. Section 2.3 presents the research methodology developed for assessing maintenance regime selection. Section 2.4 presents the methodology developed for selecting an asset specific maintenance regime, and Section 2.5 presents the summary of the assessed methods.

2.1.1 Research approach

There are several approaches to conducting research. Some of the main approaches are analytical, the system, and the actor's approach (Craig *et al,* 2001). The analytical approach strives to objectively explain reality. The researcher seeks to explain causes of phenomena or results. The system approach also considers reality to be objective, but differently constructed. The system approach strives to explain a situation by applying it into a comprehensive perspective (Holland, 2009. The actor's approach suggests that it is difficult not to influence the phenomenon being studied and that reality exists as a social construct and is not independent of the researcher (Wright, 2009).

Both technical and organisational aspects in maintenance management were investigated within the water utility industry. The technical aspect was the assessment of assets condition and the organisational aspect focused on maintenance regimes. The system approach was applied in conducting the research because its reality is constructed as components with mutual dependences and assets condition assessments explore different performance indicators with or without dependencies. The analytical approach was used in developing a strategy to select a maintenance regime where no data exist to support such decision. The actor's approach was found to be not appropriate because much emphasis is put on human behaviour aspect. It would be suitable for assessing human contribution in maintenance quality. Asset condition assessment focused on evaluating the condition of assets where there was no data in the research. The research also focused on over-ground assets of a water distribution system.

2.1.2 Data collection

Case studies, comparative studies, literature reviews, questionnaires and interview surveys were used in developing the research methodology and data collection. The choice of research methods was based on both theoretical and empirical studies. Theoretical studies were performed in order to establish the latest developments in asset condition assessments and to evaluate what data to collect for testing the methods developed to meet the research objectives.

a) Case Studies

According to Stake (2006a), a case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident. A case study is preferred when 'how' and 'why' questions are being posed. One prejudice to case study research is that it is impossible to get general results. The results can be generalized to theoretical propositions, but cannot be generalised to populations (Stake, 2006b). In this research, case studies were used to gather empirical data by conducting focus group surveys. A case study was also used to apply and test the developed models. This is because the approaches developed for decision support in asset management in this study did not require data. Data had to be collected through real practice cases. Cases studies are useful in cases where the researcher is seeking a holistic view of complex instances, the research observation, or searching for patterns (Imas, 2009a). The researcher could be asking 'why' 'what' or 'how' type of questions.

b) Surveys

Surveys are suitable when answers to questions about views, feelings, opinions, knowledge are being sought (Fowler and Floyd, 1995). The result of a structured survey can be quantitative or qualitative. They favour how much type of research questions (Imas, 2009b). Surveys in questionnaires and focus groups were used in conjunction with interviews for collecting data to assess asset condition and maintenance quality. They were also used for collecting data for applying and testing the maintenance selection approach developed. Surveys were used in order to collect primary data for the study. Surveys were used because the developed methods relied on people/expert opinions, which require focus group survey meeting (O' Hagan, 2006). Focus groups of expert engineers were organised where data and information was elicited by using informal discussions and formal questionnaires. Surveys are widely used in water utility as Ofwat policies are based on consultations with stakeholder (Ofwat, 2010) and by other asset management organisations in carrying out consultations with their partners and stakeholder (Environment Agency, 2005).

c) Literature reviews

All research should be based on, or take into account, previous research that has been undertaken within the same subject (Bryman, 2008a). Literature reviews are conducted by investigating a broad application of the subject under investigation and narrowed down to be more specific at later stages of research. Literature studies were conducted throughout the research on asset condition assessment, maintenance effectiveness assessment and maintenance regime selection. This was to understand other authors' research in the field and compare this research with others' work.

d) Comparative studies

Comparative studies or just simply comparison is used as a research method within several scientific fields (Bryman, 2008b). The method compares different events, products, or subjects. For example, cases may be both similar and different in other aspects, and the goal is to find out why the cases are different (Bryman, 2008c). Two different styles are available when performing comparative research; the descriptive and the normative. The descriptive style aims at explaining and describing the differences between the cases. The normative style focuses on improving the state of the case being compared. In this research, comparative studies were carried out for results obtained from different subjects on the same enquiry. Improving the approaches found in the case-studies was the aim of developing new and improved asset condition and maintenance effectiveness approaches. Comparative studies were mainly used in the literature review in this research because a background understanding was necessary for the research subject.

e) Interviews

When looking for answers about views, feelings, opinions and knowledge from people, interviews can be used. Interviews can be structured or unstructured. McNamara (1999) describes different types of structures for interviews; structured semi-structured and unstructured interviews. The structured interview gives the opportunity to answer questions regarding 'how much' of a phenomenon. Unstructured interviews give the interviewee a lot of freedom to decide what to talk about. The interviewer starts the dialogue but steps back to listen. The unstructured interviews were mainly used to gain both qualitative and quantitative experts' opinions regarding asset condition, maintenance quality and maintenance regime preference. Printed questionnaires were given to the experts during the focus group sessions. Informal verbal interviews were also conducted during the elicitation sessions.

f) Pilot studies

A pilot study is a small scale preliminary study conducted in order to evaluate feasibility, time, cost, adverse events, and effect size (statistical variability) in an attempt to predict an appropriate sample size and improve upon the study design prior to performance of a full-scale research project (Hulley, 2007).

Although sometimes not relevant for case studies, the pilot study was done for this research because the case study involved sampling, questionnaires and needed feasibility assessment that needed testing before being applied. Section 2.2.2.6 details the method applied in carrying out the case study.

2.1.3 Research process

Each type of empirical research follows a research design. Research design as an action plan for getting from here to there, with "here" meaning from the initial sets of questions and "there" meaning some sets of conclusions (Tourangeau, 1999). This section explains the research process, i.e. how the research has been performed and how the approaches for meeting the objectives of the research were developed.

Literature studies were conducted throughout the research. In the beginning, more general literature studies were performed as the research questions were being formulated. As papers and reports were being written, more directed literature studies were performed. The main literature included books and journals publications (including doctoral dissertations). Conference proceedings, journals, and in some cases, internet publications were also reviewed.

The methodology was developed through literature search and research about current industry practices in all three areas of the research. Research about approaches for assessing asset condition where no data exists was conducted. A new approach for assessing assets condition was then developed considering the findings of water utility current practices and literature findings. The same workflow was adopted for maintenance effectiveness assessment (objective 2) and maintenance regime selection (objective 3) for cases where there is sparse data. The following sections detail the methodology for each of the major part of the research. Section 2.2 discusses the methodology followed in developing the asset condition and maintenance effectiveness assessment approaches. Section 2.3 addresses the maintenance regime selection approach. This research focused on approaches that consider sparse or no data situations or uncertainty addressing approaches.

2.2 Asset condition assessment methodology

The sustainability in asset management can be said to be; capital and operating costs (economic), customer service (social) and habitat pollution (environmental). Only the economic aspect of sustainability was the focus of the study. The cost focused on the constraints imposed by the need to balance maintenance costs and return on assets.

The study also explored the use of asset performance variables in assessing the condition of assets. It was outside the scope of the study to explore all of the condition impacting factors and hence, only certain variables influencing the asset conditions were explored. The interest was only in indicating the asset condition and not particularly to diagnose the causes of the conditions of the assets.

Expert elicitation is the method used to accesses the assets condition in the research. The method was adopted because a tool for maintenance decision support where there is limited data was developed. Expert elicitation was found to work well as a tool elicit expert reliable opinions to support limited data. The other reason for using expert elicitation was because the case study water utility was personnel was familiar with it and intended to develop it further in the organisation.

2.2.1 Expert elicitation

Expert elicitation refers to a systematic approach to synthesize subjective judgments of experts on a subject where there is uncertainty due to insufficient data, when such data is unattainable because of physical constraints or lack of resources. It seeks to make explicit and utilizable the unpublished knowledge and wisdom in the heads of experts, based on their accumulated experience and expertise, including their insight in the limitations, strengths and weaknesses of the published knowledge and available data. An expert elicitation procedure should be developed in such a way that minimizes inherent biases in subjective judgment and errors related to that in the elicited outcomes.

Expert elicitation has been used in many applications of engineering science. The areas of reliability and maintenance are known for their lack of data. Obtaining the component lifetime distributions is one of the major bottlenecks for implementation of maintenance optimisation (van Noortwijk *et al*, 1992a). Expert elicitation in reliability and maintenance community has been applied by some researchers (Cooke and Slijkhuis, 2003a; Bedford, 2006b). This research developed an expert elicitation model for condition assessment as a solution to the bottleneck of lack of data.

Since assessing the probability of failure or specifying a meaningful remaining life can be challenging, grade systems are often used to summarize the condition and performance of the asset. Condition grades are assessed through visual examination of an asset and with reference to specified descriptions of each grade. An asset's condition grade can only be allocated reliably after explicit visual inspection of the asset. Grading asset condition in this way gives a measure of the extent of physical deterioration with respect to the 'as new' condition. Different 'levels' of condition grades can be established depending on the type of data used and the certainty of the condition grade. Where visual inspections are not possible or have not yet

Several elicitation protocols for conducting expert elicitation have been developed. The much-used Stanford/SRI protocol was the first (Spetzler and von Holstein, 1975; Risbey *et al.,* 2001a). The European Union and the US Nuclear Regulatory Commission, Cooke and Goossens (2000) have developed a European guide for expert judgement on uncertainties of accident consequence models for nuclear power plants.

2.2.1.1 Elicitation protocol

The elicitation protocol provides an explicit assessment of the quality of the uncertainty information (Risbey *et al.,* 2001b). The following steps are involved in the elicitation protocol:

a) Identifying and selecting experts - It is important to assemble an expert panel representing all points of view.

b) Motivating the experts - Establish a relationship with the expert. Explain the nature of the issue the elicitation is organised for and the analysis being conducted. Explain the issue of motivational biases and let the experts be aware of any motivational bias that may distort their judgements. Explain the methodology and the structure of the elicitation process.

c) Structuring - The objective is to arrive at a clear and unambiguous definition of the quantity to be assessed. Characterise the selected variable with familiar units. Identify assumptions that the expert is making.

d) Elicit values - Let the experts state their opinion assessments or values for the variable.

e) Aggregation of experts opinions- Combine experts' judgements. Verify the probability distribution constructed against the expert's beliefs, to make sure that the distribution correctly represents those beliefs.

f) Post elicitation- In communicating the results of experts' assessments, address any expert disagreement. Feedback on the results of the aggregate assessments is given to the experts.

This standard protocol was modified and used in this research. Section 2.2.2.5 outlines the elicitation protocol used in this study.

2.2.1.2 Expert elicitation considerations

a) Major sources and characteristics of uncertainties

Sources of uncertainties (Ayyub, 2001) include context uncertainty (ecological, technological, economic, social and political representation), data uncertainty (measurements, monitoring, survey), model uncertainty, boundary definitions (e.g. which environmental causes, pathological mechanisms and health outcomes are included and excluded?), input data (measurements, monitoring, survey), structure (parameters, relations), technical (software, hardware), and output uncertainty (indicators, statement).

Aleatory uncertainty is due to random and unpredictable variation. Such uncertainty is difficult to resolve, but expert knowledge can be useful in quantifying it. On the other hand, epistemic uncertainty can be conceptually resolvable. This is done by obtaining more knowledge or information about the uncertain subject through expert elicitation or further research.

b) Why expert elicitation was used

In theory, expert elicitation can be useful for almost all types of uncertainties. The focus of this research however, is in its use for quantifiable elements (asset conditions and maintenance quality). In practice, resources (financial and time) limit or determine the extensiveness of an expert elicitation procedure. According to Slottje et al (2008b), conditions that warrant an elaborate expert elicitation procedure include cases where one conceptual model cannot explain and be consistent with the available evidence (model uncertainty), uncertainties are large and or related to high risks, the analysis is not practical to perform or empirical data are not obtainable (e.g. long-term mortality due to exposure to toxins in drinking water), and where judgements are required to assess whether assumptions or calculations are appropriate (mathematical modelling, input data uncertainty or parameters). In this research, the case in hand was uncertainty arising from the quality of available data, which was limited to use and draw dependable conclusions from it. Judgements from the limited data were deemed limited to develop reliable asset condition assessment models.

c) Expert elicitation costs

At a panel discussion in a conference on expert elicitation, it was observed that there appeared to be a range of estimates on the cost of conducting structured expert judgments studies among the panel (Cooke & Probst, 2006). Panellists who worked in the United States (US) reported that studies (done in support of government regulation) cost $100,000–300,000 or more. Expert elicitation in Europe tends to cost between $30,000 – 100,000, excluding experts' time. The US context imposes a high peer review burden that may account for higher costs. Time and travel costs tend to contribute large amounts to the elicitation costs. This represents the high end of expert costs. At the low-cost end, experts are appointed in-house, do not convene for a common workshop, and are interviewed in their offices. Most elicitation protocols fall between these extreme cases.

Expert elicitation costs were a major factor in the way the research was conducted. The author sought the most cost effective way to seek experts opinions due to a limited budget. Engineers from the case study water utility were therefore, asked to be the experts for the case study because the cost was lower. This is because the elicitation exercises were carried out during working hours and no extra payment was required. The same experts were asked for their opinions in collecting data for all of three research questions. This helped to minimise costs and save time, particularly because it was difficult to find time when all identified experts were available for the elicitation exercises at each of the pumping station sites.

2.2.1.3 Advantages and disadvantages of expert elicitation methodology

Weaknesses of expert elicitation include;

The fraction of experts holding a given view is not proportional to the probability of that view being correct. Secondly, the results are sensitive to the selection of the experts whose estimates are gathered. The results also differ, depending on the method used to aggregate the experts' assessments (Knol *et al*, 2010).

The *strengths* of expert elicitation include that expert elicitation offers the potential to make use of all available knowledge including knowledge that cannot be otherwise easily formalised. It can also easily include views of sceptics, which helps to reveal the level of expert disagreement on certain estimates. This allows a presentation of a broad view in the uncertainty analysis.

This research employed expert elicitation as its main method for assessing uncertainty where sparse or no data existed for assessing assets condition, maintenance effectiveness and maintenance regime selection. Although subjective probability is an imperfect substitute for established data and despite the subjective aggregate expert judgements, it was found better to use subjective probability than deterministic point-values. This was due to better approximation of the uncertainty with subjective probability estimates. As stated in Chapter 1, water utilities were found to use the deterministic point values in eliciting experts' judgements for their asset condition assessments. Such deterministic point values are limited in that they allow limited scope for experts in stating their true opinions.

It was also found that water utilities sometimes do not follow the elicitation protocol when eliciting experts' opinions. Asset condition assessment is typically carried out without following the elicitation protocol. No method was found to be used to assess maintenance effectiveness by utilities when they had sparse or no data.

The expert elicitation methodology is adopted and improved on its current application in the UK water sector asset condition assessment. It was also extended to incorporate evidence from asset historical performance. The evidence data from historical asset performance was found to be not enough to use on its own databases are still being developed. According to Brint *et al* (2009b), such database scenarios are prevalent in the UK water industry, the methodology developed in this research could be useful across the water sector.

2.2.1.4 Condition descriptions used by utilities (control approach).

Condition grades give a broad categorization of an asset's ability to function in accordance with a water utility's requirements. They are assessed by using operational knowledge of the asset, with reference to specified descriptions of each grade. A performance grade can be allocated reliably with reference to detailed operational knowledge. Asset grading systems can be simple (Grade 1 to 5), intermediate (Grade 1 to 5 with sub grading for worse three grades), and sophisticated (multiple faceted ranking schemes), although these are usually reduced to 1 - 5. Ideally, the observations made during a condition or performance assessment are recorded as a combination of a number of distinct observations into a single grade at the point of survey.

The current condition grade method applied to assess asset condition does not clearly define performance. For example, percentages levels are sometime used to define the performance grade (Table 2-1).

Table 2–1: Performance grades as currently defined

CRITERIA	GRADE				
	1 GOOD	**2 FAIR**	**3 ADEQUATE**	**4 POOR**	**5 AWFUL**
AVAILABILITY - Frequency of breakdown - Unexpected stoppages - Does it always start when required - Does it achieve the function for which it was designed	> 95%	90% - 94%	80% - 89%	50% - 79%	< 49%

The definition of each percentage performance criteria is not given. For example, what frequency of breakdown equates to what percentage for a particular asset group. Each asset is given a grade of 1, 2, 3, 4, or 5. Other sectors such as flood management and housing sectors use similar approaches (HESA, 2009).

Secondly, the elicited values do not allow for uncertainty to be sated in both the experts' confidence and the condition assessments, as illustrated in the pilot study results in Figure 2 – 2.

The major identified limitations of the current experts' approaches include the following;

- Experts do not express their level of uncertainty pertaining;
    - The asset condition grade they give.
    - Their belief in the opinions they give.

- Expert elicitation is carried out only for reporting purposes. Condition assessments are sometimes carried out when Ofwat reports are due (five yearly).
- Few of the formal techniques for elicitation and are applied.

2.2.1.5 Developed condition assessment approach

The developed research methodology combined expert elicitation and some asset's historical data as evidence to evaluate asset condition. Some asset performance data was used in conjunction with the expert elicitation. Asset failure rates were obtained and presented to experts after they had stated their asset condition opinions. They were asked to review their opinions after seeing the asset performance data. Expert elicitation was used because poor data quality within the sample asset group was found. The method was based on its ability to acquire quality data from experts and the flexibility to incorporate evidence from quantitative data.

The method adopted and improved on the major common applied approach for condition assessment used by water utilities when there is limited data. The expert elicitation methodology was adopted and improved in order to increase the margin of error or confidence range on currently the existing used approaches. Figure 2-1 outlines the developed methodology.

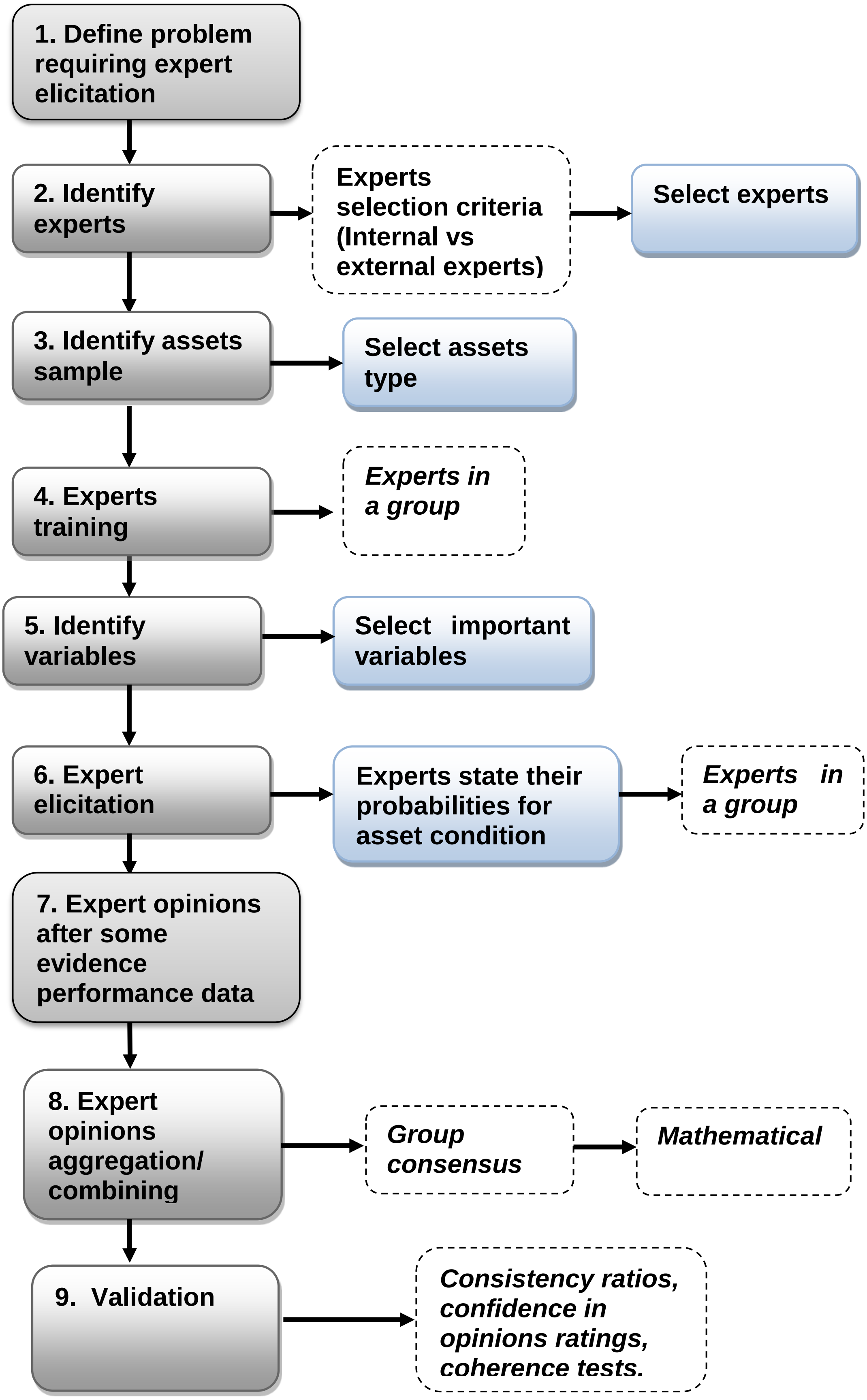


Figure 2-1: Asset condition methodology

Where, although some processes overlap, the following colours strictly represent;

= Condition assessment methodology

= Description

= Approach

For the condition assessment, a grading scale is represented by a score that is consistent with the level of the asset distress indicated by the defects. A protocol of asset condition assessment that was applied in this study follows;

(1) Clear definition of the task or problem – in this research case, asset condition assessment with limited data was the problem. Since the method was largely applied for Section 4 and 5, the problems were assessing maintenance effectiveness and selecting a maintenance regime where there are limited data, respectively.

(2) Identifying and selection of experts. Experts were selected from the case study organisation. This was due to financial constraints because funds would be required to pay any experts asked to take part in the elicitation exercise. The case study company engineers were asked to take part as experts in assessing the assets condition during their working hours. Experienced maintenance and operations engineers were selected as experts. This saved on costs but the author believes that it compromised the quality of opinions because a diverse mix of expertise could have been secured from external experts. Internal experts were also more likely to have more biases due to familiarity with the assets and the organisation's systems. More experienced experts could also have been employed from outside the organisation. Although internal engineers experts could have been biased, they had advantage in that their working knowledge of the sample assets and the organisation. They would better assess the asset condition due to previous

maintenance work they have carried out on the asset, which knowledge an external experts would not have. The same group of experts gave their opinions in the three case studies conducted in this research (water pump condition assessment, maintenance effectiveness assessment and maintenance regime selection).

(3) Identifying and selection of sample assets. The objective of the research was to conduct the research on over-ground assets. The sample assets were therefore, selected from over-ground assets. Water pumps were selected as sample assets for the case studies because of the principle of availability. The most available sample is selected in this case. Water pumps were the most available sample because they have engineers most available who were mostly based at the pumping stations. The engineers were most available to get for the elicitation exercise and the pumps were most available because they are located at the same pumping stations.

(4) Training experts on the condition definitions and probability assessments. A brief training session was conducted before the actual elicitation exercise. Experts were mainly trained in the basics of fractions percentages, probabilities and biases. The elicitation problem was also defined.

(5) Elicitation and selection of variable. An asset can have many specific variables impacting its condition. Seven most performance variable were selected by the experts for the water pump in this research case study. Only the three most important variables were finally selected and used to assess the water pumps condition. The variable selection steps are;

- Step A - Identification of variables influencing the condition of an asset. Seven variables impacting on the water pump were identified.
- Step B - Weighting the variables to assign an importance/weight score to each. The three highest scored variables were selected to use for the condition assessment.

(6) Definition of the grades of each variable that impact asset condition.

(7) Elicitation of asset condition:- Experts scored the assets condition based on variable scores. Experts were allowed to score values above and below whole

number values. This was to indicate asset conditions that were between whole number value condition grades.

(8) Pinions after evidence data:- Experts were shown data on the number of failures in the previous twelve months and asked to review their opinions about the asset condition grades.

(9) Experts' opinions aggregation: The experts' condition scores were aggregated to a single condition score. Equal weight and weighted aggregation methods were used in pooling the experts' opinions (Table 3-10 and Table 3-11).

(10) Validation of experts' opinions:- Experts and their scores were assessed for coherence, confidence levels and consistency (Table 3-18, and Table 3-19).

2.2.1.6 Pilot study

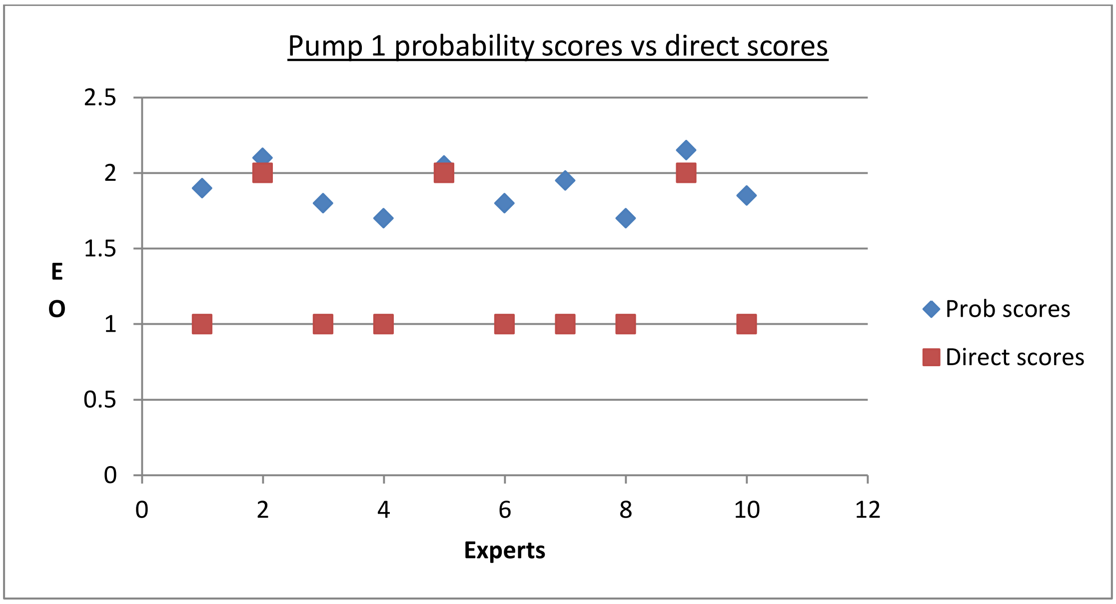
A pilot study was conducted to test the method developed in this section before an actual case study was conducted with the water utility. The case study was good in that it helped the author to test and refine the method and was better prepared when conducting actual the case study.

Ten process engineering students were asked to volunteer as experts and assess the condition of a multi-phase flow demonstration equipment The equipment was chosen because they were relatively familiar with it since it was in their department.
The 5-step expert elicitation and condition assessment process was followed in carrying out the pilot study. A group of ten students from engineering department process systems took part as experts in the pilot study. A demonstration multi-phase flow equipment (based at the University engineering department) condition was assessed. The students were chosen because they were familiar with the equipment. The most available sample of MSc process systems students were asked to participate as experts. Table 2-2 presents the results of the pilot study.

Table 2-2: Pilot study asset condition assessment results.

Expert	Condition grade control method	Condition grade new method
1	1	1.9
2	2	2.2
3	1	1.8
4	1	1.7
5	2	2
6	1	1,8
7	1	1.95
8	1	1.7
9	2	2.0
10	1	1.85

Figure 2–2 shows the results of a pilot study, indicating the difference in the final grade the new approach introduces – leading to identification of misclassification of the assets' grades.



EO = Experts opinion

Figure 2–2: The new versus old approach experts' scores (*pilot study*)

Figure 2-2 also illustrates the limitation of the mostly used current condition assessment approach in terms of lack of precision and poor calibration, resulting in large uncertainty in the allocated asset condition grades.

Lessons were learnt from the pilot study. The questionnaire for the actual case study was refined after the pilot study. Some of the questions were rephrased because of some of the student experts indicated they did not understand them. The training session for the actual case study was also modified to include more aspects identified from the pilot study.

2.2.1.7 Actual case study

The new elicitation approach to condition assessment was applied and tested within a water utility. Experts were invited to assess water pumps at seven different sites. Due to time and other resource constraints, the organisation's engineers were used to elicit opinions about the asset conditions. Experts were chosen according to their area of expertise. Engineers currently working in the specific asset sampled were chosen to be experts (both operations and maintenance engineers). In summary, the methodology steps are; training, selection of asset performance variables, elicitation of asset conditions, aggregation of opinions, and validation. Chapter 3 presents the case study results in detail.

2.3 Maintenance effectiveness method process

Maintenance effectiveness can be measured by using different approaches, including total effectiveness, availability, cost of maintenance, difference between planned and unplanned work and reliability (Al-Momani *et al,* 2006). This research develops an approach that is related to the reliability method. The reliability of a maintenance action is assessed by using expert opinions.

The developed maintenance effectiveness approach was based on the current assessment approach applied by some water utilities (Wood, 2007b). The approach employs expert elicitation to assess asset conditions after a five years period. A group of experts are convened at each financial year end to assess assets condition.

The variables to use when assessing the assets condition or performance were selected by experts prior to the elicitation exercise. The variables were selected only once and upgraded whenever necessary. The assessment then followed the standard elicitation process as presented in Figure 2-3.

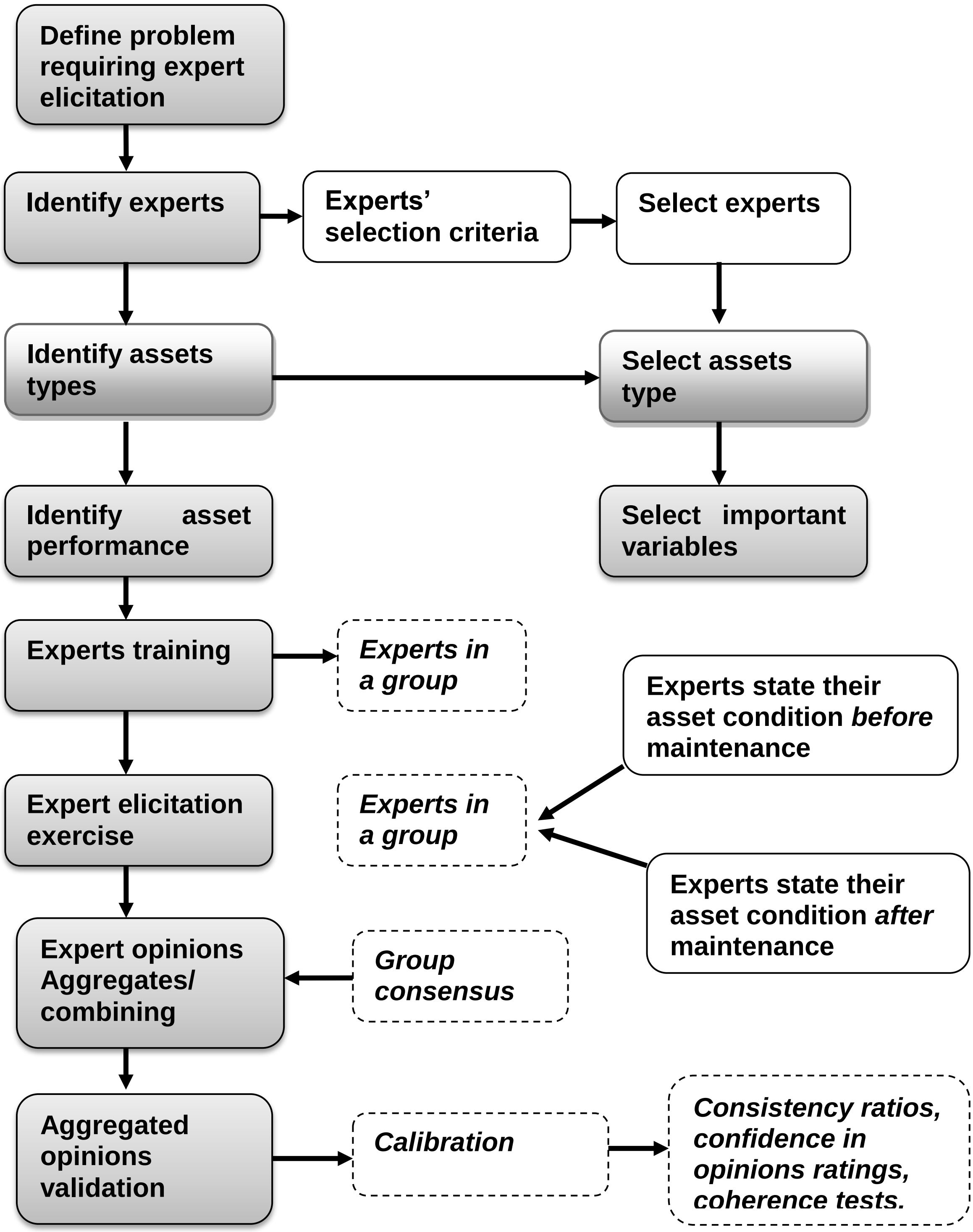


Figure 2-3: Maintenance effectiveness methodology

Where although some processes overlap, the following colours strictly represent;

= Method

= Description

= Approach used

The method assessed maintenance quality by asking maintenance engineers to rate the sample asset condition before and after planned maintenance.

In assessing maintenance effectiveness, the experts first determined the asset condition and give their condition rating before a maintenance activity, in line with Equation (2-1). Experts then gave their opinions about the asset condition after the maintenance action. In qualitative terms, the asset could be 'as bad as before', 'better than before', or 'worse than before'. The maintenance effectiveness is, therefore, given by;

$$\text{ME} = \sum_{i=1}^{N^e} \sum_{j=1}^{M^f} G_j C_{ij}^a - \sum_{i=1}^{N^e} \sum_{j=1}^{M^f} G_j C_{ij}^b \qquad (2\text{-}1)$$

Where C_{ij}^a represents the condition grade after a maintenance action and C_{ij}^b represents the condition value before the maintenance action (Figure 2-4). The asset condition value given by experts for *a* and *b* could be the same, indicating an ineffective maintenance (as before). Where the maintenance effectiveness value (ME) is positive, the asset could be classed as 'better than before'. A negative maintenance effectiveness value would be classed as 'worse than before'.

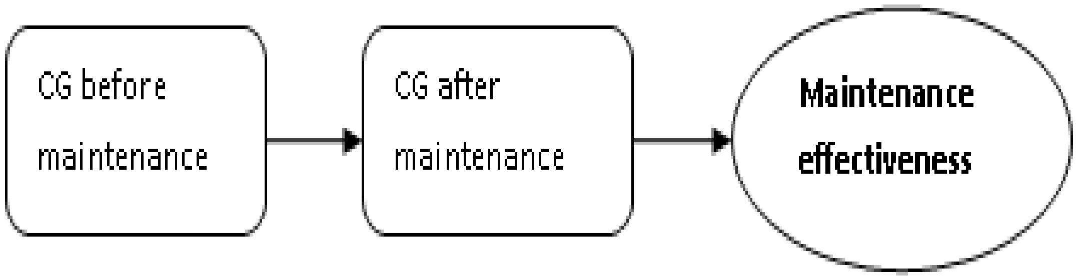


Figure 2-4: Maintenance effectiveness assessment process

2.3.1 Expert elicitation assessment in maintenance effectiveness.

The developed equation for maintenance effectiveness assessment was derived from the condition assessment equation. The asset condition before a maintenance action was assessed by experts. The difference between the two is the value of the effectiveness of the maintenance. Only planned maintenance was used to measure maintenance effectiveness. The maintenance effectiveness method extends from the condition assessment method and the same experts were asked to assess the maintenance quality after the condition assessment exercise. The condition assessment being;

$$\sum_{i=1}^{N^e} \sum_{j=1}^{M^f} G_j C_{ij}. \qquad (2 - 2)$$

Where G_j represents the rating of the asset condition in relation to each of the M^f variables. C_{ij} represents the rating of the importance of the j-th variable as assessed by the *i*-th expert.

2.3.2 Data sample and quality

The data sample was collected from the same sample of assets used in applying the the condition assessment method (Section 2.2). The difference in the methodology was that experts were asked to state their opinions on the condition of the asset before a maintenance action and after a maintenance action. The experiment was also not practical in the same way as the actual condition assessment because actual maintenance work on the water pump could not be carried out for the case study. Experts were asked to recall the most recent planned maintenance work they carried out on the sample water pumps. Their opinions on the condition before and after the actual maintenance were recorded. The major limitation of the maintenance effectiveness data was the fact that experts were required to recall the maintenance action and some could probably not clearly recall the asset condition state or grade. Since experts had already carried out the condition assessment exercise, it is expected that they were familiar and better in their maintenance effectiveness assessment exercise.

Experts opinions were also validated using biases checks, coherence checks, and calibration against seed variables.

2.4 Maintenance regime selection method process

There are several multi-criteria decision making (MCDM) approaches for selecting a maintenance regime in the literature. Almeida and Bohoris (1995) discuss the application of decision making theory to maintenance with particular attention to multi-attribute utility theory. Reliability centred maintenance (RCM) is a method for preserving functional integrity of assets and is designed to minimise maintenance costs by balancing the higher cost of corrective maintenance against the cost of preventative maintenance, taking into account the loss of potential remaining life of the asset in question (Crocker, 2000a). The RCM methodology (for example, Rausand, 1998) is one of the most widely used techniques. One of the tools more frequently adopted by companies to assess a possible maintenance regime categorises assets into several groups of risk is based on the concepts of failure mode effect and criticality analysis technique (FMECA). This methodology has been proposed in different possible variants, in terms of relevant criteria considered and/or risk priority number formulation (Gilchrist, 1993). Using this approach, the selection of a maintenance regime is performed through the analysis of the obtained priority risk number, which number is according to the level risk of failure of each asset. Among the most common types of multi-criteria analysis tools are “decision trees” (branched models with a finite number of alternatives and a finite estimation of occurrence for each of these alternatives). Expert systems, artificial neural networks, fuzzy logic and neuro-fuzzy systems are also widely used techniques in decision support systems **(**Christodoulou *et al*, 2009).

After analysing several multi-criteria decision approaches (Chapter 1), the Analytical Hierarchy Process (AHP) was adopted to develop a maintenance policy selection approach where there is no data. The Analytical Hierarchy Process is a decision support tool where alternatives are compared between themselves in pairs and a normalised preference scores of their significance is obtained based on the pair-wise comparisons. Triantaphyllou *et al* (1997a) suggest the use of Analytical Hierarchy Process by considering only four maintenance criteria: cost, reparability, reliability and availability. This research adopts and extends the AHP multi-criteria decision analysis by utilising eleven maintenance criteria. Expert elicitation is combined with the AHP for purposes of this research.

The reason for choosing the AHP is its simplicity in composing priorities by deriving composite priorities of alternatives with respect to multiple criteria. It can also incorporate many criteria or performance indicators as possible. The AHP also has the ability to normalised preference score choices in the order of their effectiveness in meeting conflicting objectives. AHP calculations are logical sequences, which can show what led to particular judgements. The AHP's ability to detect inconsistent judgements is also attractive.

The larger the number of aspects to be considered, the more complex the process becomes (Al-Najjar and Alsyouf, 2003c). The potential for combining the AHP with expert elicitation also made it attractive for this research because only no data situations are considered. The AHP has been applied in maintenance regime selection at asset design stage (Bevilacqua and Braglia, 2000a), with other methods such as fuzzy logic (Tahir *et al* 2008), and in other different settings other than maintenance regime selection. The application of the AHP in this research extends the method employed by Bevilacqua and Braglia (2000b) who considered selecting a possible maintenance regime for assets at their design stage. The AHP is applied at the operational stage of the asset life in this research.

This research adopts and develops on the AHP after maintenance programmes are applied and are being evaluated for support in choosing the optimum regime where there is limited data. The AHP is a decision-support procedure with a sequence of actions that allow decision-makers to solve problems in a systematic manner that follows predefined steps: definition of the problem, formulation of alternate solutions, effect analysis, selection of the ideal solution and application, evaluation and feedback. The developed method combines expert elicitation and the AHP multi-criteria decision making approach. The lack of data is an obvious limitation, but incorporating as many criteria as possible provides a holistic approach to decision making and the tool can be applied in various scenarios.

Scales of expressing preferences in the AHP process are summarised in Table 2-3.

Table 2-3: Other scales for expressing preferences (after Ishizaka and Labib, 2009).

Scale type	**Values**								
Linear	1	2	3	4	5	6	7	8	9
Power	1	4	9	16	25	36	49	64	81
Geometric	1	2	4	8	16	32	64	128	256
Logarithmic	1	1.58	2	2.32	2.58	2.81	3	3.17	3.32
Root square	1	1.41	1.73	2	2.23	2.45	2.65	2.83	3
Asymptotical	0	0.12	0.24	0.36	0.46	0.55	0.63	0.70	0.76
Inverse linear	1	1.13	1.29	1.5	1.8	2.25	3	4.5	9
Balanced	1	1.22	1.5	1.86	2.33	3	4	5.67	9

The criteria to express relative priority are selected by the experts through a variable selection method. The experts are presented with a long list of variables that affect a specific asset group and they select the main five variables. A minimal number of very important variables is considered ideal because it minimises the matrix iteration complexity. The linear scale of 1/9 ....9 is used to weigh the five criteria. For the aggregation of experts' opinions, the behavioural approach is used in order for experts to be able to discuss and come to a consensus on the relative priorities (O'Hagan, 2005).

2.4.1 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) was proposed by Saaty (1980a). Subjective assessments of relative importance are converted to a set of overall scores or weights in the method. The methodology is based on pair-wise comparisons of how important criterion C*i* relative to criterion C*j*. This is used to establish the weights for the criteria and the alternatives (Cheung and Suen, 2002).

The weights of the criteria are derived by first assuming that the *m* criteria are not arranged in a tree-structure. For each pair of criteria, the decision maker is required to give a pair-wise comparison rating of the relative importance of the two. The ranking of the pair can use a nine-point scale. The rating expresses the intensity of the preference for one criterion over another;

1= Equal importance.
3= Moderate importance.
5= Strong or essential importance.
7= Very strong importance.
9= Extreme importance.

Let *cij* denote the value obtained by comparing criterion C*i* relative to criterion C*j*. If the judgement of criterion C*j* is more important than criterion C*i*, then the reciprocal of the relevant index value is assigned. The decision maker is assumed to be consistent in making judgements about any one pair of criteria and it is assumed that all criteria will always rank equally when compared to themselves. Then, *cij*=1/*cij* and *cii*=1. This means that it is only necessary to make 1/2*m*(*m* - 1) comparisons to establish the full set of pair-wise judgements for *m* criteria. The entries *cij*, *i,j*=1,.,*m* can be arranged in a pair-wise comparison matrix of size *m* x *m*.

The set of weights that are most consistent with the relativities expressed in the comparison matrix are estimated. There is complete consistency in the (reciprocal) judgements made about any one pair. However, consistency of judgements between pairs is not guaranteed (Cheng and Li (2003). The task is to search for an *m*-vector of the weights. The weights should be such that the *m* x *m* matrix *W* of entries *wi*/*wj* will provide the best fit to the judgments recorded in the pair-wise comparison matrix *C*.

Saaty's (1980b) original method to compute the weights is based on matrix algebra and determines them as the elements in the eigenvector associated with the maximum eigenvalue of the matrix. The prioritisation and consistency of the eigenvalue method has been criticized for being subjective (Gass and Rapcsák, 2004). Chapter 4 of this thesis provides a case study on selecting a maintenance regime by using the AHP.

The AHP develops matrices from paired comparison of alternatives. It then uses the principal eigenvalue method to derive priority values from each matrix. This method is applied in the research because it has been proven to be better than other methods, such as the Logarithmic Least Square Method (Saaty, 1998). Consistency in the matrix is important to ensure the preference scores can be trusted. Consistency checks are carries out be using the consistency ratio method in the research (Saaty, 1994c). It is noted that, unlike the evidence theory of decision making (Fioretti, 2002), the AHP does not necessarily match the change in one input variable to a change in output. For example, a change in the economy that brings a change in the cost of maintenance may not necessarily result in a change in asset failure – unless the preventative maintenance budget is cut as a consequence.

The consistency ratio (CR) is calculated in order to assess the consistency of the matrix. Figure 2-5 summarises the method of the research in this section.

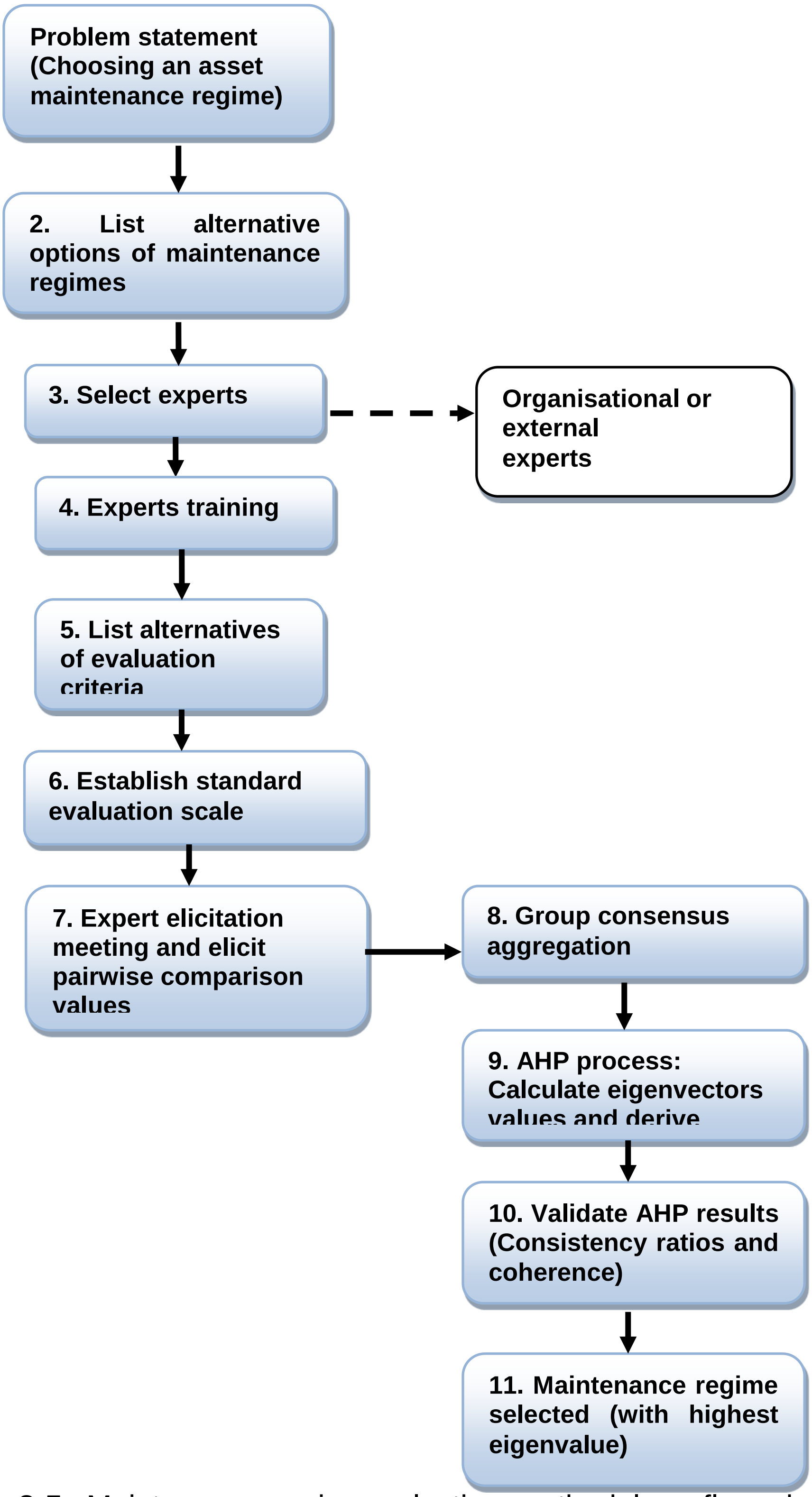


Figure 2-5: Maintenance regime selection methodology flow chart (Modified after Saaty, 1980c).

2.4.2 AHP Decision making process

Decision making is the research of identifying and choosing alternatives based on the values and preferences of the decision maker (Baker *et al,* 2001a). Making a decision implies that there are alternative choices to be considered. Many alternatives as possible can be identified in order to choose the one that best fits goals, objectives, desires or values. According to Baker *et al* (2001b), decision making should start with the identification of the decision maker(s) and stakeholder(s).

The methodology applied for selecting a maintenance regime in this research followed the following process, which was modified after the AHP process;

- ***Step 1. Problem definition***

The research question as presented by the objective in this section was defined. It was to develop asset management decision support tools for selecting an optimal maintenance regime for specific asset groups where there is limited data. These maintenance regimes are referred to as criteria

- ***Step 2 Define the criteria***

Different asset maintenance regimes to choose an optimal one from were defined. The three maintenance regimes were condition-based maintenance, corrective maintenance and preventative maintenance.

- ***Step 3 Select experts***

The same experts whose opinions were selected for assessing asset condition and maintenance effectiveness were. Section 2.3 elaborates the method used to select the experts.

- ***Step 4 Experts training***

Experts were trained before the formal elicitation exercise was carried out. This was done to ensure that they understood the requirements of the exercise. Training is believed to assist experts to understand the elicitation problem and therefore, five better quality opinions in their assessments (Ouchi, 2004c).

- ***Step 5 Identification alternatives and definition the criteria***

A list of alternatives were defined and the experts were asked to rate and select the most important five alternatives. The alternatives used to assess the maintenance regime choice were; asset importance for the process, spare parts availability/ obsolescence, maintenance cost, in-house maintenance capability and Asset type (active or passive).

- **Step 6 Establish standard evaluation scale**

The scale for rating the preference of the criteria and alternatives was determined. Different scales can be used by the experts to state their preference (Table 2-3). The linear scale was used in this research because it is easy for experts to understand and apply in stating their preferences.

- **Step 7 Expert elicitation meeting and elicit pair-wise comparison values**

Values of experts expressing their preference between alternative maintenance regimes by using the linear scale method (1 – 9) were obtained.

- **Step 8 Aggregation of expert opinions**

The opinions of preferences by experts were aggregated and developed into matrices.

- **Step 9 Calculate eigenvectors values and derive**

The matrices of experts preferences were used to calculate the preference scores.

- ***Step 10 Validate solutions against problem statement***

The results in this research were validated by assessing the consistency ratio, which determines if the matrices were consistent. If the ratio is more than 1, it is considered high and the results are considered not to be of quality as the matrices from which they were calculated were not consistent. The highest consistency ratio in this research was considered negligible as it was 1.02.

2.4.3 Advantages and disadvantages of AHP

The limitations of the AHP are that it works when the matrices are all of the same mathematical form – known as a positive reciprocal matrix. To create such a matrix requires that, if one uses the number 9 to represent A is absolutely more important than B. One has to then use 1/9 to define the relative importance of B with respect to A. Some experts expressed they would have wanted to rate their preferences in percentages. This was because they sometimes did not absolutely prefer one maintenance regime over the other.

The other seeming disadvantage is that if the scale is changed from 1 to 9 to, say, 1 to 29, the numbers in the end result will also change. In many ways, that does not matter as it simply indicates that something is relatively better than another at meeting some objective. The AHP indicates the best alternative – without indicating the extent to which it is a better choice. The maintenance regime selection in this research was only interested in the best alternative. The extent to which it is a better maintenance regime would be established as asset performance data become available.

The main *advantage* of the AHP is its ability to rank choices in the order of their effectiveness in when there are conflicting objectives. If the judgements made about the relative importance of the objectives and those about the competing factors' ability to satisfy those objectives have been made in good faith, then the AHP calculations lead inexorably to the logical consequence of those judgements. Another advantage of the AHP is its ability to detect inconsistent judgements.

The AHP is a useful technique for discriminating between competing options in the light of a range of objectives to be met. The calculations are not complex and it is relatively easy to apply the technique. This means water utilities can easily use the technique in-house to quickly make decisions whilst they are still developing databases to introduce data-based techniques.

The AHP was found to be a good tool to adopt because it incorporates expert elicitation, which was already used in the research. Experts were already available and the use of group decision-making to contribute to data quality is another reason the AHP was used in the research. The AHP was also found to be advantageous due to its ability to apply multi-criteria factors in selecting a maintenance regime where there is limited data. The multi-criteria aspect means that all necessary factors can be considered in selecting the maintenance regime. The quantitative aspect of the AHP was also found to be effective in presenting clear results and verifying them.

The methodology was also found to be limited in application in water utility.

Summary

Expert elicitation and AHP methodologies were analysed and adopted in developing approaches to meet each of the objectives of the research. The expert elicitation approach was adopted in developing asset condition assessment and maintenance effectiveness assessment decision support tools. The tools development and testing are detailed in Chapter 3 and 4. The AHP method was adopted for maintenance regime selection (Chapter 5).

3 ASSESSING ASSET CONDITION

3.1 Introduction

The objectives of this section were to investigate the current asset condition assessment approaches for water utilities and develop improved approaches, accordingly. The primary goal of the research in this section was to develop more efficient and cost-effective means to conduct condition assessment for use in supporting asset management planning. Specific research objectives included:

- Identify and characterise the state of condition assessment approaches.
- Evaluate quality of the current condition assessment approaches used in the water industry and their applicability to efficiently allocate maintenance resources.
- Develop and demonstrate an improved approach to assess asset condition where there is limited data in order to better allocate maintenance resources and manage risk in water utility.

The UK water utility Asset Planning Capital Framework (APCF) and the regulatory requirements by the office for water regulation service (Ofwat) are some of the major drivers in asset condition assessment innovation and improvement for water utilities. The APCF requires that water utilities be proactive and innovative in their asset maintenance strategies. Ofwat also requires efficient asset management in water utilities in order to ensure good customer service, fair service costs, minimum risk to the environment and prudent investment in asset maintenance. Substantive research has been undertaken in water underground asset condition assessment and this research is not easily transferable to over-ground assets due to the difference in usage mode (pipes are non-active in operation) and mode of deterioration (pipes are underground). Water utilities have to demonstrate that they are proactive in this regard, hence the need for research in this area, particularly for over-ground assets.

To meet the research objectives, the expert elicitation approach was used to assess asset conditions because data was limited. Experts opinions were sought about water pumps (over-ground assets). Expert groups were organised to collect data from a water utility to use in applying and testing the developed methodology of asset condition assessment. The results demonstrate there is a wide scope for improvement in over-ground asset condition assessment in the water sector. Both water utilities and research bodies are faced with the opportunity to meet the research needs, as well as development and application of new tools in assessing the condition of water assets. Meeting these needs would be indicated in improved asset life through better asset management (*risk management*), improved customer service (*social*), better meeting of regulatory requirement *(legal*), improved environmental protection (*environmental*) and better resource allocation and returns for water utilities (*economic*).

With any approach used to characterise an asset's condition/performance, it is important to attempt to optimize the extent and frequency at which the assessments need to be carried out. The extent of assessment is influenced by:
- The type and criticality of the asset
- Variations in operating context and environmental conditions

Assessment frequencies may be based on regular intervals (determined by regulatory and other factors), condition, risk, or other factors such as maintenance cost. Aboveground assets can be accessed and assessed more readily, so comprehensive programmes may be economic. However, the benefits of the assessment must be compared against the costs. Section 3. Of this thesis presents an analysis of a case study of the costs implications for poor condition assessments.

3.2 Theoretical background

When a new asset is installed, it begins to deteriorate at a rate dependent on local environmental conditions, operating context, and maintenance strategy. Condition progressively deteriorates until it reaches the point where the asset needs to be replaced. Asset management techniques do not seek to manage asset condition as such, but rather seek to manage overall service levels within the context of acceptable risk and available budgets. However, there is a general relationship between the condition of an asset and its propensity to fail. Some failures would be expected in the early part of an asset's life (due to defects in materials, installation and commissioning), failures due to fatigue, corrosion, and wear-out start to predominate as the asset reaches the end of its useful life. It is therefore, still important to understand the structural condition of assets and the rate at which asset condition deteriorates. Condition assessment can be used to develop this understanding, in conjunction with assessments of all other performance criteria.

Utilities should design assessment programmes to obtain the outputs needed for their asset management systems, consider the extent and frequency of the assessments necessary to meet their asset management objectives, and ensure that a consistent approach to the assessment is developed and applied. Some of the reasons for the need of effective asset condition assessment in water utilities are discussed.

3.3 Methodology

Expert elicitation was used in assessing assets condition. Experts stated their opinions of the condition of the assets. Assets were graded according to their condition – with lower number representing a good condition grade and a higher number representing a poor condition grade. Experts could state their assessments as values between each whole number condition grade. For example, condition values between condition grade 1 and 2 could be stated by experts – allowing better precision in the condition rating. Figure 1-7 outlines the methodology process employed. The asset condition assessment methodology developed in this research is presented in detail in Chapter 2.

3.4 Condition assessment of water pumps (case study).

Clean water pumps from a water utility were used for testing the method developed in the case study. Based on evidence data and opinions from the experts, the pumps' conditions were investigated. The results from the case study are discussed following the methodology.

Figure 3-1: Typical water utility pumping station

Many performance indicators or variables impact on the pump's performance and could be used in assessing its condition. It was established only a few of the pump performance variables contribute significantly and can be used to assess its condition. Experts were invited to select the most important pump performance variables to use in assessing its condition.

Seven (M^m) variables that are associated with the pump condition were identified and the experts invited to rate the importance of each of the seven variables (Table 3 - 4). The highest rated three (M^f) variables were then used in determining the pump condition (Table 3 - 5).

The condition assessment experiment was carried out in line with expert elicitation protocol, as outlined in the new approach methodology detailed in Chapter 2. The protocol includes preparation, experts training, elicitation, aggregation of experts' variables and decision making. The results from each step of the condition assessment are presented and described below.

3.4.1 Preparation and variable selection

Preparation included sampling of assets to use in the case study. As detailed in Chapter 2, over-ground assets were sampled because of their ease of access and limited studies conducted on them. Sites where the identified experts were available for the asset condition assessment exercise were also sampled for the case study exercise. Experts were identified and selected based on their area of expertise in managing the water utility assets. Only engineers with experience in managing the sampled assets were selected to participate as experts in assessing the pumps' condition. The asset condition was then carried out and experts were trained on how to express their opinions.

a) Experts training

Experts were trained by explaining terms used in the elicitation questionnaire and practicing answers with some sample questions. Feedback sought at the end of each exercise showed that experts found the training helpful in giving their opinions. This emphasises the importance of giving training to experts as they stated that they would not be confident in their opinions if the training was not conducted prior to the elicitation exercise, with some indicating they would not know the meaning of some terms used. For example; the terms used for describing different types of maintenance (Section 6.4) and the meaning of upper and lower quartile when stating their uncertainty in the condition grade.

The results from this research survey emphasize the need for training. Experts stated that the training session helped them understand the elicitation requirements. This indicates that lack of training could have undermined the results as experts would have given poor assessments or not stated their true values due to lack of understanding. For example, all of the experts indicated that the training helped them understand the questionnaire better and would have given different responses if they did not receive the training. Table 3-1 presents the experts' responses.

Table 3-1: Experts' assessment of elicitation training (very useful, quite useful, and not useful)

Expert	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
1	Very useful	Quite useful	Very useful	Quite useful	Very useful	Very useful	Quite useful
2	Quite useful	Very useful	Quite useful	Quite useful	Quite useful	Quite useful	Very useful
3	Very useful	Quite useful	Quite useful	Very useful	Very useful	Quite useful	Quite useful
4	Very useful	Very useful	Quite useful	Very useful	Very useful	Very useful	Very useful

About 46% of experts indicated that the training was quite useful, whilst 54% stated that it was very useful. None of the experts indicated that the training was not useful at all.

b) Variable importance

The variables that affect the asset condition were defined per asset group and were given by the experts. This is currently not the case with the widely used methodology discussed in Section 3. The criteria defining the variables for assessing the assets is standard and applied across all asset groups, which is only differentiated between above ground, below ground and mechanical and electrical (M & E). Above ground assets criteria tend to also cater for electrical and mechanical. The variables influencing the condition of the asset group were identified. Weighting the variables to assign weight score to each gave the overall importance. The variables with the highest importance were selected and used in assessing the pump condition. The results were obtained from two survey sites and applied across other sites. The other sites were asked to state their three most important variables and the results supported the importance ratings obtained from the first site. This shows that the experts generally had similar views on what variables mostly influenced the water pumps. The rating of the variables' importance could not be verified from the other sites since they were not asked to rate them.

The variable selection exercise emphasized the importance of choosing specific variables for each asset group because each group is unique. The use of generic asset performance variables across the water distribution undermines the quality of the results of the condition assessment. This is because assets have very different performance variables that are sometimes not even relevant to other asset groups. For example, temperature may be relevant for a water pump condition assessment and not quite as relevant for water pipe assessment. Some variables may apply to two asset groups, but vary widely in importance. For example, corrosion could be very important for a water pipe condition assessment than for a water pump assessment. Therefore, it is important to select important variables for each asset group.

Studies in variable selection are mostly quantitative based studies such as computer programming. Authors exploring expert elicited variable selection were not found. This could be an opportunity to evaluate the value of employing experts' services to select variables, compared to giving experts one's own variables. Assessing if experts are better at prioritising variables would enhance the quality of condition assessment as attention would be placed on meaningful variables as some assets have too many variables to consider at any one time. Maintenance efforts would also be better focused for each asset group.

It is worth noting that performance related variables in water supply are not related to specific asset performance assessments, but are for assessing the whole network and organisation performance. Performance variables of the assets in this research were considered to be management tools, fundamental to monitoring the conditions of the assets, as indicated by Alegre *et al,* (2006c). Selection of performance indicators/variables is very crucial to asset management. Performance variables can be influenced by a range of factors such as experts' perception or operational experiences. According to UKWIR (2002e), an ideal performance indicator would allow assessing the scope for improvement in system efficiencies and tie it in with the organisation's maintenance policy and plans. There are costs and efforts involved in gathering data and maintaining each performance measure. Therefore, the selection of performance measures regarding each asset group should be carefully evaluated in terms of their strategic value to either maintenance decision making, importance to asset performance and should be also justified on a maintenance cost benefit basis. Performance variables should provide objective quality evidence to assist in decision making regarding the condition of the asset (Matichich *et al,* 2006c). Each year water and sewerage companies in England and Wales are required to submit this information on their performance against various aspects of service (Ofwat, 2008b).

These are known as serviceability indicators, which are focussed on the service to the customers. These serviceability indicators measure the performance of the system instead of performance of a particular asset or asset category. It is 'serviceability to customer' and not 'serviceability of the assets' (Parsons, 2006c). Inadequate pressure can be directly related to asset maintenance however the other variables clearly have little direct connection with network operation or asset maintenance issues. Variable selection in this research only focussed condition issues affecting the asset group directly.

The set of variables to be considered for each group of assets in assessing their condition and assessing maintenance effectiveness can be large. Variable selection is an important challenge. It is critical to determine the set of variables that provide a relevant representation of the phenomenon under research. There are many different procedures for selecting relevant or *significant* variables, from statistical correlation (Salvador-Carulla *et al,* 2007a) through multivariate analysis to artificial intelligence techniques. Variables selection using experts' opinions (EO) is limited (Garthwaite and Dickey, 1996a and Garthwaite, 1983a). There is a need to employ variable selection in reliability analysis because a large number of variables contribute to item performance, failure or condition. An expert elicitation approach to variable selection might consider only the variable set that the expert proposes to be important in asset condition assessment. A large number of variables may have impact on an asset, but not all of them can be used in practice because their contribution to the item condition may be negligible. Determining the major variables that impact on the asset condition is a major step in the process of condition assessment.

Suppose that there are M^i variables that might impact the condition of an asset. However, the value M^i might be too large and therefore, need to select only variables with significant impact on asset condition. We invite N^e experts for their opinions on the most important variables.

Within the M^i variables, experts are required to select a proportion (M^m). The experts also rate the importance of the variables they have already selected. They rate their M^m variables to be R_{ij}, where *i*=1,…, N^e, *j*=1,…, M^m. C_{ij} means the importance of the j-th variable assessed by the *i*-th expert. Some R_{ij} might be zero, indicating, the variable, does not contribute much to the asset condition.

After ranking $\sum_{i=1}^{N^e} R_{ij}$ in descending order, where *j*=1,…, M^m, the most important M^f variables that have the largest importance $\sum_{i=1}^{N^e} R_{ij}$ are selected.

For example, for a given set of water pumps, we might select only three variables: wear status, sound/vibration and oil leakage from a set of candidate variables such as wear status, rotation speed, water quality, sound/vibration, appearance, etc.

It should be noted that there are two widely used approaches to reaching a consensus. These include behavioural approach and mathematical approach.

- Behavioural aggregation: to elicit their views as a group by bringing them together and treating the group as a single 'expert'. That is, this approach requires the experts to reach a consensus.

  Behavioural aggregation is achieved by experts discussing the most important *M* variables among themselves and reaching consensus. In the final step, the consensus selected variables are ranked by experts according to their importance. The highest ranking variables in importance are chosen as the final M^f variable to be used to assess asset condition.

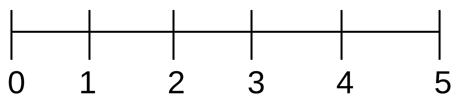
- Mathematical aggregation elicits the judgements of each expert separately, and then applies an algorithm to combine the separate judgements.

The mathematical and behavioural methods have been found to be similar in performance, with the mathematical rules having a slight edge (Clemen and Winkler, 1999 and Ouchi, 04a). On the other hand, Mosleh *et al.* (1988) reported that, although empirical evidence indicates that mathematical methods of aggregation generally yield better results than behavioural methods, the latter methods are often perceived to be appealing. This is particularly the case when experts have knowledge in different areas and the synthesis of their expertise is needed.

Table 3-2: Variable selection and importance rating

Variable (M^m)	**Importance**	**Importance score**
V_{i1}	S_{ij1}	I_{i1}
V_{i2}	S_{ij2}	I_{i2}
V_{i3}	S_{ij3}	I_{i3}
V_{i4}	S_{ij4}	I_{i4}
V_{i5}	S_{ij5}	I_{i5}
V_{i6}	S_{ij6}	I_{i6}
V_{i7}	S_{ij7}	I_{i7}

Experts were then asked to rate the importance of each of the M^i variables they have selected in the initial shortlist. The importance of each variable is ranked from 1 to 5 – with one being the least important and five, the most important ranking (Figure 3-2).



Least important *Most important*

Figure 3-2: Variable importance rating scale

Experts rate their M^m variables to be R_{ij}, where i=1,…, N^e, j=1,…, M^m, and R_{ij} means the importance of the j-th variable assessed by the i-th expert. Some of R_{ij} might be zeros. A variable can be selected several times by different experts and the importance total on the same variable is assessed. With all of the variables with difference importance weights, the most important M^f variables are then selected. Table 3-3 shows standard water pump's performance indicators. Experts select a few of the indicators for assessing the pump's condition.

Table 3-3: Typical pumps performance indicators (after ISO 13380, 2003)

Fault	Fluid leakage	Length/ dimension	Power	Head pressure	Flow	Speed	Vibration	Temperature	Wear status	Appearance	Oil leak
Damaged Impeller		✓	✓	✓	✓	✓	✓	✓	✓		
Damaged external seal	✓	✓		✓		✓	✓				
Eroded casing		✓									
Worn sealing rings			✓	✓	✓						
Eccentric impeller			✓	✓		✓	✓	✓	✓		
Bearing damage		✓	✓			✓	✓	✓	✓	✓	✓
Bearing wear		✓					✓	✓	✓	✓	
Mounting fault							✓	✓			
Unbalanc e								✓			
Misalign ment		✓						✓			

Experts finally select major performance variables to use in assessing the pump condition from the list of performance variable. These were corrosion (wear status), vibration/ sound and rotation speed. This step was introduced in order to ensure that assets were assessed based on the particular performance indicators associated with each specific asset group. The currently used criterion (Table 3-6) is limited in the use of specific performance indicators.

The three variables with the highest importance were finally selected. Table 3-4 presents the percentage weights for each variable. The survey was carried out only at two sites in order to be able to use uniform variables across all the other sites. The second site survey was to validate first site survey results.

Some variables are internal to the asset, which emphasizes the value of in-house experts. Experts from outside the organisation usually do not have time to assess assets components that are not external. They may not objectively assess some variables that are not directly related to certain components internal to the assets.

Table 3-4: Total variables experts selected from

Variable initial list		% Importance
V_{i1}	*Rotation*	30
V_{i2}	Bearing (wear)	8
V_{i3}	Suction conditions (Impeller)	6
V_{i4}	*Vibration*	25
V_{i5}	External seals	10
V_{i6}	*Corrosion*	15
V_{i7}	Oil leak	6

Table 3-5: Final variables selected

Site	Variable	Importance %
1 and 2	V_{i1} R	43
1 and 2	V_{i4} V	36
1 and 2	V_{i6} C	21

The three most important variables chosen by experts were;

- Vibration (V)
- Corrosion (C)
- Rotation (R)

3.4.2 Defining the grades asset condition

This section defines the grades of each variable that might impact asset condition. In generic terms, for the pump mentioned in Step A, could define the grades of the wear status as; as-new, minor wear/tear, and significant signs of wear/tear. The grades for each variable were defined using the same criteria as used for the overall asset condition.

Table 3-6: Condition grade criteria currently used by a water utility

CRITERIA	GRADE				
	1 GOOD	2 FAIR	3 ADEQUATE	4 POOR	5 AWFUL
VISUAL **External** - corrosion - Wear and tear - Leaking glands - Does it sound "healthy" - Does it look as if it is being maintained (greased, painted)	As new	Superficial wear	Significant wear & tear	Work required	Worn out
Internal - corrosion - Wear and tear - Leaking glands - Does it sound "healthy" - Does it look as if it is being maintained (greased, painted)	As new	Superficial wear	Normal wear & tear for current age of asset	Significant wear & tear	Worn out

Condition grade criteria definition (Table 3-6);

i. Grade 1 (good). Pump is in 'as-new' condition. Very little sound or vibration. Paint finish intact.

ii. Grade 2 (fair). Pump operating quietly without vibration but showing signs of minor wear and tear.

iii. Grade 3 (adequate). Still functioning acceptably but showing significant signs of wear and tear, possibly with reduced efficiency and minor failures. This is typically the best condition possible for an old line-shaft pump, most of which are 30+ years old.

iv. Grade 4 (poor). Still functional and operational but in rough order, possibly excessive vibration. Maintenance costs are high. Overhaul or remedial action required in medium term.

v. Grade 5 (awful). Life exceeded. May be unsafe to use or too costly.

The experts then gave their opinions on four sections of questions regarding water pump performance variable selection, condition assessment, maintenance effectiveness and maintenance regime paired comparison weighting. For variable selection, experts scored each variable defined according to the importance they attached to it. Experts gave individual assessments for the pump condition grade and preventative maintenance effectiveness.

3.4.3 Experts' condition assessment aggregates

The asset condition of each asset was then estimated to be, for example, if a mathematical approach is applied;

$$\sum_{i=1}^{N^e} \sum_{j=1}^{M^f} G_j C_{ij}. \qquad (3 - 1)$$

Where G_j represents the rating of the asset condition in relation to each of the M^f variables. C_{ij} represents the rating of the importance of the j-th variable as assessed by the *i*-th expert. Both weighted and un-weighted methods were used to aggregate the experts' condition assessments.

a) Equal weights

Equal weights and weighted aggregation methods were used to aggregate the experts' opinions. An opinion pool is a method of combining a number of different opinions about some unknown quantity θ to generate a single pooled opinion about θ. The two most widely used opinion pool methods are linear and logarithmic opinion pools. Suppose there are n experts, *pi(*θ*)* represents expert *i*'s probability distribution for unknown quantity θ, i =1, …, n, and *wi* be expert *i*'s weight. The combined probability distribution *p(*θ*)* is a weighted linear combination of the experts' probabilities (weighted arithmetic mean model) in a linear opinion pool. In a logarithmic opinion pool *p(*θ*)* is expressed as a multiplicative averaging (weighted geometric mean model):

Linear opinion pool *p(*θ*)* = Σ*i wi* * *pi(*θ*)*

Logarithmic opinion pool *p(*θ*)* = *k* Π*i pi(*θ*)wi*

Table 3-7 and 3-8 summarises the experts' condition assessment and aggregates for site 2. The aggregates were equally weighted.

Table 3-7: Experts individual condition assessments, site 2

Expert	Quartile	Pump 1	Pump 2	Pump 3
E1	L	0.40	0.01	0.90
	M	0.45	0.06	0.93
	U	0.49	0.09	0.95
E2	L	0.10	0.10	0.80
	M	0.20	0.15	0.90
	U	0.25	0.19	0.95
E3	L	0.05	0.05	0.75
	M	0.07	0.10	0.70
	U	0.10	0.14	0.80
E4	L	0.60	0.55	0.80
	M	0.65	0.58	0.90
	U	0.70	0.60	0.95

Where; L = Lower quartile
M = Median
L = Upper quartile

Table 3-8 shows the aggregates (equal weight) for experts' assessments from site 2. The aggregates for all sites are presented in Appendix 3-3.

Table 3-8: Experts equally weighted aggregates, site 2

	Pump 1	Pump 2	Pump 3
	CG	**CG**	**CG**
Group CG	1	2	2
L	0.29	0.18	0.81
M	0.34	0.22	0.86
U	0.39	0.26	0.91
Grade	0.34	0.22	0.86

The results from the condition assessment equal weight pooling are presented in Table 3-8. The results show that the experts did not deviate too far from the mean. The deviations from the mean were no more than 10% for each pump. This indicates that the experts generally agreed, with little deviations on the conditions of the water pump.

b) Performance-based weight aggregates

The second approach of combining experts' opinions that was used in the research pooled experts opinions based on the weight of their performance. The problem of opinion pools generally reduces down to determining the optimal weights *wi* for experts. Various methods for finding the optimal models are explored by DeGroot and Mortera (1991). The simplest choice of weights is assigning all experts an equal weight, $wi = 1 / n$. A simple arithmetic averaging of experts' assessments is used in many studies, including a U.S. Nuclear Regulatory Commission research on the frequency of accidents at nuclear reactors.

Each expert's contribution to the aggregate was assessed based on the performance against the seed variable. The seed variable being a value that is known to the facilitator but known to the experts after they have given their assessment scores. The seed variable performance for site 2 is presented in Table 3-9. Appendix 3-4 presents weights for all sites.

Table 3-9: Experts' weights based on performance, site 2

Experts	Weight
E1	0.17
E2	0.28
E3	0.31
E4	0.24

The experts were asked to estimate the average number of failures in the previous twelve months for pump 1 at each site. The answer was obtained from the case study water utility prior to asking the experts and the assessor already knew the answer.

The performance-based weighted averaging model is proposed by Cooke (1991A) and it uses properties of scoring rules, known as the classical model. He emphasizes that the fundamental goal of science is to build rational consensus and, therefore, the process of collecting expert assessments must be subjected to the following five basic principles (the first and second principles are later combined as a accountability principle (Cooke and Goossens, 2004):

1. *Reproducibility*: All results must be reproducible, with calculation models and data being clearly specified and made available.
2. *Accountability*: The source of data (name and institution) must be identified, and data must correspond to the exact source from which the data are elicited.
3. *Empirical Control*: Experts' assessments must be, in principle, physically observable.
4. *Neutrality*: The elicitation process must ensure that the actual beliefs of experts are elicited.
5. *Fairness*: All experts must be regarded equally before the aggregation process.

The term classical comes from the calibration measure's close association with classical hypothesis testing. The classical model is designed to satisfy all these principles of rational consensus. In case of continuous variables, the model requires experts to provide a set of fixed quantiles for some unknown variables (seed variables) *X1 , …, XN*. The decision-maker then determines the intrinsic range (lower and upper bound, [*ql , qh*]) of each variable for each expert.

The results from the condition assessment with weighted pooling are presented in Table 3-10.

Table 3-10: Experts' weighted aggregates, site 2

	Pump 1	**Pump 2**	**Pump 3**
U	0.26	0.18	0.80
M	0.20	0.09	0.70
L	0.21	0.07	0.52
Value	0.22	0.11	0.68

The results show that pump 3 was assessed as more than 50% past the grade given by the group, CG 2. .

The experts weighted aggregates show that the experts did not deviate too far from the mean. The deviation was 10%. This shows that the experts generally agreed, with little deviations, on the conditions of the water pump. Only pump 2 had had an outlier.

Table 3-11: Weighted and equal weight aggregates, site 2.

Asset	**Weighted aggregates**	**Equal weights**	**Difference**
Pump 1	0.22	0.34	+12
Pump 2	0.11	0.22	+11
Pump 3	0.68	0.86	+18

The results (Table 3-11) show that there is a difference between the results of performance weighted and equally weighted opinion pooling. For pump 2, the difference was 50%. Since equal weights reflect the opinions of the experts as a simple average, the weighted aggregates are used. This is because each expert contribution to the aggregate value.

c) Control approach and new asset condition assessment approach

Pumps' condition grades from the developed methodology were assessed against the control condition assessment approach. Table 3-13 presents the results for site 2. The results for all other sites are presented in Appendix 3-6.

Table 3-12: Old and new condition results, site 2

Site 2	**Pump 1**	**Pump 2**	**Pump 3**
Old CG	1	2	2
New CG value	1.22	2.11	2.68

Figure 3-3 presents the two approaches' results in a bar chart.

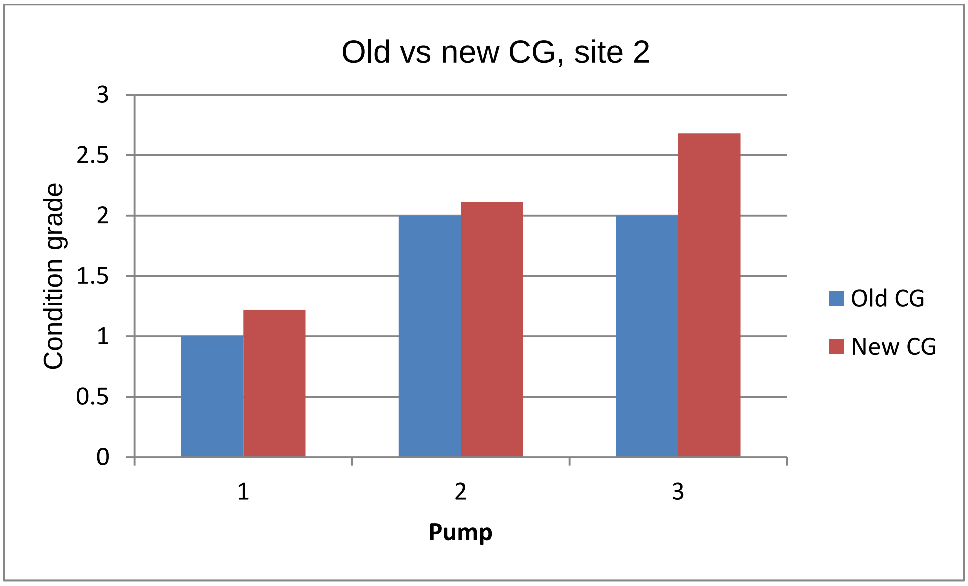


Figure 3-3: Developed condition grade and old method compared

Figure 3-3a shows the condition of pump 1 – 3 results for the control and the new approach.

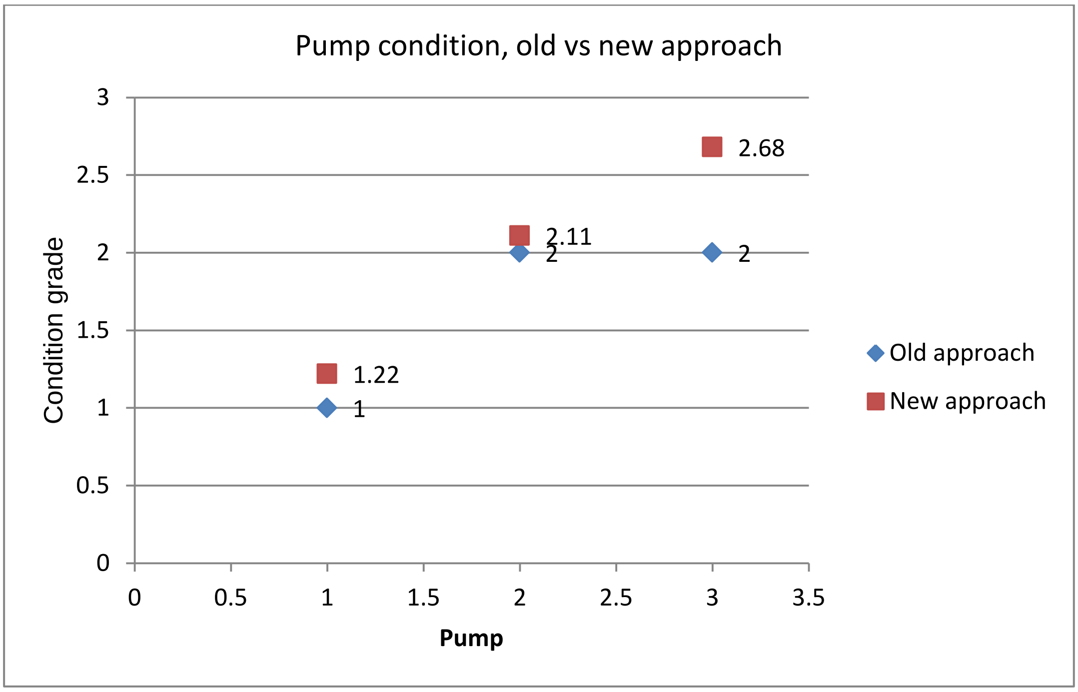


Figure 3-3a: Pump condition using old versus new approach, site 2

The results presented in Figure 3-3a show that all the three pumps had already passed the condition grade given by the old method (control approach). Pump 3, for example, was assessed as condition grade 2 under the control method. However, the pump was in condition grade 2.68 according to the new condition assessment approach. Pump 3 was more than 50% past condition grade 2 and hence, closer to CG 3 than CG 2. This reveals the gap in the magnitude of error the new approach is able to close, which leads to much improved precision in the asset condition assessments. Precision improved by 11% and 22% for pump 1 and 2, respectively.

3.4.4 Experts condition assessments with evidence

Condition assessment values were sought without evidence and with evidence. The experts were asked to review their condition assessments in the light of evidence of the number of corrective maintenance for each pump in the preceding twelve months (Table 3-13a). The table shows an example of the record of the evidence from the case study organisation for site 2. Another evidence data (site 1) source table is presented in Appendix 3-9.

Table 3-13a: Asset performance evidence data source

Site 2 Maintenance history: 2002 to 2010				
Order	Order Type	Service product	Bas. start date	Description
11741558	WMS3	9583	18/06/2010	JARVISSA UTILITY (TECO) on 01.07.2010
11741560	WMS3	9583	18/06/2010	BRADLEYC UTILITY (COMPLETE) on 24.06.201
11741621	WMS3	9592	18/06/2010	9592 - RWM - Appointment 1hr - EB - Meet
9752980	WMS3	EMER	24/07/2008	SITE WPS - POWER TO MCC FAILED
4287496	WMS2		10/04/2002	PUMP HEALTH CHECK
4287497	WMS2		10/04/2002	CHANGE PUMP DUTY
4359280	WMS2		08/05/2002	PUMP HEALTH CHECK
4359321	WMS2		08/05/2002	CHANGE PUMP DUTY
4432193	WMS2	CW110000039	05/06/2002	ROUTINE INSP. WPS
4432194	WMS2	CW120000020	05/06/2002	PUMP HEALTH CHECK
4432195	WMS2	CW130000015	05/06/2002	CHANGE PUMP DUTY
4484804	WMS3	9122	29/05/2002	9122-Respond to RTS Svce Delivery Alarm
4498677	WMS2	CW120000020	03/07/2002	PUMP HEALTH CHECK
4498678	WMS2	CW130000015	03/07/2002	CHANGE PUMP DUTY
4563249	WMS2	CW120000020	31/07/2002	PUMP HEALTH CHECK
4563250	WMS2	CW130000015	31/07/2002	CHANGE PUMP DUTY
4629917	WMS2	CW110000039	28/08/2002	ROUTINE INSP. WPS
4629918	WMS2	CW120000020	28/08/2002	PUMP HEALTH CHECK
4629919	WMS2	CW130000015	28/08/2002	CHANGE PUMP DUTY
4850333	WMS2	CW110000074	20/11/2002	SRE/WTR & WPS ROUTINE INSPECTION 3M
4874704	WMS3	9122	11/11/2002	9122-Respond to RTS Svce Delivery Alarm
5005692	WMS2	CW110000074	12/02/2003	SRE/WTR & WPS ROUTINE INSPECTION 3M
5058717	WMS2	CW080000098	10/02/2003	SRE/WTR & WPS ROUTINE INSPECTION 3M
5058718	WMS2	CW080000106	10/02/2003	WPS HEALTH CHECK & CHANGE PUMP DUTY 4W
5064348	WMS2	CW080000106	10/03/2003	WPS HEALTH CHECK & CHANGE PUMP DUTY 4W
5128299	WMS2	CW080000106	07/04/2003	WPS HEALTH CHECK & CHANGE PUMP DUTY 4W
5194093	WMS2	CW080000098	05/05/2003	SRE/WTR & WPS ROUTINE INSPECTION 3M
5194094	WMS2	CW080000106	05/05/2003	WPS HEALTH CHECK & CHANGE PUMP DUTY 4W
5256642	WMS2	CW080000106	02/06/2003	WPS HEALTH CHECK & CHANGE PUMP DUTY 4W
9163757	WMS2	CW080000106	07/01/2008	WPS HEALTH CHECK & CHANGE PUMP DUTY 4W
9382821	WMS2	CW080000106	31/03/2008	WPS HEALTH CHECK & CHANGE PUMP DUTY 4W
9604781	WMS2	CW080000106	30/06/2008	WPS HEALTH CHECK & CHANGE PUMP DUTY 4W
9687999	WMS3	9122	28/06/2008	9126-Respond to RTS ICA Alarm
9759892	WMS3	9122	27/07/2008	9126-Respond to RTS ICA Alarm
9763056	WMS3	EMER	28/07/2008	Site road wps - pump no2
9812868	WMS2	CW080000106	15/09/2008	WPS HEALTH CHECK & CHANGE PUMP DUTY

				4W
9975596	WMS3	9126	17/10/2008	9126-Respond to RTS ICA Alarm//D kenyon
9975598	WMS3	9122	17/10/2008	9122-Respond to Service Delivery Alarm//
9975626	WMS3	9126	17/10/2008	9126-Respond to RTS ICA Alarm
9975637	WMS3	9122	17/10/2008	9126-Respond to RTS ICA Alarm
9976671	WMS3	9122	17/10/2008	9122-Respond to Service Delivery Alarm//
9976768	WMS3	I1TB	17/10/2008	Site WPS pressure control. Pressure con
10052303	WMS2	CW080000106	08/12/2008	WPS HEALTH CHECK & CHANGE PUMP DUTY 4W
10276617	WMS2	CW080000106	02/03/2009	WPS HEALTH CHECK & CHANGE PUMP DUTY 4W
10522077	WMS2	CW080000106	25/05/2009	WPS HEALTH CHECK & CHANGE PUMP DUTY 4W
10621555	WMS3	9118	30/05/2009	9118-Network Operation
10662295	WMS3	9118	12/06/2009	9118-Network Operation
10685078	WMS3	9122	21/06/2009	Site Road Pump 2 failed
10766871	WMS3	9118	15/07/2009	Pump No 2 failed pls reset
10772893	WMS2	CW080000106	17/08/2009	WPS HEALTH CHECK & CHANGE PUMP DUTY 4W
10791723	WMS3	9118	24/07/2009	9118-Network Operation
10843983	WMS3	9118	11/08/2009	9118-Network Operation
10885531	WMS3	9118	25/08/2009	9118-Network Operation
10908426	WMS3	9118	02/09/2009	Please investigate pump 3 failure
10952234	WMS3	9118	18/09/2009	Pumps 2 and 3 failed please reset - Plea
10957100	WMS3	9118	20/09/2009	Site road pumps 2 and 3 failed - Pleas
10969353	WMS3	9118	24/09/2009	9118-Network Operation
10986503	WMS3	9118	30/09/2009	9118-Network Operation
11002098	WMS3	9122	05/10/2009	Pls reset pump No 2 failed Thanks
11004493	WMS3	9122	06/10/2009	Pump No 2 failed again- pls call control
11009216	WMS3	9118	07/10/2009	9118-Network Operation
11014944	WMS2	CW080000106	09/11/2009	WPS HEALTH CHECK & CHANGE PUMP DUTY 4W
11026995	WMS3	9122	14/10/2009	Pumps 2 and 3 failed pls reset Thanks
11053219	WMS3	9118	24/10/2009	9118-Network Operation
11060843	WMS3	9118	26/10/2009	9118-Network Operation
11079940	WMS3	9118	02/11/2009	9118-Network Operation
11086202	WMS3	9118	04/11/2009	9118-Network Operation
11108159	WMS3	9118	13/11/2009	9118-Network Operation
11117942	WMS3	9122	16/11/2009	Pump No 3 failed - pls reset
11120874	WMS3	9122	17/11/2009	Pump 3 failed please reset Thanks
11130060	WMS3	9118	20/11/2009	9118-Network Operation
11130606	WMS3	9118	22/11/2009	Pump No 2 failed please reset Thanks
11141607	WMS3	9118	24/11/2009	9118-Network Operation
11167514	WMS3	9118	04/12/2009	9118-Network Operation
11168919	WMS3	9118	05/12/2009	Reset pumps 2 and 3, both failed - Pleas
11169604	WMS3	9118	05/12/2009	9118-Network Operation
11185206	WMS3	9118	10/12/2009	9118-Network Operation
11186053	WMS3	9118	10/12/2009	9118-Network Operation
11187769	WMS3	9118	12/12/2009	9126-Respond to RTS ICA Alarm
11201352	WMS3	9122	16/12/2009	9126-Respond to RTS ICA Alarm
11243198	WMS2	CW080000106	01/02/2010	WPS HEALTH CHECK & CHANGE PUMP DUTY 4W
11260241	WMS3	9118	08/01/2010	9118-Network Operation

11261576	WMS3	9118	09/01/2010	9118-Network Operation
11308053	WMS3	9118	24/01/2010	Site Road pump 3 failed - Please reset
11314823	WMS3	9118	26/01/2010	9118-Network Operation
11325464	WMS3	9122	30/01/2010	9122-Respond to Service Delivery Alarm
11366270	WMS3	9122	10/02/2010	9126-Respond to RTS ICA Alarm
11369933	WMS3	9118	13/02/2010	9118-Network Operation
11370808	WMS3	9118	13/02/2010	9118-Network Operation
11375936	WMS3	9118	14/02/2010	9118-Network Operation
11382150	WMS3	9118	17/02/2010	Pump 3 failed. Please reset. Thank You
11387653	WMS3	9118	19/02/2010	Site Road pump 3 failed - Please reset
11392431	WMS3	9118	20/02/2010	9118-Network Operation
11399319	WMS3	9118	24/02/2010	9118-Network Operation
11484331	WMS2	CW080000106	26/04/2010	WPS HEALTH CHECK & CHANGE PUMP DUTY 4W
11650724	WMS3	9122	19/05/2010	9122-Respond to Service Delivery Alarm
11651847	WMS3	9118	19/05/2010	9118-Network Operation
11743567	WMS2	CW080000106	19/07/2010	WPS HEALTH CHECK & CHANGE PUMP DUTY 4W
11755024	WMS3	9122	22/06/2010	9122-Respond to Service Delivery Alarm
11799631	WMS3	9118	06/07/2010	9118-Network Operation
11828279	WMS3	I1IB	15/07/2010	Pump control does not appear to be worki
5514418	WMS2	E1000000327	22/09/2003	MOTOR & STARTER SERVICE
5514419	WMS2	E1000000327	22/09/2003	MOTOR & STARTER SERVICE
5514420	WMS2	E1000000327	22/09/2003	MOTOR & STARTER SERVICE
7136444	WMS2	E1000000327	19/09/2005	MOTOR & STARTER SERVICE
7136445	WMS2	E1000000327	19/09/2005	MOTOR & STARTER SERVICE
7136446	WMS2	E1000000327	19/09/2005	MOTOR & STARTER SERVICE
8872065	WMS2	E1000000327	17/09/2007	MOTOR & STARTER SERVICE
8872066	WMS2	E1000000327	17/09/2007	MOTOR & STARTER SERVICE
8872067	WMS2	E1000000327	17/09/2007	MOTOR & STARTER SERVICE
10979534	WMS2	E1000000327	28/10/2009	MOTOR & STARTER SERVICE
10979535	WMS2	E1000000327	28/10/2009	MOTOR & STARTER SERVICE
10979536	WMS2	E1000000327	28/10/2009	MOTOR & STARTER SERVICE
9975600	WMS3	EMER	17/10/2008	Site wps - x3 pumps tripped out

Table 3-13 shows the results of the asset condition assessments after the evidence for site 2. The results for all the surveyed sites are presented in Appendix 3-7 and Appendix 3-8.

Table 3-13: Condition with performance evidence, site 2

	Pump 1	Pump 2	Pump 3
Group condition	1	2	2
Before CM	0.34	0.22	0.86
After CM	0.22	0.11	0.68
Condition before	1.34	2.22	2.86
Condition after	1.22	2.11	2.68
Change	-12	-11	-18

Figure 3-4 and Figure 3-5 show the condition assessments before evidence of the assets performance was shown to experts, after evidence was shown, and group consensus among the experts. It demonstrates the value and contribution that evidence can contribute to the condition assessment quality. Experts were asked to give their condition assessments of each pump after knowing the number corrective maintenance carried out due to failures on each pump.

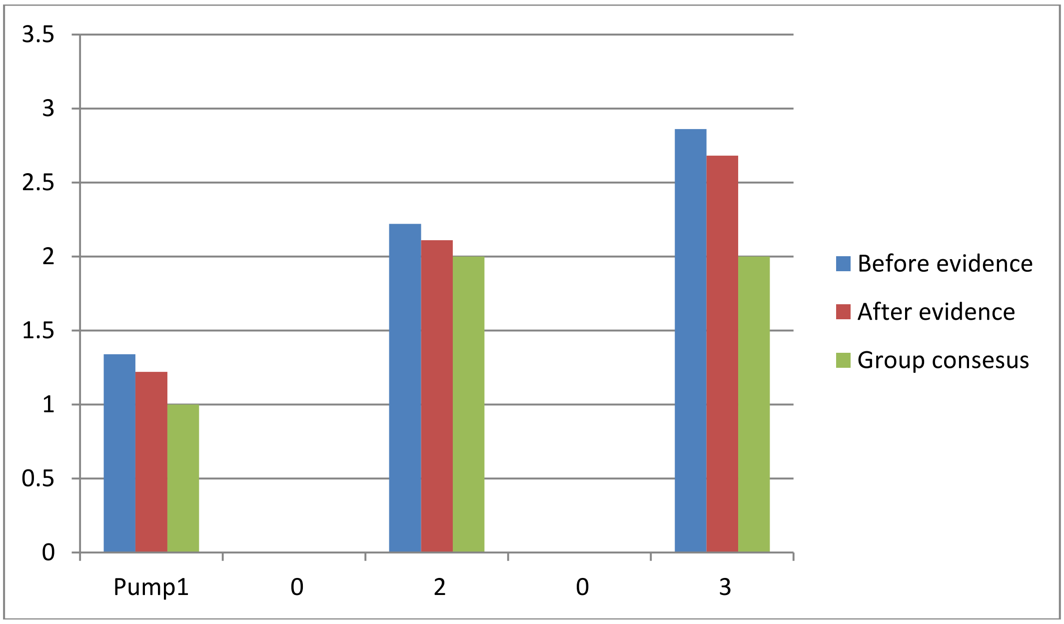


Figure 3-4: Condition rating of each pump before evidence, after evidence and group assessment

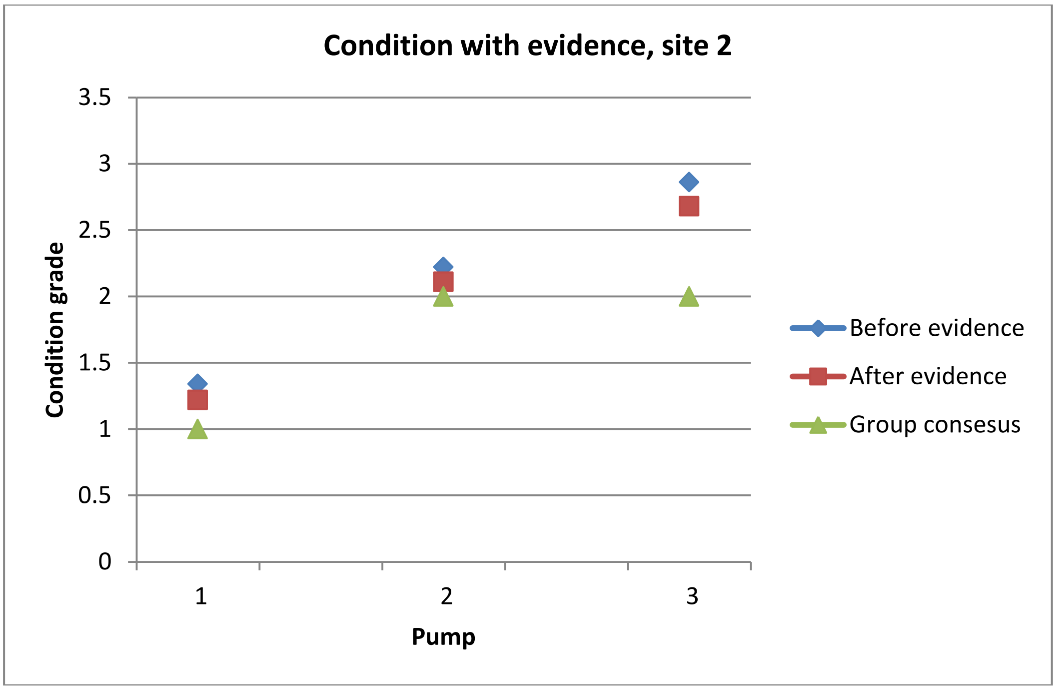


Figure 3-5: Condition rating points before, after evidence and group assessment

Figure 3-6 shows the percentage change after experts reviewed their opinions on seeing corrective maintenance evidence for pump 3. For other pumps the difference was larger and for some, smaller.

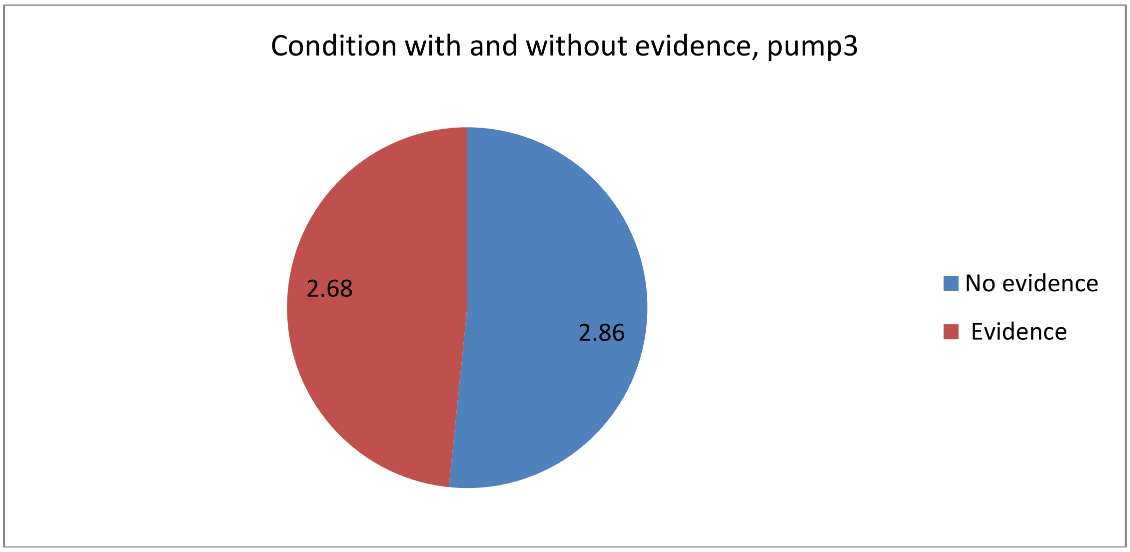


Figure 3- 6: Percentage change after evidence

Pump 3 assessment changes for the condition assessments for each pump after evidence are presented in Table 3-14. The results for all other surveyed sites are presented in Appendix 3-8 and 3-9.

Table 3-14: Experts' unit changes after corrective maintenance evidence, site 2.

Pump	Unit change
1	-12
2	- 11
3	-18

Table 3-14a presents all surveyed sites change values in asset condition assessments, after evidence was presented to experts.

Table 3-14a: Changes in assessments after evidence, site 1-7

Evidence	Pump 1	Pump 2	Pump 3	Site
Change	-25	-1	-71	Site 1
Change	-12	-11	-18	Site 2
Change	- 12	-0.02	-33	Site 3
Change	+14	-8	-34	Site 4
Change	-12	-11	-14	Site 5
Change	-3	+10	+6	Site 6
Change	+24	-	+33	Site 7

The unit (Table 3-14a) changes in the experts opinions due to asset performance evidence further emphasizes the meaningful contribution that evidence can add to the quality of asset condition assessment where there is sparse data. More evidence can be introduced into the elicitation exercise as more asset performance data are collected in a water utility.

3.4.5 Heuristics and biases

The analysis also considered heuristics and bias in the survey. Heuristics are personal tendencies that reduce objectivity in human response to questions. The experts were aware of biases from the training sessions. Table 3-16 shows some of the responses experts gave when asked about types of bias they think they had when giving their opinions. Availability and personal gain motivation were the dominant bias sources for most experts (100%), followed by anchoring (75%). Anchoring is the tendency for experts to give opinion to a question based on a previous answer they have given. Experts also (100%) said they gave answers based on potential gain of better funding for their pumping station as well because they perceived management as not very interested in their asset maintenance needs. Personal gain is the tendency to consider the personal effect (gain or loss) of a particular response to a question. 50% of the experts believe they were influenced by group think and 50% indicated it they considered what they thought the assessor wanted.

Table 3-15: Responses to bias assessment, site 2

Question	Response	Heuristic	Experts
1. Subjective motivation to assessments.	- What I think assessor wants. - To attract priority management attention.	- Bias. - Personal gain.	- 50% - 100%
2. Group influence.	- Yes. Group conformity	- Group think.	- 50%
3. Other influences.	- Previous responses. - Work experience	- Anchoring - Availability	- 75% - 100%

Different results from the seven surveyed sites are presented in Appendix 3-10. The emerging theme from the results was that the most common bias from all the sites was Availability and responses motivated by personal gain (100%).

Distributions of experts' assessments

The beta distribution is widely used to assess experts' opinions. This is because some software programmes only incorporate the beta distribution in their assessment (such as, SHELF) and others recommend it as standard practice (O'Hagan, 2011). The experts, results for each are presented in Table 3-16.

Table 3-16: Individual expert's assessments distributions

	Expert	**Pump 1**	**Pump 2**	**Pump 3**
		CG	**CG**	**CG**
Site 1	E_{11}	0.03	0.09	0.11
		0.09	0.15	0.17
		0.14	0.21	0.19
	E_{12}	0.22	0.02	0.09
		0.35	0.08	0.13
		0.45	0.13	0.21
	E_{13}	0.50	0.09	0.11
		0.66	0.15	0.16
		0.70	0.21	0.21
	E_{14}	0.01	0.02	0.09
		0.03	0.07	0.17
		0.05	0.14	0.22
CG		2.00	3.00	2.00
Site 2	E_{21}	0.40	0.01	0.90
		0.45	0.06	0.93
		0.49	0.09	0.95
	E_{22}	0.10	0.10	0.80
		0.20	0.15	0.90
		0.25	0.19	0.95
	E_{23}	0.05	0.05	0.75
		0.07	0.10	0.70
		0.10	0.14	0.80
	E_{24}	0.60	0.55	0.80
		0.65	0.58	0.90
		0.70	0.60	0.95
CG		2.00	2.00	1.00
Site 3	E_{31}	0.50	0.10	0.60

		0.55	0.15	0.65
		0.57	0.18	0.70
	E_{32}	0.20	0.30	0.55
		0.22	0.33	0.57
		0.25	0.39	0.59
	E_{33}	0.01	0.02	0.10
		0.03	0.04	0.16
		0.05	0.06	2.00
	E_{34}	0.30	0.40	0.70
		0.35	0.45	0.74
		0.39	0.60	0.78
CG		1.00	1.00	1.00
Site 4	***E_{41}***	0.10	0.10	0.65
		0.15	0.12	0.70
		0.18	0.15	0.80
	E_{42}	0.01	0.40	0.40
		0.03	0.50	0.50
		0.05	0.55	0.60
	E_{43}	0.20	0.10	0.80
		0.22	0.15	0.90
		0.25	0.19	0.95
CG		1.00	1.00	1.00
Site 5	***E_{51}***	0.05	0.05	0.10
		0.10	0.15	0.20
		0.15	0.20	0.25
	E_{52}	0.45	0.01	0.70
		0.50	0.03	0.75
		0.55	0.05	0.80
	E_{53}	0.01	0.02	0.01
		0.03	0.50	0.02
		0.05	0.10	0.05
	E_{54}	0.07	0.80	0.10
		0.09	0.85	0.15
		0.10	0.90	0.20
CG		2.00	2.00	3.00
Site 6	***E_{61}***	0.05	0.50	0.05
		0.10	0.60	0.10

		0.12	0.80	0.15
	E_{62}	0.40	0.40	0.10
		0.50	0.50	0.12
		0.60	0.60	0.15
	E_{63}	0.70	0.80	0.05
		0.90	0.90	0.07
		0.95	0.95	0.09
	E_{64}	0.80	0.80	0.10
		0.82	0.82	0.13
		0.85	0.85	0.15
	E_{65}	0.50	0.40	0.12
		0.55	0.45	0.15
		0.60	0.50	0.16
CG		3.00	4.00	3.00
Site 7	***E_{71}***	0.05	0.05	0.40
		0.10	0.01	0.50
		0.15	0.02	0.55
	E_{72}	0.22	0.03	0.10
		0.20	0.05	0.20
		0.25	0.08	0.25
	E_{73}	0.75	0.10	0.50
		0.70	0.02	0.60
		0.80	0.05	0.65
	E_{74}	0.80	0.09	0.70
		0.85	0.10	0.75
		0.90	0.15	0.80

3.4.6 Evaluation of results

This research explored calibration, coherence, and experts' confidence to evaluate and validate the data and results. Experts' opinions weights were also assessed to validate the aggregate opinions.

a) Calibration

In simple terms, calibration refers to the standardisation a process by determining its deviation from the standard. In expert elicitation, calibration studies are concerned with the appropriateness of assessors' subjective probability estimates, or confidence in their judgments and predictions. Calibration is the assessment of experts' performance based on a test question which answer is known to the analyst and known to the experts post hoc (O' Hagan *et al*, 2006a). It can be categorized in two groups: one that elicits judgments about discrete propositions, and one that attempts to identify probability density functions assessed over continuous variables (such as, uncertain numerical values). The customary definition for discrete probability statements is that judgments are well calibrated if in the long run, for all propositions assigned a given probability, the proportion that is true is equal to the probability assigned (Hardman, 2009b). Discrete probability statements can be classified according to the number of possible alternatives the expert is exposed to, and the corresponding range of the probability scale. The expert is required to make a probability judgment with regard to a single event or statement. The appropriate probability response in this case ranges between 0 and 1.0. In the *two alternatives case* the assessor has to choose between two alternatives, and then provide a probability judgment for the chosen alternative in the range of 0.5 to 1.0. Finally, in the multiple alternatives case, the assessor is asked to select the most likely response.

Calibration is one way to evaluate probability judgments. A central problem with the strict view is its strict definition of calibration, namely the accuracy by which probability judgments correspond to reality. The loose approach is based on a broader standard which allows the assessment of the adequacy of probability judgments (and in which calibration is just one of a larger criteria). An adequate probability statement is meant to convey information and should be accurate as far as possible. However, the criterion for accuracy when applied to probability judgments is often ambiguous and controversial and, under certain circumstances, meaningless. Moreover, the information contained in a probability statement should be evaluated not just by precision, but also by amount and quality as could be determined by the measure of resolution. In this research, the interest is in the adequacy of the experts' judgements and improvement in the resolution of the assessments in informing decision makers.

Results from experts' performance were assessed against a known assessment (seed variable). It is assumed that all experts should know the assessment value if they are 'good'. Deviation from the seed variable was analysed.

The calibration scores for each site are presented in this section (Table 3-17).

Table 3-17: Experts' calibration scores, site 1 - 7

	Expert	**Expert assessment**	**Deviation (O)/ (U)**	**Site O/U**
Site 1	E1	0.32	**+**	**O**
	E2	0.21	**+**	**O**
	E3	0.29	**+**	**O**
	E4	0.18	**+**	**O**
Site 2	E1	0.17	**-**	**U**
	E2	0.28	**+**	**O**
	E3	0.31	**+**	**O**
	E4	0.24	**+**	**O**
Site 3	E1	0.25	**+**	**O**
	E2	0.28	**+**	**O**
	E3	0.16	**-**	**U**
	E4	0.31	**+**	**O**
Site 4	E1	0.27	**+**	**O**
	E2	0.23	**+**	**O**
		0.31		

	E3		**+**	**O**
	E4	0.19	**0**	**-**
Site 5	E1	0.20	**+**	**O**
	E2	0.16	**-**	**U**
	E3	0.28	**+**	**O**
	E4	**0.36**	**+**	**O**
Site 6	E1	0.18	**-**	**U**
	E2	0.31	**+**	**O**
	E3	**0.36**	**+**	**O**
	E4	0.15	**-**	**U**
Site 7	E1	0.24	**+**	**O**
	E2	0.20	**-**	**U**
	E3	0.29	**+**	**O**
	E4	0.27	**+**	**O**

Where: U = Under-confident
O = Over-confident

The results show that experts were more over-confident than under-confident. The experts' highest over-confidence level being 36%, expert 3 (site 6) and expert 4 (site 5). Under-confidence was as low as 15%, expert 4 (site 6). One expert was perfectly calibrated, expert 4 (site 4).

b) Coherence requirements

Coherence tests are for evaluating experts' probability assessments. The essence of this criterion is to assure that the relations between assessments are governed by the laws of probability and it is also referred to as internal consistency (Yates, 1982a). A set of probabilities is said to be coherent if it does not lead to a loss of independence of the observed outcome (Kadane and Lichtenstein, 1982a). It is noted that tests of coherence can be meaningfully applied to events that are unrelated and essentially unique. For example, if a rainy day is dependent on a cloudy day, they test of coherence cannot be meaningful. It was therefore, important to make experts understand this and chose questions that are suitable to test the experts' coherence.

Coherence was assessed by one question asked and the expert had to give a mathematically consistent response consistent with the law of probability that the sum of probabilities should not exceed one. Experts whose assessed probability of an occurrence and non-occurrence of an event exceeded one were deemed to be not coherent. The purpose was to test if the experts understood simple probability and their therefore, their opinions' quality. All experts were coherent except expert E3, as indicated in Table 3-18. Results for other sites are presented in Appendix 4-2.

The probability that pump 1 was exactly in condition grade 1 was assessed. Experts were then asked for their probability that pump1 was not exactly in condition grade 1.

Table 3-18: Coherence test results, site 2

Expert	Probability pump 1 in CG 1	Probability pump 1 in CG 1	Total
E1	0.90	0.10	1.00
E2	0.99	0.01	1.00
E3	0.90	0.20	1.10
E4	0.80	0.20	1.00

The coherence test results seemed to relate to the experts' work experience, as indicated in Table 3-19. The expert with only one year work experience was the only one who was not coherent in his assessment. The sum of his probability estimates was more than 1, which should not be the case for a coherent assessment (E3). It was not obvious how work experience and coherence would relate. This was true for five of the seven surveyed sites (71%). The coherence could be due to confidence garnered from previous experience with a similar exercise for the experienced experts.

Table 3-19: Experts work experience, site 2.

Expert	Work experience (years)
E1	25
E2	10
E3	1
E4	12

Appendix 3-11 presents the experts' work experience for all other sites.

c) Experts overall contribution to aggregate value

The results show that none of the experts individual opinions had significant impact on the overall score (more than 50%) as indicated in Table 3- 20. This could be due to the fact that all the experts were engineers who maintain the assets regularly and similar experience with the assets. The performance weights for other sites are presented in Appendix 3-12.

Table 3-20: Weights against seed variable, site 2

Experts	Performance	Weights	True value
E1	5.00	0.17	7.33
E2	8.00	0.28	
E3	9.00	0.31	
E4	7.00	0.24	
Total	29.00		

The performance weights were derived from experts' performance in relation to a seed variable. Experts were asked to give their opinion on a question whose answer was known to the assessor, also known as the seed variable. The experts' response was given as a weight indicating the quality of opinions they would give in all other assessments. The performance weights for site 2 were within a reasonable range. No expert could be considered an obvious outlier, indicating that each expert contributed fairly to the asset condition value. No individual expert dominated by contributing too much to the asset condition assessment aggregate value. The same was true for all other sites, except site 6 where expert 1 and 4 contributed less than half of the other experts' asset condition aggregate value. The results for a weighted pooling method of aggregating experts' opinions are considered fair even in such cases. This is because each expert contributed according to their performance quality, as indicated by the weights.

d) Experts confidence

Experts were asked to state their confidence in their assessment according to their understanding of the different maintenance regimes and their application to different asset groups within the organisation. Table 3-22 summarises the experts' confidence for site 2. Confidence assessments for all other sites are presented in Appendix 3-13.

Table 3-21: Experts confidence in their condition assessments, site 2

Experts	Confidence
E1	95%
E2	95%
E3	85%
E4	70%

Expert (E4) was the least confident. This expert indicated that he had been in asset maintenance for less than a year at the time of the survey. This could be the reason for his lack of confidence, compared to his colleagues who had been with the organisation for at least ten years. The average confidence (86%), which is limited because of the new experts indicates the confidence in the research results. A more reflective confidence (91%) is derived from the three experienced experts as the inexperience (E4) is an obvious outlier, as stated by the expert himself. Validation is intended to measure the accuracy of probability assessments, but the question that remains is that of 'accuracy in what sense'? The strict view of probability conceives the 'true' probability to be reflected by relative frequencies measures. Although the notion of the very existence of a ‘true’ probability is still debated, for purposes of this research, the subjective view of probability is adopted because the nature of an asset condition and the experts’ opinion quality is not a frequency estimate.

3.5 Cost penalties in condition grade misallocation

There are several implications to the misallocation of assets condition grades. These could be related to the assets reliability, customer services, environmental impact, regulation and maintenance cost. Only misallocation impact on maintenance cost was explored in this research. This is because cost is always important for profit-making organisations. Table 3-22 presents a cost allocation methodology for CG 1 pumps from the sample.

Table 3-22: CG 1 budget cost allocation

CG1 pumps	**CG1 EW**	**Cost allocation**	**Group Agreement CG**		
1	1.05		1		
7	1		1		
12	1		1		
17	1		1		
20	1		1		
22	1		1		
24	1		1		
26	1		1		
29	1		1		
38	1.16		1		
40	1.2		1		
42	1		1		
43	1.13		1		
52	1.16		1		
53	1.22		1		
59	1		1		
63	1		1		
67	1		1		
77	1		1		
83	2.23		1		
88	1		1		
93	1		1		
95	1.148		1	Cost allocation	Total budget
Total	25.32	47374.65/grade	23	52173.91/ grade	1200000/ year
	Assumed maintenance budget = £ 1.2 Million / year / CG				

By using the mathematical aggregation there are 2.3 extra CG 1 equivalents than the behavioural method. This means that the budget allowance application to Ofwat for

CG 1 pump maintenance will be lower than it should have been. This is because some of the pumps have gone past CG 1 and need more maintenance than is presented by behavioural methods results.

Table 3-22 shows CG 1 pumps require £52173.91 maintenance cost for the five year budget period. When using the mathematical method, pump 20 is not to be in CG1, leaving 22 pumps in CG1. That means the budget allocation per pump will be (£1200000/ 22) = £54545.45 instead. As more and more assets are misallocated, the budget is further distorted such that there will be over or under investment in maintenance.

Table 3-22 also shows that pump 1, 29, 43, 52, 53, 83, 95 conditions are under rated in the behavioural method. This suggests that less maintenance attention will be given to these pumps than they actually require. It would lead to faster deterioration of these pumps – shortening their service life. As this misallocation continues over time, the assets lives will be shortened and the organisation will not achieve maximum benefit from them.

Misclassification penalty costs, Approach 2

The optimum classification of assets condition grades is important because asset management plans are based on such grades. The amount of maintenance and capital investments for five year asset plans are based on the condition grades assessments, which are used as the basis for forecasting in water utility. Therefore, getting the condition grades right is necessary to ensure sound investment in asset management. Failure to do so could result in poor maintenance or having too much resource invested in maintenance and compromising the utilities' profitability in the short and long-term. A model for condition grades misclassification costs penalty assessment for different scenarios is presented.

A water pump was assessed for its condition grade by experts according to methodology outlined in Section 3,2. In reality, the water pump's condition was grade 2 (CG2). Three scenarios are presented where the pump was wrongly classed as

CG1, CG3 or CG4. The cost of each misclassification was assessed based on the following assumptions (Table 3-23),

- Each pump condition grade incrementally costs £2000 per year in maintenance.
- The misclassification results from consensus expert opinions.
- The misclassification is only likely for two grades above or below the true grade.

Maintenance costs associated with the classified grades are;

$CG_2 = C_O$ = maintenance cost £4000/year

$CG_2 \text{---} CG_1 = C_1$ = maintenance cost - £2000/year instead of £4000

$CG_2 \text{---} CG_3 = C_2$ = maintenance cost £6000/year instead of £4000

$CG_2 \text{---} CG_4 = C_3$ = maintenance cost £8000/year instead of £4000

Table 3-23: CG misclassification costs

Costs, Condition grade	**Misclassification C_1**	**True grade C_0**	**Misclassification C_2**	**Misclassification C_3**
	CG1	CG2	CG3	CG4
CG1, **CG2**, CG3, CG4	£2000	£4000	£6000	£8000
CG1, **CG2**, CG3, CG4	-£2000	0	+£2000	+£4000

The results show that the lower the grade an asset is misclassified to, the less the maintenance cost incurred. This is because the asset is assumed to be in a better condition than it is actually supposed to be. The higher the grade an asset is misclassified to, the higher the maintenance resources are invested in it. This is because the asset is assumed to be in a worse state than it actually is.

As less maintenance attention is given to lower misclassification, the asset service life is shortened and could lead to an increased number of failures. In the long term, a lower misclassification may be more costly than a higher misclassification. This would be due to cost of repairs and lost earnings due to downtime as the failure rate increases. A higher misclassification may be short-term waste, but the asset may benefit from more than average maintenance. This could lead to increased reliability and an increased service life.

It is worth noting that the CG misallocation would be more detrimental if the asset was in the latter stages of its life (CG 4 or 5). A condition grade 5 asset put under CG 3 would also receive less maintenance investment and attention. Since the asset is already almost at the end of its life, it will be assessed as having longer time remaining before its end of life. On the other hand, it is likely to fail unexpectedly leading to increased downtime, risk of pollution to the environment, risk to human health, and increased maintenance/repair costs as well as possible early replacement costs.

3.6 Strategic fit of asset condition assessment

The results from the research were obtained by experts stating their condition grade 1 to 5 and then stating their uncertainty level regarding the condition grade. The uncertainty level sought was regarding how much the experts believed that the asset had already passed the condition grade they had first given. This entailed elicitation of an expert's point estimate of the grade and then stating their uncertainty for the given interval above the grade. The results in Table 3-12 show the experts' responses for both condition grade point estimates and uncertainty regarding the estimate. Experts gave their lower quartile, mean and upper quartile. The results show that experts expressed lack of confidence in the point estimates and increased their confidence when they were able to state their uncertainty (Figure 3-4).

Experts were then shown historical data for each of the water pumps whose condition they had assessed and were asked to re-state their opinions if they wanted to. The data were all corrective maintenance carried out for each water pump in the past twelve months – representing some of the evidence of the performance of each pump. The results show that experts reviewed their opinions after being shown the corrective maintenance evidence. The experts gave a worse condition than stated before the evidence where there were relatively a large number of corrective maintenance actions and an improved condition where the number was lower.

As, stated earlier, expert opinions based condition assessments in water utility have tended to only elicit point estimates and with quite large margins of error as experts could only state condition 1 – 5. The results from this research mitigate the problem by introducing uncertainty estimates and hence, allows a reduction in the margin as experts can state estimates between 0 – 1. Other studies explore this method mainly as probability estimates. It has therefore, been proven to be better than point estimates and water utilities would be improving their assessments for their asset capital planning framework requirements and better fulfilling their regulatory requirement to the regulator, Office for water regulation/ Ofwat. The Capital Planning Common Framework and Ofwat require water utilities to continuously improve their asset planning and budgeting for their five yearly reviews by the regulator.

One of the major limitations in the research is that water utilities tend to undertake asset condition assessments only for purposes of regulation. That is, they carry out intensive network-wide asset condition assessments only once in five years for the purpose of submitting their asset investment plans to the regulator. Such assessments are crudely carried out in passing – with the aim of using them to assess asset remaining life. A few assets are assessed per asset group and estimates are made for the whole network. For example, the number of assets in each condition grade is estimated from a sample and then used to estimate the percentage of assets with a specific remaining life. The limit being that asset condition assessment is therefore, not part of the value-chain and not mainstreamed within the water utility. Therefore, the lack of data to assess asset condition would continue. Making condition assessment part of the maintenance routine would mainstream condition assessment within the organisation over time and hence, increase the availability of historical performance data over time. Such data would be further used to better assess asset condition by increased availability of evidence data of each asset performance.

The use of specific performance indicators for each asset group introduced in this research's condition assessment approach further enhanced the data gathered for each asset group as it was be specific and unique to each asset group. This contributes to a more focussed and therefore, efficient allocation of maintenance resources and hence defining how condition assessment feeds into both tactical and strategic asset management. Marlow and Burn (2008e) define the importance of asset condition assessment in water utility as defined by International Infrastructure Management Manual (IIMM), guide to infrastructure management developed in Australia and New Zealand and Publicly Available Standards 55 (BSI, 2008c). On the other hand, they lament how it fails to express its link with tactical and strategic asset management.

3.7 Summary

In order to improve asset investment decision-making and achieve sustainable improvements in business performance, utilities must better understand asset condition, asset performance, asset remaining life and risks. A structured condition assessment program can provide a greater understanding of risk associated with different assets and help a utility move from a reactive unplanned environment to a proactive environment. The application of uncertainty measures in asset condition assessment in water utility is an improvement on the current CG methods. Probabilistic measures are currently used mainly for assessing asset risk of failure and not overall asset condition assessment. Most models that have been applied in water asset condition assessments tend to be specifically tailored to pipe performance indicators such as corrosion levels and instruments such as leak detectors are sometimes used to assess pipe condition. The developed tool also offers an improved method for presenting expert opinions and hence, better condition assessment in water utility.

Figure 3-7 summarises this chapter's process of the approach developed for asset condition assessment where there is limited data.

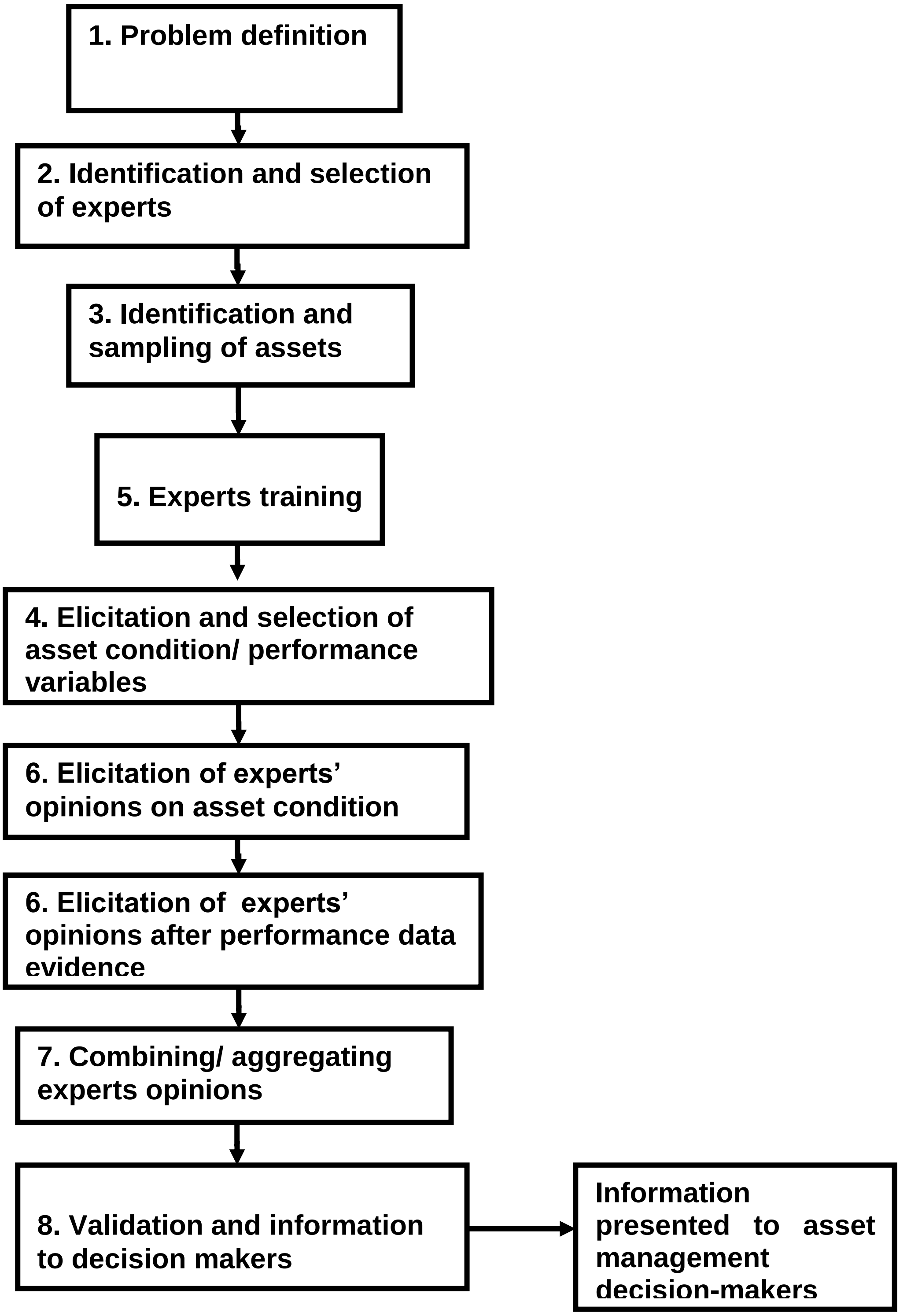


Figure 3-7: Asset condition assessment process for decision support

The condition methodology stages are described in detail in Chapter 2

4 ASSESSING ASSET MAINTENANCE EFFECTIVENESS

4.1 Introduction

Maintenance is the combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function (British Standards 3811, 1993a). It provides critical support for heavy and capital-intensive industries by keeping machinery, equipment and infrastructure in a reliable operating condition. It is generally accepted that maintenance is a key function in sustaining long-term profitability of capital-intensive organisations (BSI, 2008d). Maintenance costs must be contained and minimised to maximise profits. Such costs include capital expenditure and operating costs. In order to manage these costs, asset managers have to plan maintenance programmes in advance. This requires organisations to assess the effects of each maintenance action on the reliability or condition of the asset, which is referred to as 'maintenance effectiveness' (ME) assessment. Neely *et al.* (1994) defines maintenance effectiveness as the process of quantifying the efficiency and effectiveness of a maintenance action. Assessing maintenance effectiveness is important because it allows asset managers to determine the quality of their maintenance programmes for possible improvement.

Water utilities are particularly asset intensive and allocate a large proportion of their capital and operating expenditure to maintenance activities. Government regulation of the water industry means that water utilities cannot easily pass on maintenance costs to customers. Therefore, they have pressure to minimise maintenance costs in order to maximise profits. Water utilities also maintain assets in order to preventatively manage risks to public health and the environment. To achieve optimal operation levels, utilities have to evaluate the quality of their maintenance and minimise maintenance costs by assessing maintenance effectiveness. Maintenance effectiveness assessment can be useful in (a) planning future investment, (b) scheduling maintenance regimes; (c) selecting maintenance companies; and (d) evaluating the residual value of maintained systems.

The aim of the research in this section was to highlight issues that are critical in using expert elicitation when assessing maintenance effectiveness. The objective was to identify and develop a framework for assessing maintenance effectiveness. The focus is on factors that affect the maintenance process and asset condition assessments that are directly introduced in the process by the use of experts opinions.

4.2 Theoretical background and rationale

Many factors can affect maintenance quality: human factors, technological advance, among others. For example,

- Human factors: different levels of maintenance skill can affect maintenance quality;
- Technological advance: a failed component can be replaced with a more reliable one, because technological advance produces more reliable components.

In general, maintenance quality can be categorised into the following two classes (Wu and Zuo, 2010b):

- Age reduction maintenance. A maintenance activity can bring a maintained item back to a younger status (due to good maintenance) or an older status (due to poor maintenance). For example, in Figure 4-1, the maintenance activities reduce the age of the maintained item. The shape of the failure rates of the maintained item after each PM (preventative maintenance activity) do not change, while the age of the maintained item after each PM becomes younger.
- Age defying maintenance. A maintenance activity can defy or speed up the ageing/deterioration process of an item. For example, in Figure 4-1, the maintenance activities could speed up the ageing process of the maintained item. In the figure, the failure rate after each PM increases quicker than before, but the maintained item becomes younger.

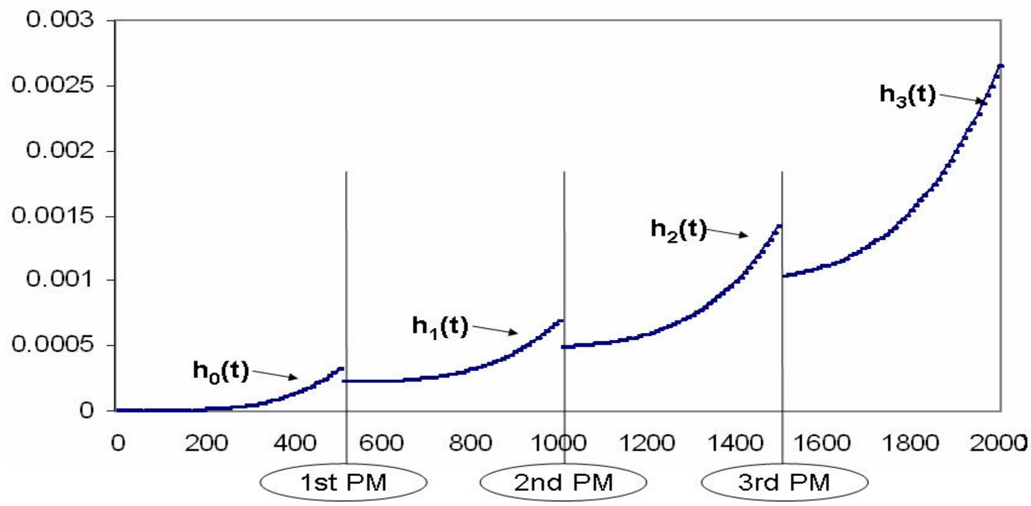


Figure 4 - 1: Preventative maintenance activities and the ageing process (the X-axis represents the age, the Y-axis represents failure rate).

All these two approaches are intended to reduce the risk of failure of the asset. Figure 4-2 shows the level of maintenance effectiveness assessment in the risk assessment process.

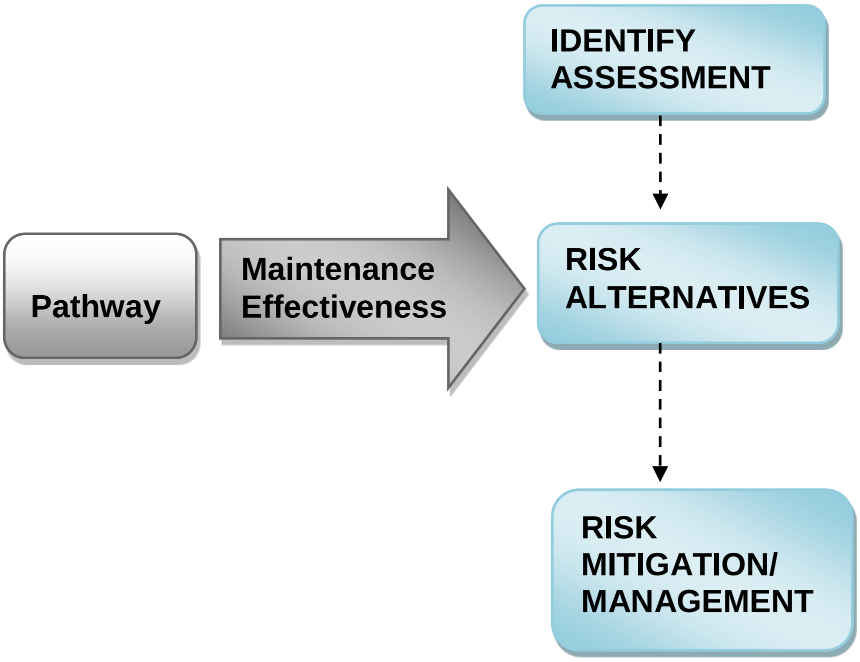


Figure 4-2: Maintenance effectiveness as a risk management tool

4.2.1 Corrective maintenance process

Corrective maintenance, which is also known as corrective maintenance, is applied when an asset fails. The repair process follows (Figure 4-3); fault discovered upon failure, diagnosis of cause failure, communication, spare parts order, repair or maintenance action, and maintenance effect (ME) assessment.

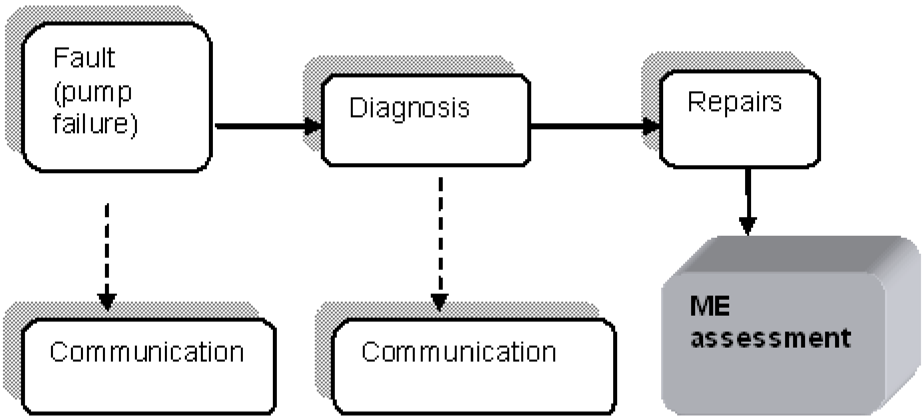


Figure 4-3: Corrective maintenance process

A typical water pump failure and the corrective maintenance process that would follow are demonstrated in the fishbone figure below (Figure 4-4).

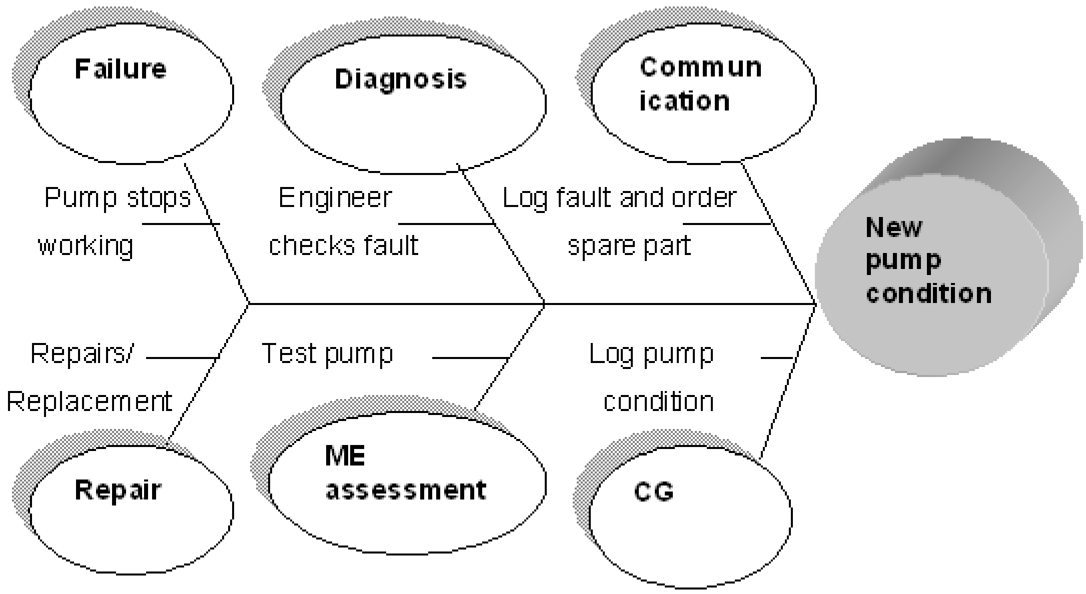


Figure 4-4: Water pump maintenance action process

The maintenance process involves expert elicitation and subjective judgements have to be made at different stages of the process, particularly at the following stages.

i) Fault diagnosis

ii) Repair or maintenance action

iii) Repair or maintenance effectiveness assessment

The water pump maintenance process in Figure 4-3 illustrates the action taken by maintenance personnel at each stage of the maintenance process. The nodes represent the process and the branches show the action taken by maintenance personnel at each stage of the process. Since this research models a corrective maintenance process, the water pump has to fail first before a maintenance action is taken. Human bias due to expert opinions is introduced at each of the above three stages in the corrective maintenance process.

4.2.2 Water pump maintenance process example

A water pumps fails and an engineer investigates the failure. The engineer spends about two hours investigating the incident. The engineer concludes the pump rotor needs to be replaced.. The engineer logs the failure diagnosis and the maintenance action to be taken.

A maintenance action is arranged to replace the rotor. The engineer then places an order with the organisation's stores department and the stores department does not have the rotor in stock. An order is placed by the stores department with a water pump spare-parts supplier and it takes four days for the part to be delivered. The engineer is informed of the part delivery on the fifth day and he replaces the rotor on the same day. After replacement, he tests the water pump by starting it and it fails to start.

The engineer then gets a colleague to do the diagnosis of the pump failure with him. They discover that the pump failed due to a cut of a cable, which resulted in an electric power supply cut. They immediately perform a maintenance action on the water pump by re-connecting the electric cable. This indicates that asset maintenance effectiveness can be affected by other aspects such as diagnostics.

4.2.3 Maintenance effectiveness and expert opinions

Maintenance effectiveness assessment can be subjective when not assessed through data approaches.

Table 4-1: Expert opinion log of maintenance effectiveness

Asset	Condition before maintenance	Action	Condition after maintenance	Condition after second maintenance
Water pump	Failed	Part replacement (rotor)	Failed	Operating
Performance grade	CG 2		CG 5	PG 2
Maintenance effect			As bad as old (ABAO)	Slightly better than old (SBTO)

The expert opinion log *CG2* is italicized to show that this information is not the current engineer's assessment, but a previous engineer's opinion. The rotor has already been replaced with a new one and it means the pump has a new part. It is because of the new components that the expert classes the pump condition as SBTO. Human error therefore, affect the maintenance quality assessment process at different stages and Figure 4-5 presents a summary of the maintenance process as impacted by human error at different stages.

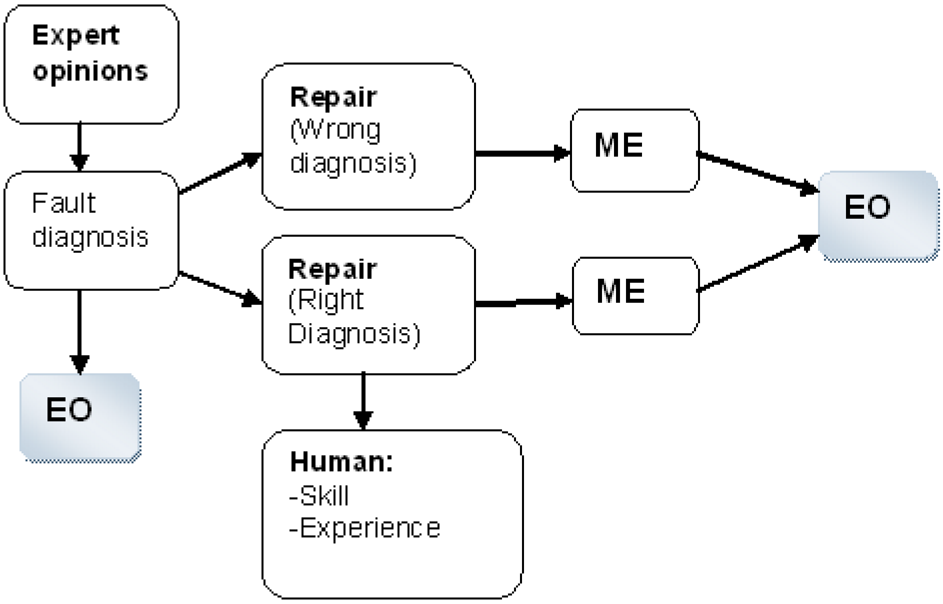


Figure 4-5: Expert opinions in the maintenance process

4.2.4 Maintenance effectiveness and organisational goals

The water company in this case study employs time-based maintenance schedules for the majority of assets that require maintenance. 80% of the origination's maintenance costs still remain related to breakdowns and over 30% of job numbers are logged as requiring an emergency response within 24 hours. In many cases, this can lead to inappropriate and costly repairs. Where whole life costing is the driver, an alternative solution could be more appropriate. Processes are now in place to monitor and control emergency repair workflows via the Central Control Asset Optimisation Manager (CCAOM). This is aimed at containing and ultimately reducing maintenance costs, ensuring optimum levels of assets availability, and effectively supporting management decisions at strategic, tactical and operational levels. The disruption of the maintenance process (Figure 4-5) therefore, may significantly undermine this overall organisational strategy.

Figure 4-6 further illustrates the process presented in figure 4-5. It presents levels where experts' opinions come into the maintenance process and affect it as subjective judgements become part of the process. The broken line shows maintenance effect after the first maintenance action and the solid line shows the asset condition after maintenance action 2. ME_2 shows that maintenance personnel should minimize errors in order to realise positive effects of maintenance on the asset condition.

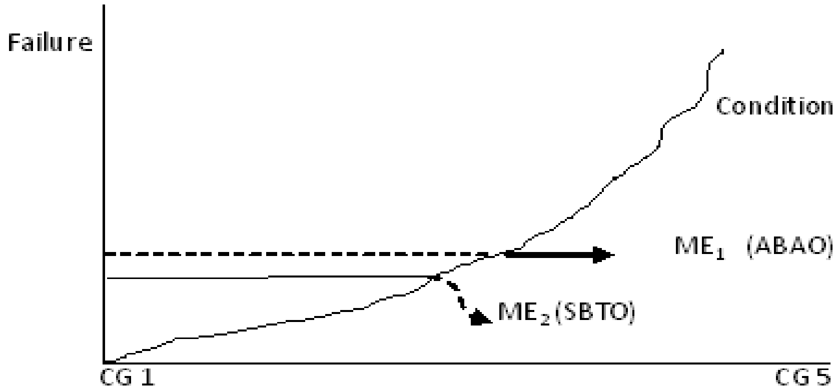


Figure 4-6: Maintenance action effect on the pump condition

The limitations of sorely relying on experts opinions in assessing the asset condition are also illustrated by Figure 4-6. The previous expert who assessed and logged the pump condition as PG 2 may have been wrong or too subjective in his/her assessment. This is a human error and would be determined by several factors, such as how long the engineer/expert has been with the organisation, length of experience as an engineer, and the length of experience with a particular asset type.

4.3 Methodology

Maintenance effectiveness can be measured by using different approaches, including total effectiveness, availability, cost of maintenance, difference between planned and unplanned work and reliability (Al-Momani *et al,* 2006). This research developed an approach that is related to the reliability method. The reliability of a maintenance action is assessed by using expert elicitation.

The developed maintenance effectiveness approach was based on the developed asset condition assessment approach. The approach employs expert elicitation to assess asset condition after a five years period. A group of experts were convened to assess assets condition. The same asset variables used when assessing the assets condition were also used in assessing maintenance effectiveness. The same sample assets (water pumps) were also used.

The approach employed experts' elicitation method where experts were asked to state their opinion of the asset condition. The methodology followed the same approach used for assessing asset condition. The difference is that the asset condition was assessed twice, before and after a maintenance activity

In assessing maintenance effectiveness, first the experts determine the asset condition and gave their condition rating before a maintenance activity, in line with Equation (4-1). Experts were then asked to give their opinions about the asset condition after the maintenance action.

$$ME = \sum_{i=1}^{N^e} \sum_{j=1}^{M^f} G_j C_{ij}^{a} - \sum_{i=1}^{N^e} \sum_{j=1}^{M^f} G_j C_{ij}^{b} \qquad (4\text{-}1)$$

Where C_{ij}^{a} represents the condition grade after a maintenance action and C_{ij}^{b} represents the condition value before the maintenance action (Figure 4-1). The asset condition value given by experts for *a* and *b* could be the same, indicating an ineffective maintenance (as before). Where the maintenance effectiveness value (ME) was positive, the asset could be classed as 'better than before'. A negative maintenance effectiveness value could be classed as 'worse than before'.

The methodology for assessing maintenance effectiveness is detailed in Chapter 2.3 and Figure 4-7 summarises the method process.

4.4 Maintenance effectiveness assessment case study (water pump)

This section presents results obtained from the application of the approach developed for the assessment of maintenance effectiveness. A water pump was assessed for planned maintenance quality by eliciting experts' opinions.

4.4.1 General pump performance indicators

The sample asset (water pump) performance indicators were listed as suggested by the maintenance expert engineers. The indicators were narrowed down to only three as experts indicated those they deemed most important in affecting the overall condition of the asset group. Experts had to rate the importance of the performance indicator. The chosen three major performance and condition indicators were;

- Rotation speed
- Vibration
- Corrosion levels.

These are further abbreviated and, from here, referred to as R, V, and C.

The performance indicators where used as a major premise to define the condition of the asset by experts. Such condition of the asset can be said to be an operating state of the asset. The condition of each performance part/indicator assessed by the experts is different at any particular time due to different aging speed, processes, design and maintenance quality. An asset, made up of such components can therefore, be said to operate as a multi-state system.

The effectiveness of asset maintenance can be said to be assessed regarding assets operating in multi-states. Each of the condition grades assessed in Chapter 3 is different operating levels of the assets. Site 1 is presented as an example of the assessed maintenance effectiveness.

4.4.2 Expert assessments

Experts assessed the effectiveness of a preventative maintenance action for a water pump. All the preliminary work to the methodology was done in chapter three.

The results of the assessments of maintenance effectiveness were based on the assessment of the most recent planned preventative maintenance the expert engineers had carried out at each site. The lower, the median and the upper quartile were sought for the condition of each pump. The results for assets condition before the maintenance as are presented in Table 4–2.

Table 4-2: Asset condition before maintenance

Performance indicators	**CG pump 1**	**Site**	**Condition before**
R	2.00	Site 1	0.11
C			0.10
V			0.19
R	2.00	Site 2	0.14
C			0.15
V			0.21
R	2.00	Site 3	0.11
C			0.10
V			0.21
R	1.00	Site 4	0.40
C			0.30
V			0.60
R	1.00	Site 5	0.12
C			0.05
V			0.18
R	2.00	Site 6	0.14
C			0.15
V			0.21
R	3.00	Site 7	0.11
C			0.10
V			0.21

The results (Table 4-2) show that introducing uncertainty allows experts to better assess the level of maintenance effectiveness. This is particularly applicable where the effectiveness of maintenance is small.

4.4.3 Experts aggregates

The opinions of each expert were aggregated by using group consensus. The results for all site condition before planned maintenance opinions are presented in Table 4-3 for pump1.

4.4.3.1 Assessments after a maintenance action

Experts assessed the R, V, C after a planned maintenance was carried out.

Table 4-3: Experts' assessments after maintenance

Performance indicators	CG pump1	Site	Condition after
R	2.00	Site 1	0.02
C			0.05
V			0.10
R	2.00	Site 2	0.14
C			0.15
V			0.19
R	2.00	Site 3	0.07
C			0.11
V			0.02
R	1.00	Site 4	0.30
C			0.35
V			0.39
R	1.00	Site 5	0.01
C			0.05
V			0.10
R	2.00	Site 6	0.12
C			0.15
V			0.19
R	3.00	Site 7	0.05
C			0.10
V			0.15

4.4.3.2 Maintenance effectiveness assessments values.

The results of the maintenance effectiveness (ME) assessment for all sites is summarised in Table 4-4. Pump 1 only is presented.

Table 4–4: Maintenance effectiveness values

Performance indicators	Site	Condition after	Condition before	ME	ME value
R	Site 1	0.02	0.11	0.09	0.23
C		0.05	0.10	0.05	
V		0.10	0.19	0.09	
R	Site 2	0.14	0.14	0.00	0.02
C		0.15	0.15	0.00	
V		0.19	0.21	0.02	
R	Site 3	0.07	0.11	0.04	0.22
C		0.11	0.10	-0.01	
V		0.02	0.21	0.19	
R	Site 4	0.30	0.40	0.10	0.26
C		0.35	0.30	-0.05	
V		0.39	0.60	0.21	
R	Site 5	0.01	0.12	0.11	0.19
C		0.05	0.05	0.00	
V		0.10	0.18	0.08	
R	Site 6	0.12	0.14	0.02	0.04
C		0.15	0.15	0.00	
V		0.19	0.21	0.02	
R	Site 7	0.05	0.11	0.06	0.12
C		0.10	0.10	0.00	
V		0.15	0.21	0.06	

Only V from sites 3 and 4 obtained a negative result after the maintenance. Where experts assessed the quality of maintenance as ‘better than before’, a positive maintenance effectiveness value was obtained and where it was ‘worse than before’, a negative value was obtained.

Only group assessments were carried out for maintenance effectiveness. Experts were asked to give their opinions pertaining to each of the performance variables condition. The same concept of a condition grade was applied in the maintenance effectiveness assessment. The experts stated their condition assessment for a water pump before and after a planned maintenance. The experts had to recall the last time they carried out a planned or preventative maintenance. No real maintenance action was carried out during the survey.

Site 2 and 6 were generally the outliers in terms of improvement on the asset after the maintenance action. Site 3 had a -5% and site 4 a -1% change effect after the maintenance for the corrosion performance variable. This could be due to experts realising the extent of the corrosion was higher than they first assessed when they inspect hidden parts of the asset components during the maintenance. Only corrosion variable was found to have not improved after the maintenance at site 3 and 4, as indicated by negative maintenance effect values. On the other hand experts may find some corrosion as they carry out the maintenance, which they may have not seen during the pre-maintenance condition assessment.

4.4.4 Evaluation of results

This research explored calibration, coherence, and experts’ confidence. The results show that the experts were coherent (Table 4-6), were generally well calibrated (Table 3-6), and were relatively confident of their assessments (90% average confidence).

a) Calibration

In simple terms, calibration refers to the standardisation of a process by determining its deviation from the standard, In expert elicitation, calibration studies are concerned with the appropriateness of assessors' subjective probability estimates, or confidence in their judgments and predictions, and can be categorized in two groups: one that elicits judgments about discrete propositions, and a second that attempts to identify probability density functions assessed over continuous variables (e.g., uncertain numerical values). The customary definition for discrete probability statements is that judgments are well calibrated if on the long run, for all propositions assigned a given probability, the proportion that is true is equal to the probability assigned (Hardman, 2009c). Discrete probability statements can be classified according to the number of possible alternatives the expert is exposed to, and the corresponding range of the probability scale. The expert is required to make a probability judgment with regard to a single event or statement. The appropriate probability response in this case ranges between 0 and 1.0. In the *two alternatives case* the assessor has to choose between two alternatives, and then provide a probability judgment for the chosen alternative in the range of 0.5 to 1.0. Finally, in the *multiple alternatives* case, the assessor is asked to select the most likely response.

Calibration is one possible way to assess probability judgments. A central problem with the strict view is its strict definition of calibration, namely the accuracy by which probability judgments correspond to reality. The loose approach is based on a broader standard which may be termed as the adequacy of probability judgments (and in which calibration is just one of a larger criteria ensemble). What are adequate probabilities? Since any probability statement is meant to convey information, it should be accurate as far as possible. However, the criterion for accuracy when applied to probability judgments is often ambiguous and controversial, and under certain circumstances meaningless. Moreover, the information contained in a probability statement should be evaluated not just by precision, but also by amount and quality, as for instance offered by the measure of resolution. In this research, the interest is in the adequacy of the experts' judgements.

Calibration scores

Results from experts' performance were assessed against a known assessment (seed variable). It was assumed that all experts should know the assessment value if they are 'good'. Deviation from the seed variable is analysed.

The same results of calibration scores from Table 3-18 in Chapter 3 were used to assess experts for their maintenance effectiveness assessments. This was because maintenance effectiveness assessments were elicited from the same experts as the condition assessments.

The results show that experts were more over-confident than under-confident. Only two experts were well calibrated. This is in line with most studies, as experts tend to be over-confident (O'Hagan *et al*, 2006b).

b) Coherence requirements

Coherence tests are for evaluating experts' probability assessments. The essence of this criterion is to assure that the relations between assessments are governed by the laws of probability and it is also referred to as internal consistency (Yates, 1982b). A set of probabilities is said to be coherent if it does not lead to a loss of independence of the observed outcome (Kadane and Lichtenstein, 1982b). It is noted that tests of coherence can be meaningfully applied to events that are unrelated and essentially unique. For example, if a rainy day is dependent on a cloudy day, they test of coherence cannot be meaningful. It was therefore, important to make experts understand this and chose questions that are suitable to test the experts' coherence.

Coherence was assessed by one question asked and the expert had to give a mathematically consistent response consistent with the law of probability that the sum of probabilities should not exceed one. Experts whose assessed probability of an occurrence and non-occurrence of an event exceeded one were deemed to be not coherent. The purpose was to test if the experts understood simple probability and therefore, assess their opinions' quality.

The probability that pump 1 was exactly in condition grade 1 was assessed. Experts were then asked for their probability that pump1 was not exactly in condition grade 1. Table 4-5 shows results from site 2 and Appendix 4-2 presents results for all other sites.

Table 4-5: Experts' coherence test results, site 2

Expert	Probability pump 1 in CG 1	Probability pump 1 in CG 1	Total
E1	0.90	0.10	1.00
E2	0.99	0.01	1.00
E3	0.70	0.15	0.85
E4	0.80	0.20	1.00

The coherence test results seemed to relate to the experts' work experience, as indicated in Table 4-5. The expert with only one year work experience was the only one who was not coherent in his assessment. The sum of his probability estimates was less than 1, which should not be the case for a coherent assessment (E3). It was not obvious how work experience and coherence would relate. This was true for five of the seven surveyed sites (71%). The coherence could be due to confidence garnered from previous experience with a similar exercise for the experienced experts.

c) Experts confidence

Experts were asked to state their confidence in their assessment according to their understanding of the different maintenance regimes and their application to different asset groups within the organisation. Table 4-6 summarises the experts' confidence for site 2. Confidence assessments for other sites are presented in Appendix 4-3.

Table 4-6: Experts confidence in their assessments, site 2

Experts	Confidence
E1	90%
E2	95%
E3	60%
E4	85%

Expert (E3) was the least confident. This expert indicated that he had been in asset maintenance about a year at the time of the survey. This could be the reason for his lack of confidence, compared to his colleagues who had been with the organisation for a minimum of over ten years. The average confidence (85%), which is limited because of the new expert indicates the confidence in the research results. 90% was the average confidence when the outlier was excluded. E3 was considered an obvious outlier. Table 3-20 shows that E3 had significantly less experience than E1, E2 and E4.

Validation is supposed to measure the accuracy of assessments, but the question still remains, ‘accuracy in what sense’? The strict view conceives the ‘true’ probability to be reflected by relative frequencies measures. Although others have questioned the notion of the very existence of a ‘true’ probability, for purposes of this research, the subjective view of probability is adopted because the nature of an asset condition estimate has less to do with frequency.

4.5 Summary

Measuring maintenance effectiveness is essential for optimum asset management, but it can be complex and requires the commitment of both financial and human resources. Developing maintenance databases is crucial in order to capture and store performance or operational data, which is necessary to effectively measure maintenance effectiveness.

Bias in expert opinions and human errors can occur even when all maintenance programmes are performed according to procedure and most reliable methods of eliciting experts' opinions used. Measures should be in place to respond to these possibilities by making policies that are beneficial to maintenance effectiveness assessment and business management practices.

Experts' opinions were invaluable for assessing maintenance effectiveness where data are not available. Expert elicitation offers a consistent and verifiable consensus as a management decision support tool. The limitations posed by human factors and biases are to be considered when assessing maintenance effectiveness and eliciting opinions. The results of the research show that expert opinions can ensure accountability, empirical control, neutrality and fairness in supporting decision making.

Figure 4-7 summarises this chapter's process of the approach developed for asset maintenance effectiveness where there is limited data.

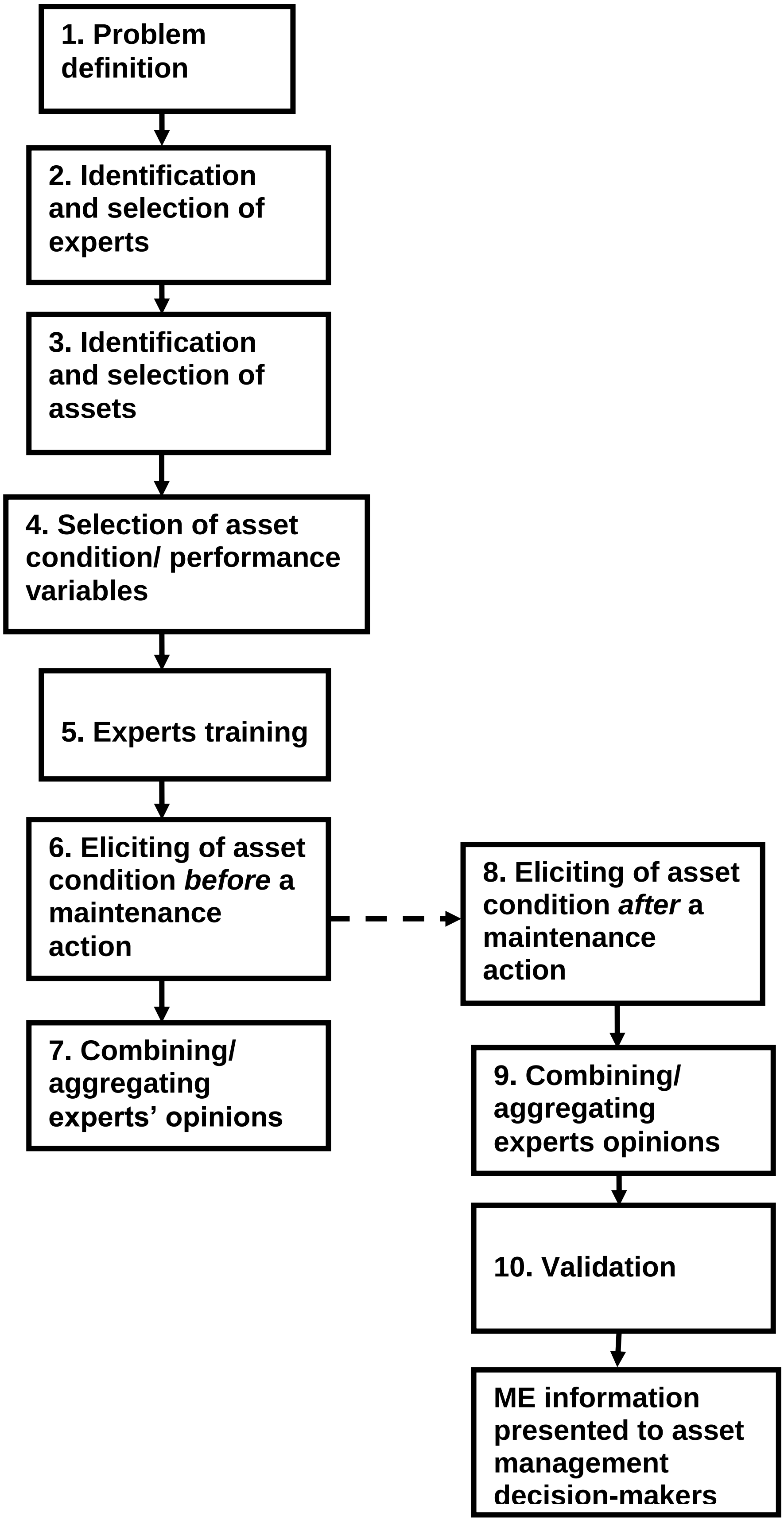


Figure 4-7: Maintenance effectiveness assessment process.

The asset maintenance effectiveness process stages are described in detail in Chapter 2.

5 MAINTENANCE REGIME SELECTION

5.1 Introduction

The objectives of the research in this section were to investigate and develop approaches to use in selecting an asset maintenance regime where there is sparse asset performance historical data. Asset maintenance regime strategies are mostly developed for situations where there is asset performance data and they are hardly applied in practice. The specific objectives of the research in this chapter therefore, were to develop a practical and verifiable approach that can be utilised in selecting an asset maintenance regime for specific asset groups where no historical performance data exist. An asset management policy is a requirement of PAS 55-1, which states that the policy shall:

- be derived from and consistent with the organisational strategic plan, be appropriate to the organisation's assets and operations, and be consistent with other organisational policies and the organisation's risk management framework
- state any principles to be applied (such as sustainable development or corporate social responsibility principles)
- provide the framework for the production and carrying out of the asset management strategy, targets and plans
- commit to continuous improvement of its asset management and to comply with current legislation, regulation, statutory requirements and any voluntary requirements relevant to the organisation (for example, voluntary agreements such as the WRAP utility industry agreement.
- be visibly authorised and endorsed by the organisation's senior management with clear procedures for documentation, carrying out and maintenance, including periodic review be communicated to relevant stakeholders (such as employees and contractors).

For infrastructure organisations, the business of the organisation will be dependent on the assets that it owns or manages and will quite frequently be externally regulated, or subject to specific legislation, so it is important that the asset management policy:

- is fully integrated with other policies and any overarching regulation and legislation, but is flexible enough to accommodate changes in regulation and legislation
- is realistic, such that its broad objectives can be accomplished and also developed, and its targets and milestones achieved
- considers and possibly defines whole-life. Because infrastructure assets are expected to operate indefinitely, the organisation can benefit from defining the period over which whole-life asset management should occur.

The analysis and justification of maintenance regime selection is a critical and complex task due to the large number of attributes (multi-criteria) that can be considered and lack of data. The term "multi-criteria analysis" refers to any structured approach utilized in determining and evaluating the effects of variable options and through the normalised preference scores of the objectives that each of these alternatives meets. Most utilities have an inadequate understanding of their assets but have data constraints. The data that is available with the water utilities is often incomplete. There are often poor records about the condition and location of the assets (Hobson, 2005b). Wood (2007a) reported that the data collection challenges mainly consist of missing and conflicting historical data, poor reliability of existing data and non-computerised information.

As the research's aim, was to develop decision-support tools where there is limited or no data, the specific objective in of the work described this chapter was to support the selection of an optimal maintenance regime, where there is no data. This research investigated and developed the application of the AHP with expert opinions in selecting an ideal maintenance regime. Section 5.2 presents the theoretical background and Section 5.3 presents the methodology. Section 5.5 presents a case study results and Section 5.6 presents the summary of the research.

5.2 Theoretical background

The research explored situations where there is limited or no data to support asset management decision-making. In selecting a maintenance regime for a specific asset group, a multi-criteria approach in decision making was proposed because it is based on the combined effects of more than one criterion, which supports real-life scenarios. It is also useful in cases of hard-to-quantify parameters and non-numeric inputs.

The backward-looking approach to assess capital maintenance needs, based on historical capital maintenance investments and the historical serviceability trend, was criticised and led to the development of a new forward-looking risk based approach, known as the Common Framework, which allows a more proactive approach to assessing capital maintenance needs. The concepts of probability and consequences of asset failures are at the core of the Common Framework. The Common Framework advocates three stages of analysis namely historical analysis, forward looking analysis, and a comparison of these two for capital maintenance planning (Day, 2007a).

5.2.1 Asset management policy

Stakeholders generally influence the weighting of factors taken into account in decision making. They drive asset management strategies, communication policies, and information sharing policies. PAS 55- 1 sets requirements for consultations with stakeholders to ensure that their input is incorporated into the development of the asset management strategies and developing policies related to specific asset types of management processes.

Policies set out the rules and structure that an organisation will work within, and they could be imposed externally or developed internally. They are generally agreed at board level and they require reviewing and updating, as well as ensuring its adoption across the organisation. Policies can be established to embody legal obligations and to meet the organisation's social (for example, an environment or sustainability policy). For an organisation that depends on infrastructure assets to deliver its business, it is essential that staff and stakeholders understand the asset management policy.

The asset management policy outlines how and why asset management will be undertaken across the organisation as a whole and it sets the broad framework undertaking asset management in a structured and co-ordinated way. It defines organisational context and importance of asset management organisation's overall vision and goals. It also supports asset management vision and goals underpinning the strategic goals key performance measures. These include frequency of asset preventative maintenance plans and reviews. Lastly, it states how asset management integrates into the organisation's business processes or value chain.

For whole-life infrastructure asset management, the asset strategy should pay particular attention to areas such as;

- taking a long-term view over several decades - as infrastructure assets have a long life span,
- asset performance and customer service metrics - reflecting legislative, regulatory and stakeholders' requirements,
- the potential impact of high risk failures - to ensure critical assets are identified and treated according to the maintenance approach - such as run to failure, time-based, risk-based or condition based intervention,
- how asset condition data will be collected and information stored - as many infrastructure organisations already collect such data, but may not store it in a way that supports asset management
- how activities will be planned and delivered - including identifying the responsibilities and competencies required to deliver asset management research, and
- identifying the management responsibility for monitoring, review and improvement.

It is also important that the asset management strategy to be adopted for the assets under consideration starts by viewing them as a system. Care should be taken to put in place an appropriate strategy. When an organisation intends to manage a group of assets first time, it is important to review the strategy soon after its introduction, within a year or two. Good practice in asset management is based on continuous improvement rather than aiming for perfection from a single improvement research. Regular reviews that include carrying out of identified maintenance activities, allow organisations to integrate asset management effectively with changes in stakeholder requirements, technology, and other existing systems in the organisation. The maintenance regime strategy should be in line with the asset risk assessment process (Figure 5-1)

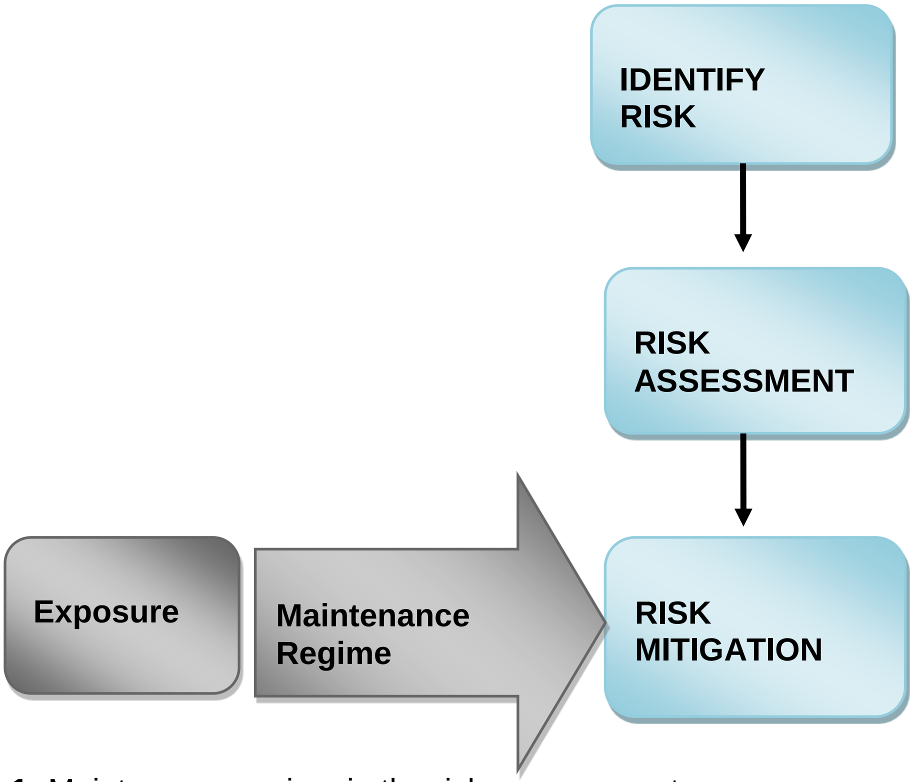


Figure 5-1: Maintenance regime in the risk management process

A longer-term view is essential for effective management of those assets which have long service lives. This means that a strategic view may need to accommodate longer-term possible changes in circumstances. These could include; climate change, legislative change, changes in national government and its policies and possible changes in the type and level of use of the asset. The level of service delivered by an asset may also vary in the long-term because of changes in demand and specific actions to be undertaken by an organisation to improve asset management capability and achieve specific strategic objectives.

A structured set of actions aimed at enabling improved asset management by the organisation and they include (Marlow and Burn, 2008f);

- a description of the current status of asset management practices (processes, asset data, and information systems) organisation's future vision of asset management,
- a description of the required status of asset management practices to achieve the future vision,
- identification of the gap between current status and the future vision (a gap analysis),
- identification of strategies and actions required to close the gaps, including resource requirements and timeframes,
- long-term plans (usually 20 years or more) that outline the asset activities for each service area. Asset management plans also outline actions and resources to provide a defined level of service in the most cost effective way,
- a summary of an organisation's strategic goals and key asset management policies definition of levels of service and performance standards demand forecasts and management techniques,
- a description of the asset portfolio ,
- a broad description of the life cycle management activities for operating, maintaining, renewing, developing or disposing of assets, and
- a cash flow forecast key asset management improvement actions including resources/ timeframes.

Given different types of maintenance, in cost terms over the life time of an asset, the most expensive type of maintenance is corrective maintenance and the least expensive is predictive maintenance. However the selection of reactive against proactive maintenance strategies is not very simple. The proactive maintenance strategies require estimating the probability of failure of assets, which is a very complex and requires good quality data. It is therefore, importance what maintenance regime an organisation employs, particularly an asset intensive organisation. As the UK water industry Common Capital Planning Framework advocates both historical analysis and forward looking analysis, it is not always easy to select a maintenance regime where no historical data exist for an individual asset or asset group. An approach to establish a formal verifiable maintenance policy selection method for an asset group is, therefore, developed and outlined in the following section.

5.3 Methodology

Expert elicitation Analytical Hierarchy process (AHP) was used to determine a suitable maintenance regime for water pumps. Expert elicitation was used to elicit value matrices for applying the AHP method. The methodology is detailed in Section 2.4 (Figure 5-6).

5.4 Maintenance regime selection case study

A case study in a water utility organisation was conducted. Maintenance experts from the organisation rated the maintenance regimes (alternatives) and criteria in a group session.

a) Alternatives

Three alternative maintenance regimes were evaluated in this case study. It is assumed that managers need to assess the regime that is suitable for each asset group. The maintenance regimes to choose from included (Table 5-1);

- Corrective maintenance (CM): The maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function (BSI, 1993).
- Condition-based maintenance (CBM): A method to sustain a desired quality of service by the systematic application of analysis techniques using centralized supervisory facilities and/or sampling to minimize preventative maintenance and to reduce corrective maintenance (BSI, 1993).
- Preventative maintenance (PM): The maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item (BSI, 1993).

Table 5-1: Alternatives used to select a maintenance regime

Alternative	**Code**
Corrective maintenance	CM
Condition-based maintenance	CBM
Preventative maintenance	PM

b) Criteria

Experts were presented with a list of criteria and were asked to choose the most important pertaining to water pump maintenance. The criteria presented below are from experts who select the most important parameters that contribute to maintenance regime suitability for different asset groups. Five criteria are considered by the experts for each maintenance regime (Table 5-2);

Table 5-2: Criteria for selecting maintenance regime

Criteria	**Code**
Asset importance for the process	C_1
Spare parts availability/ obsolescence	C_2
Maintenance cost	C_3
In-house maintenance capability	C_4
Asset type (active or passive)	C_5

5.4.1 Experts preference assessments

Experts assessed the importance of each maintenance regime by using scaling in rating the factors considered (criteria and alternatives).

a) Preference scaling

Experts express their relative priority 1/9, 1/8, 1/7 .....7, 8, 9 based on Figure 5-2 scale. One over nine indicates a low importance and nine, extreme importance. A scale of 1 is for equal importance.

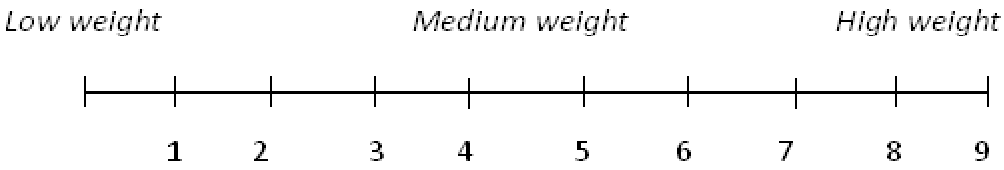


Figure 5-2: Scale for relative preference

b) Criteria preferences

Each of the criteria is given a preference score against another according to the scale (Figure 5-3). Experts allocate the score values in paired comparisons and a matrix developed. Site 1 and 2 matrices are presented (Tables 5-3 and 5-4) and all sites matrices are presented in Appendix 5-2.

Table 5-3: Criteria preference matrix, site 1

	C1	C2	C3	C4	C5
C1	1.00	0.50	2.00	0.50	2.00
C2	2.00	1.00	1.00	0.50	2.00
C3	0.50	1.00	1.00	3.00	2.00
C4	2.00	2.00	0.33	1.00	0.50
C5	0.50	0.50	2.00	2.00	1.00

Table 5-4: Criteria preference matrix, site 2

	C1	C2	C3	C4	C5
C1	1.00	0.25	2.00	0.50	0.17
C2	4.00	1.00	1.00	0.20	0.14
C3	0.33	1.00	1.00	0.11	0.17
C4	2.00	4.00	8.00	1.00	2.00
C5	5.00	0.50	5.00	0.50	1.00

Having a comparison matrix, the priority vector, which is the normalized eigenvector of the matrix, is computed in order to determine the preference scores. Sums of each column of the reciprocal matrix are obtained. Each element of the matrix is divided by the sum of its column to get the normalized relative weight. The normalized principal eigenvector can be obtained by averaging across the rows. The normalized principal eigen or priority vector shows relative weights among the compared items (Teknomo, 2007b).

c) Alternatives preferences

Paired comparison matrices are developed for the three maintenance regimes. A three maintenance regime mix is favoured by management, which includes preventative maintenance (PM), corrective maintenance (CM) and condition-based maintenance (CBM). Five of the regime matrices are developed from expert preference with respect to criteria C1, C2, C3, C4 and C5. Table 5-5 and 5-6 presents the experts' preferences with respect to C1.

Table 5-5: Regimes preference matrix, site 1

	PM	RM	CBM
PM	1.00	0.33	5.00
RM	3.00	1.00	7.00
CBM	0.20	0.14	1.00

Table 5-6: Regimes preference matrix, site 2

	PM	CM	CBM
PM	1.00	0.50	4.00
CM	2.00	1.00	6.00
CBM	0.25	0.17	1.00

5.4.2 Summaries of experts' preference scores

The summaries of preference scores are presented in hierarchies and tables (Figures 5-3 and 5-4). Hierarchies for site 1, 2 and the overall hierarchy are presented. Appendix 5-3 presents hierarchies for all other sites.

Site 1 preferences summary (Figure 5-3):

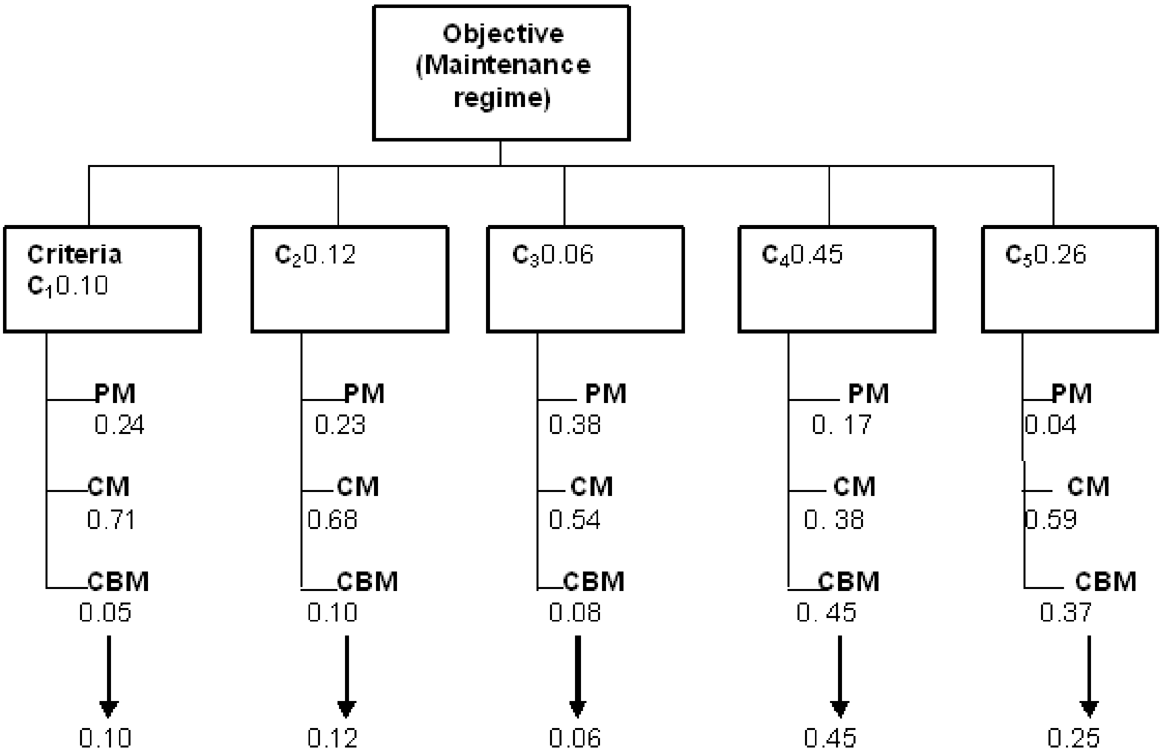


Figure 5-3: Summary of AHP results from site 1

Site 2 maintenance regime preference summary (Figure 5-4):

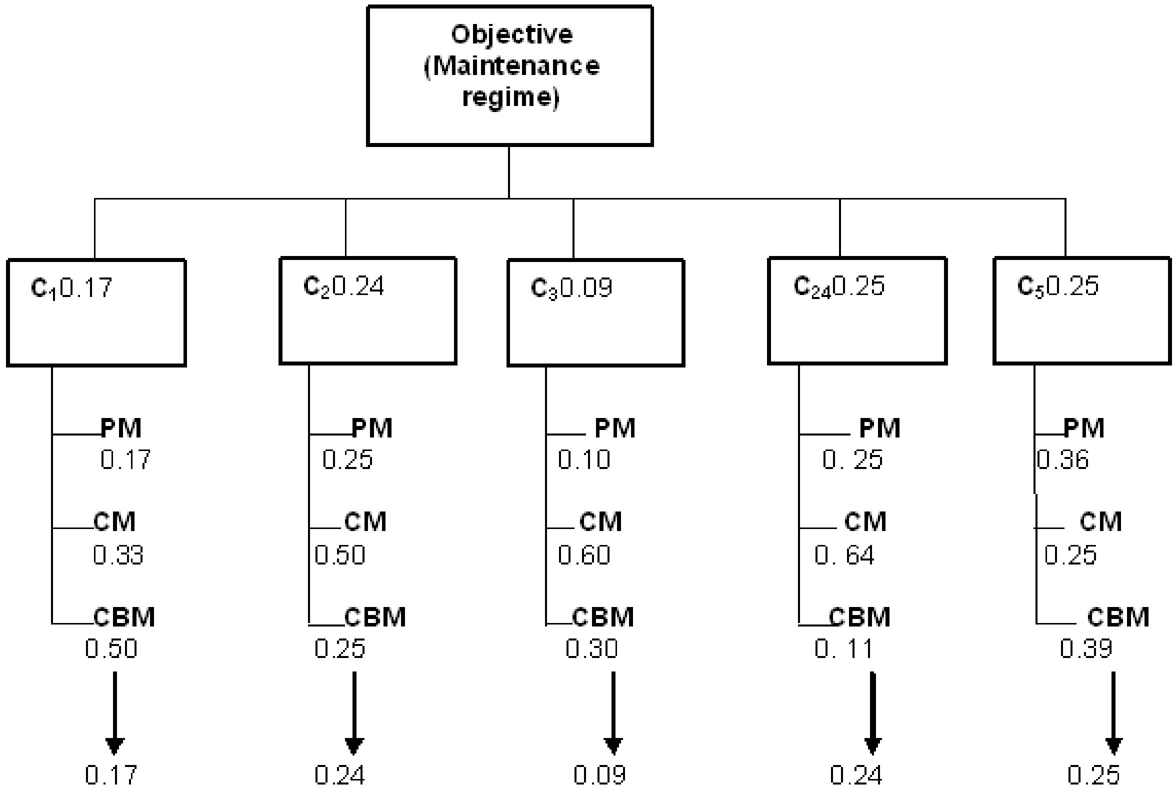


Figure 5-4: Summary of AHP results for site 2

5.4.3 Experts' preferences for all sites

The results were compared and the highest eigenvalue selected.

a) Eigen values

The eigenvalues and normalised preference scores for site 2 are presented in Table 5-7. Eigenvalues and preference scores for all the sites can be found in Appendix 5-4.

Table 5-7: Eigen values, site 2

	Normalised

Criteria	Eigenvalues	preference scores	Criteria preference
C1	0.17	0.26	C5
C2	0.24	0.25	C4
C3	0.09	0.24	C2
C4	0.25	0.17	C1
C5	0.25	0.09	C3

c) Preference scores

The preference scores for site 1 are presented in Table 5-8.

Table 5-8: Preference scores, site 1

C_1	C_2	C_3	C_4	C_5
PM 0.24	PM 0.23	PM 0.10	PM 0.17	PM 0.04
CM 0.71	CM 0.68	CM 0.54	CM 0.38	CM 0.59
CBM 0.05	CBM 0.10	CBM 0.08	CBM 0.45	CBM 0.37

Table 5-9 shows a preference for CM at site 1, with the. CBM was second in preference.

Table 5-9: Preference scores, site 2

C_1	C_2	C_3	C_4	C_5
PM 0.17	PM 0.25	PM 0.10	PM 0.25	PM 0.36
CM 0.33	CM 0.50	CM 0.60	CM 0.64	CM 0.25
CBM 0.25	CBM 0.25	CBM 0.30	CBM 0.11	CBM 0.39

Site 2 shows a preference for CM across all the alternatives.

5.4.4 Overall results for maintenance regime choice

The final maintenance regime was therefore PM, with the highest eigenvalue of 0.40 and overall score of 0.30. This section presents a summary of the results with further figures and tables of the AHP hierarchy results presented in Appendix 5. Figures for the hierarchies for site 1, site 2 and combined site hierarchy are presented here, otherwise all other sites hierarchies are in Appendix 5.

All site preferences summary (Figure 5-5):

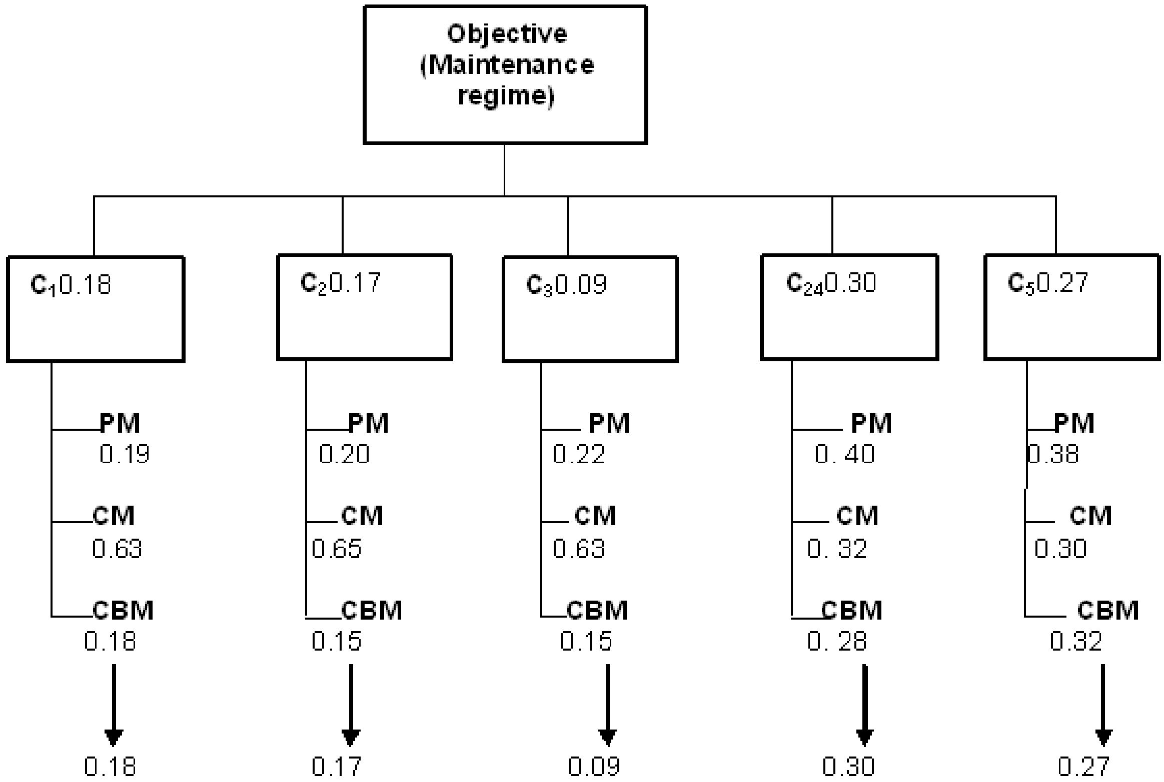


Figure 5-5: Summary of AHP results from all combined sites

The hierarchy summary of all sites surveyed (Figure 5-5) show that C_5 and PM were generally preferred. Further analysis of the results of compared sites' preference scores also show PM as the preferred maintenance regime (Table 5-10).

a) Summaries of all maintenance regimes

Table 5-10 presents a summary of preference scores

Table 5-10: Overall regime preference scores

	C_1	C_2	C_3	C_4	C_5
Criteria	0.18	0.17	0.09	0.30	0.27
PM	0.19	0.20	0.22	**0.40**	**0.38**
CM	**0.63**	**0.65**	**0.63**	0.32	0.30
CBM	0.18	0.15	0.15	0.28	0.32

Table 5-10 summarises the results of overall preference scores. The results show that show that CM is preferred for in relation to criteria C_1 – C_3. PM is preferred for criteria C_4 and C_5. The overall preference was PM, with the highest preference score.

b) Comparison of sites maintenance regime

Table 5-11: Maintenance regime choice per site

Site	C_1	C_2	C_3	C_4	C_5	Criteria choice	Alternative choice
1	0.103	0.121	0.060	**0.452**	0.259	C_4	CBM
2	0.173	0.244	0.091	0.248	**0.252**	C_5	CBM
3	0.190	0.162	0.091	**0.332**	0.238	C_4	CBM
4	0.170	0.193	0.132	0.137	**0.210**	C_5	CBM
5	0.121	0.101	0.060	0.292	**0.441**	C_5	PM
6	0.131	0.162	0.071	0.290	**0.341**	C_5	PM
7	0.180	0.172	0.090	**0.301**	0.273	C_4	PM

Overall maintenance regime = CBM (as 0.452 is the highest score).

The results (Table 5-11) show that based on site 1, CBM is the best choice (0.452 score). The second choice with a high score is PM. The choice between CBM and PM would be made by management. Management could decide on the regime choice based on, for example, number of similar assets to which the criteria apply. This would introduce a cost implication to the regime choice.

The results show that given the above final choice and considerations, management has to consider if it really makes any or much of any difference to choose the second choice of regime. For example, if the deviation is small and maintenance costs can be minimised without compromising the level of service delivery and the condition of the asset, the lesser choice of maintenance regime could be selected.

Table 5-12: Maintenance regime choice per alternative

Site	**C_1**	**C_2**	**C_3**	**C_4**	**C_5**	**Alternative choice**	**Criteria choice/ C based**	**Criteria choice/ site based**
1	0.103	0.121	0.060	***0.452***	0.259	C_4	CBM	CBM
2	0.173	**0.244**	0.091	0.248	*0.252*	C_2	CM	CBM
3	**0.190**	0.162	0.091	*0.332*	0.238	C_1	CM	CBM
4	0.170	0.193	**0.132**	0.137	*0.210*	C_3	PM	CBM
5	0.121	0.101	0.060	0.292	***0.441***	C_5	PM	PM
6	0.131	0.162	0.071	0.290	***0.341***	C_5	PM	PM
7	0.180	0.172	0.090	*0.301*	**0.273**	C_5	PM	CBM
Criteria choice site	3	2	4	1	5			C_4 C_5

Overall maintenance regime = CBM (0.452, site 1, C_4 is highest).

The results (Table 5-12) show that based on site 1, CBM is the best choice (0.452, $\mathbf{C_4}$ is highest). In terms of highest majority, CBM is the choice as well. The balance between the two would be made by management. For alternative based choice, the number of assets supporting that criterion should be the priority. Ease of carrying out the maintenance (C_4) is critical and would minimise costs and breakdowns in the long-term.

Deviation from the preferred criterion (C4) is analysed and summarised in Table 5-13.

Table 5-13: Deviation analysis of criteria-based choice

Site choice	**Value**	**Deviation**	**Maintenance**

			type
C1	0.190	0.262	CM
C2	0.244	0.208	CM
C3	0.132	0.320	PM
C4	**0.452**		CBM
C5	0.441	0.011	PM

The results (Table 5-13) show that PM and CM were preferred with regards to two criteria each. Although it was the highest rated from the AHP analysis, CBM was the highest preferred with regards to only one criterion.

Management has to consider if it really makes any or much of any difference to choose the other choice of regimes. For example, if the deviation is small and other factors are better supported by that maintenance regime. Other factors could include forecasted demand or changes in the organisation's operations.

5.4.5 Evaluation of assessments

The results of the application and testing of the maintenance regime selection approach were evaluated by using the consistency ratio to test the consistency of the matrix. Experts' coherence and confidence were also assessed in order to evaluate the quality of the data collected and analysed.

a) Consistency ratios

Consistency ratios measure the consistency of overall matrix and are presented in Table 5-14.

Table 5-14: Consistency ratios for each site

Site	CR
1	0.05
2	0.03
3	0.01
4	0.11
5	0.02
6	0.07
7	0.11

The consistency ratio should not exceed 0.1 in order for the experts' matrix to be consistent. All sites were consistent as they did not exceed 0.1.

b) Experts confidence

Experts were asked to state their confidence in their assessment according to their understanding of the different maintenance regimes and their application to different asset groups within the organisation. Table 5-15 summarises the experts' confidence for site 2.

Table 5-15: Experts confidence in their assessments, site 2

Experts	Confidence
E1	95%
E2	65%
E3	90%
E4	90%

Expert (E2) was the least confident. The average confidence (85%), which is limited because of the outlier expert (E2) indicates the confidence in the research results. A more reflective confidence (91.6%) is derived from the three experienced experts as the (E2) is an obvious outlier. It could not be established why E2 happed to be outside the range of other experts at this site. This was because E3 did not have the least work experience as E3, as indicated in Table 3-20. E2 also rated high in confidence when assessing asset condition.

5.5 Summary

The objective of the research in this section was to develop a method for selecting a maintenance regime for an asset group that has sparse or no data to inform such selection. The AHP was used in combination with expert elicitation because of its ease of understanding and application. Experts opinions where elicited for establishing preference matrices for the AHP and for validating the research. Much progress has been made in the understanding of asset maintenance regimes; however the knowledge gap in performance indicators for a particular asset group and over-ground assets still remains, particularly where data are sparse.

Key results from the research indicated that maintenance regimes can be selected and applied even where there is sparse or no data. The contribution of maintenance regime programmes in ensuring strategic resource allocation and efficiency emphasised the importance of selecting a suitable one. Secondly, implementing asset management policy requires that the maintenance regimes be in place and relevant to the asset group. This is indicated by the different asset specific alternative for different asset groups. Experts' selection is important in ensuring quality results, as indicated by less experience experts lacking confidence in the quality of their opinions. More the work experience in asset maintenance can lead to higher the experts' confidence. Lastly, the AHP is an effective tool in selecting a maintenance regime because it is easy to apply and can cater for several criteria. The inclusion of several experts can increase confidence in the results. Similarly, the participation of internal experts could boost morale – leading to better ownership of the application of the maintenance regime.

Figure 5-6 summarises this chapter's process of the approach developed for asset maintenance regime selection where there is limited or sparse data.

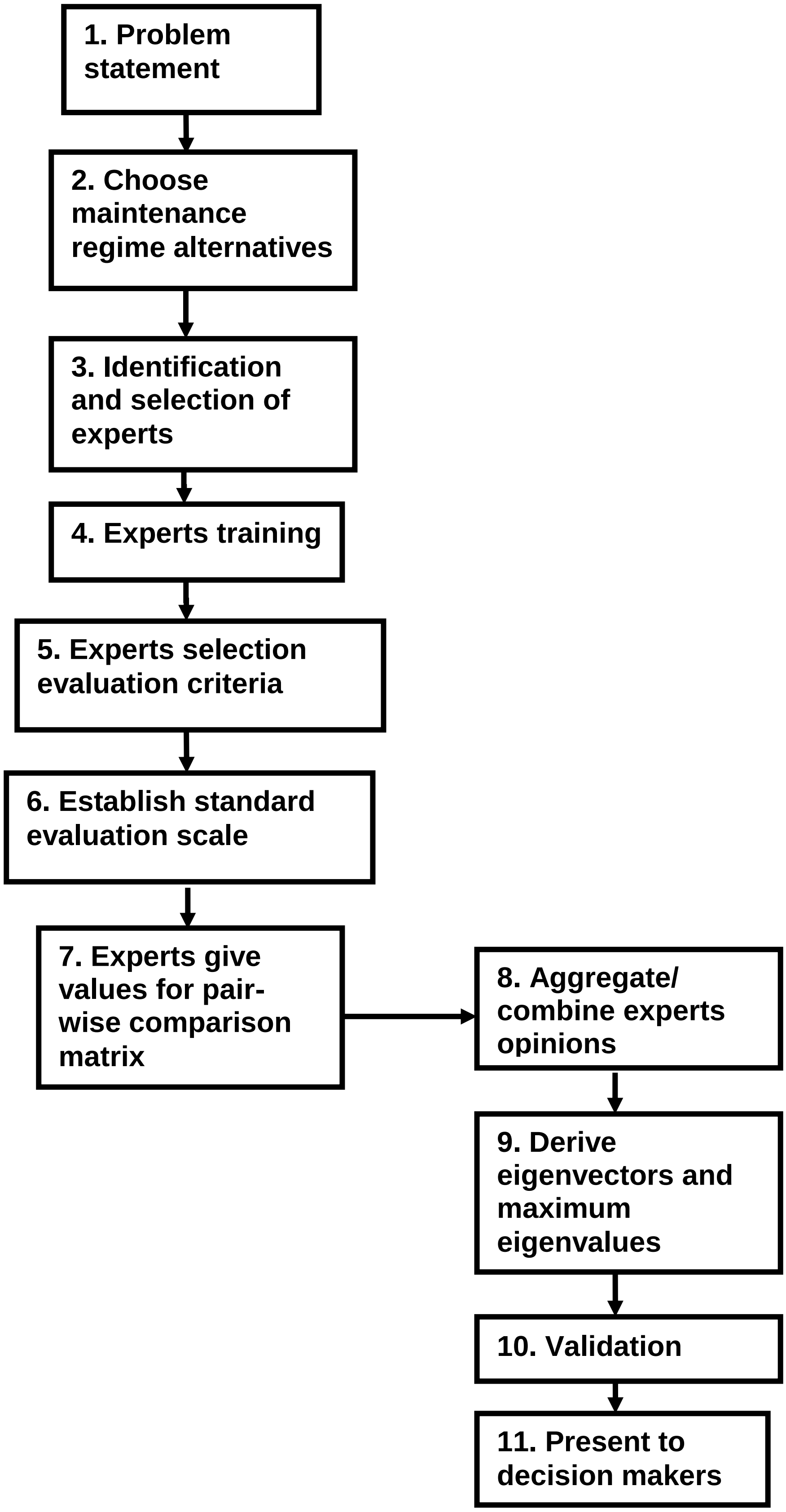


Figure 5-6: Maintenance regime selection process for decision support.

The developed asset maintenance regime selection process stages are described in detail in Chapter 2.

6 GENERAL DISCUSSION

6.1 Introduction

This research sought to investigate and develop decision support models when there is limited or sparse data to support decision-making in water utility asset management. In cases where sparse data exist to support decision-making, rule of thumb methods tend to be used to make decisions about asset management policies, assets conditions and the quality of maintenance strategies being employed. Three objectives of the research were;

- To evaluate the asset condition assessment strategies used by water utilities and develop and analyse improved assessment approaches to better support asset management decisions.
- To develop novel approaches to investigate the implications of poor asset condition assessment in maintenance resource management.
- To develop models that can be used to assess asset maintenance effectiveness or quality in order to support maintenance strategy development and reviews.
- To develop approaches to establishing asset maintenance policies when there are sparse data available to support such management decisions.

The results and findings of each objective are further discussed in the following sections.

6.2 Asset condition assessment and management

6.2.1 Introduction

The objective of the research in Chapter 3 was to investigate and develop approaches to enhance asset condition assessment in a water utility. Particular attention was paid to above ground assets because of the limited research in applying condition assessment methods to such assets (Marlow and Burn, 2008h; Brint *et al*, 2009c).

6.2.2 Research strategy

The research methodology used combined expert elicitation and some assets' historical data as evidence to evaluate asset condition. Expert elicitation was used because poor data quality within the sample asset group was found. Success of the method relied on the ability to acquire quality data from experts and the flexibility to incorporate evidence through quantitative data. A detailed rationale of the research approach is presented in Chapter 2. The method employs expert elicitation to assess assets condition. Each asset group was assessed based on its specific performance indicators or variables. Standard performance indicators are only used across one asset group and unique performance indicators are specified and used for different asset groups. The experts also state their opinions within a wider range than current methods allow. This allows for great improvement in precision of the asset condition statement and hence, better selection of maintenance regime and resource allocation.

The method adopts and improves the common approach for condition assessment used where there is little data in water utility (Rajani *et al*, 2006). The methodology allows experts to state their opinions in given five categories. Experts can only assess an asset as being in condition 1, 2, 3, 4, or 5. This allows experts to state assess the condition in magnitudes of 20% step changes. It was found that the method can be improved to allow for better precision in the condition assessments. The expert elicitation methodology was adopted and improved in order to decrease the margin of error and increase the confidence range above currently used approaches (Figure 3-4a), as identified from the literature and water utility common practices (Wang and Zhang, 2008c).

The major identified limitations of the current experts' approaches include the following;

- Experts do not express their level of uncertainty pertaining to;
  - The asset grade they give.
  - Their belief in the opinions they give.
- Experts training not factored in elicitation protocol.
- Expert elicitation is carried out only for reporting purposes.
- Few of the formal techniques for elicitation, calibration or verification have been evaluated in conditions typical of asset condition analysis, creating an opportunity to test some of them.

Figure 3-1 illustrates the limitation of the current condition assessment approach in terms of lack of precision and poor calibration, resulting in a large uncertainty in the allocated asset condition grades.

The new elicitation approach to condition assessment was applied and tested within a large asset-intensive water utility. The approach follows a risk assessment framework of asset condition assessment.

Experts were invited to assess water pumps at seven different sites. Due to time and other resource constraints, the organisation's engineers were used to elicit opinions about asset conditions. Experts were chosen according to their area of speciality. Engineers currently working in the specific area covering the sampled asset were chosen to be experts (both operations and maintenance engineers). In summary, the steps followed in applying the methodology are; training, selection of asset performance variables, elicitation of asset conditions, aggregation of opinions, and validation. The research produced a novel expert elicitation approach that produced improved specification of uncertainty in asset condition assessments for water utility (Figure 3-4a). The use of specific performance variables for each asset group also improved on current practice (Table 3-6).

6.2.3 Condition assessment case study

Clean water pumps were chosen as samples for the case study because the method was developed for above ground assets. Based on evidence data and opinions from the experts, the pumps' conditions were investigated. The results from the case study are discussed following the methodology.

6.2.3.1 Experts training

Experts were trained by explaining terms used in the elicitation questionnaire and practising answers with some sample questions. Feedback sought at the end of each exercise showed that experts found the training helpful in understanding the elicitation questions and meaning of statistical concepts required for stating their opinions. This emphasises the importance of giving training to experts as they stated that they would not be confident in their opinions if the training was not conducted prior to the elicitation exercise, with some indicating they would not know the meaning of some terms used. For example; the terms used for describing different types of maintenance (Section 6.4) and the meaning of upper and lower quartile when stating their uncertainty in the condition grade. Experts were also made aware of some of the potential sources of bias.

Other researchers have emphasised the need for training experts before the elicitation exercise and some authors leave out training from the elicitation protocol (Burgman *et al,* 2006). On the other hand, Cooke and Probst (2006) noted that experts are more likely to state their opinions correctly if they have been trained and they understand basic statistics and probability such as the meaning of variance and deviation values. Experts' training is, therefore, necessary because experts are rarely knowledgeable in probability and statistics and these are rarely understood or assessed accurately in practice (Garthwaite, 2004). The results from this research emphasize the need for training as the experts stated that the lack of training would have undermined the results on the basis of poor opinions given. The experts admitted that they would otherwise have not really stated their true values due to lack of understanding.

6.2.3.2 Variable selection and importance

Many performance indicators or variables impact on a pump's performance and could be used in assessing its condition. It was determined that, in practice, only a few of the pump performance variables can be used to assess its condition. Experts were invited to select the most important pump performance variables to use in assessing its condition. A total of (M^i) variables that are associated with the pump performance were identified and the experts were invited to rate the importance of each variable in determining the pump condition (Table 3-5). Experts were then asked to rate the importance of each of the M^i variables presented to them. The importance of each variable was ranked from 1 to 5 – with one being the least important and five, the most important rank (Figure 3-3). The three highly rated variables were then used to assess the assets condition.

This revised approach allows experts to define all the variables that affect the asset condition as they are specific to each asset group. This is currently not the case with the common methodology discussed in Chapter 3. The criteria defining the variables for assessing the assets is standard and applied across all asset groups, which is only differentiated between above ground, below ground and electrical and mechanical (E and M). The variables influencing the condition of the asset group were identified. Weighting the variables to assign weight score to each gave the overall importance. The variables with the highest importance were selected and used in assessing the pump condition. Table 3-5 shows the overall results of the importance rating. The results were obtained from the first survey site and applied across other sites.

The experts at the other sites were asked to state their three most important variables and the results supported the importance ratings obtained from the first site (Tables 3-5 and 3-6). This demonstrates that the experts generally had similar views on what variables mostly influenced the water pumps' condition. The rating of the variables' importance could not be verified from the other sites since they were not asked to rate them.

The variable selection exercise emphasized the importance of choosing specific variables for each asset group because each group is unique. The use of generic asset performance variables across the water distribution assets undermines the quality of the results of the condition assessment because each asset group has unique performance indicators. This is because assets have very different performance variables that are sometimes not relevant to other asset groups. For example, temperature may be relevant for a water pump condition assessment and not as relevant for water pipe assessment. Some variables may apply to two asset groups, but vary widely in importance. For example, corrosion could be more important for a water pipe condition assessment than for a water pump assessment. Therefore, it is important to select important variables for each asset group. This process has not been a routine asset condition assessment practice in water utility, indicating some asset have been assessed based on performance variables that were not relevant to those specific assets. Such distortions were easy to hide in the one point estimate (1/ 2/ 3/ 4 or 5) experts made in classifying the assets.

Studies in variable selection are mostly quantitative, such as computer programming (Salvador-Carulla *et al,* 2007b). Authors exploring expert elicited variable selection are also limited (Garthwaite and Dickey, 1996b; Garthwaite, 1983b). The value of employing experts' services to select variables was evaluated, compared to giving experts one's own variables. Assessing if experts are better at prioritising variables would enhance the quality of condition assessment as attention would be placed on meaningful variables since some assets have too many variables to consider at any one time as indicated by Dlamini *et al*, (2011). Maintenance resources would also be better focused for each asset group.

It is worth noting that performance related variables in water supply are not related to specific asset performance assessments, but for assessing the whole network and organisation performance. Performance variables of the assets in this research were considered to be management tools fundamental to monitoring the conditions of the assets, as indicated by Alegre *et al.* (2000b) and Alegre, (2008). Selection of performance indicators/variables is crucial to asset management. Performance variables can be influenced by a range of factors such as experts' perception or operational experiences. According to UKWIR (2002), an ideal performance indicator would allow assessing the scope for improvement in system efficiencies and tie it in with the organisation's maintenance policy and plans. There are costs and efforts involved in gathering data and maintaining each performance measure. Therefore, the selection of performance measures regarding each asset group should be carefully evaluated in terms of their strategic value to either maintenance decision making, importance to asset performance and should be also justified on a maintenance cost benefit basis. Performance variables should provide objective quality evidence to assist in decision making regarding the condition of the asset (Matichich *et al,* 2006e).

Each year water and sewerage companies in England and Wales are required to thesis information on their performance against various aspects of service as shown in Table 3-1 (Ofwat, 2008c). These are known as serviceability indicators, which are focussed on the service to the customers. These serviceability indicators measure the performance of the system instead of performance of a particular asset or asset category. It is 'serviceability to customer' and not 'serviceability of the assets' (Parsons, 2006d). Inadequate pressure can be directly related to asset maintenance. However, the other variables clearly have little direct connection with network operation or asset maintenance issues. Variable selection in this research only focussed on condition issues affecting the asset group directly.

6.2.3.3 Elicitation of asset conditions

Since assessing the probability of failure or specifying a meaningful remaining life can be challenging, grade systems are often used to summarize the condition and performance of the asset. Condition grades are assessed through visual examination of an asset and with reference to specified descriptions of each grade. An asset's condition grade can only be allocated reliably after explicit visual inspection of the asset. Grading asset condition in this way gives a measure of the extent of physical deterioration with respect to the 'as new' condition. Different 'levels' of condition grades can be established depending on the type of data used and the certainty of the condition grade. Where visual inspections are not possible or have not yet occurred, interim grades can be established based on available information such as age, material, repair history, or observations on similar assets.

Similarly, performance grades give a broad categorization of an asset's ability to function in accordance with the utility's requirements, and are allocated using operational knowledge of the asset, again with reference to specified descriptions of each grade. A performance grade can only be allocated reliably with reference to detailed local operational knowledge. Grading systems can be simple (Grade 1 to 5), intermediate (Grade 1 to 5 with sub grading for worse three grades), and sophisticated (multiple faceted ranking schemes), although these can be reduced to 1 to 5 where necessary. Ideally, the observations made during a condition or performance assessment will be recorded, as the combination of a number of distinct observations into a single grade at the point of survey results in a loss of useful information.

The results from the research were obtained by experts stating their condition grade 1 to 5, and then stating their uncertainty level regarding the condition grade. The uncertainty level sought was regarding how much the experts believed that the asset had already passed the condition grade they had first given. This is an elicitation of point estimates of the grade and then stating their uncertainty for the given interval above the grade. The results in Table 3-7 show the experts' estimates for both condition grade point estimates and uncertainty regarding the estimate. Experts gave their lower quartile, mean and upper quartile. The results show that experts expressed lack of confidence in the point estimates and increased their confidence when they were able to state their uncertainty.

Experts were then shown historical data for each of the water pumps whose condition they had assessed and were asked to re-state their opinions if they wanted to. The data were all corrective maintenance carried out for each water pump in the past twelve months – representing some of the evidence of the performance of each pump. The number of corrective maintenance actions for each pump in the twelve months preceding the elicitation exercise was shown to the experts to review their assessments accordingly. All experts reviewed their opinions after being shown the corrective maintenance evidence. The experts gave a worse condition than stated before the evidence where there was relatively a large number of corrective maintenance actions and an improved condition where the number was lower. The experts' assessments in Table 3-14a after the corrective maintenance evidence show that experts gave a 10% lower condition rating and a 13% higher rating than the previous assessment. The results clearly show that the condition of the assets could be sometimes 10% over-rated and 13% under-rated without evidence. This emphasizes the value of evidence in supporting expert elicitation. Evidence improves the quality of the opinions and thereby, reducing uncertainty levels.

a) Distribution of experts' assessments

Experts' assessments were plotted on distribution curve to determine the distribution differences between experts' assessments. The beta distribution was mainly used because available packages for expert elicitation tend to favour it and is recommended by elicitation experts. Others recommend the exponential distribution if the expert's assessments are below 0.3, the beta distribution for assessments between 0.3 and 0.7, and the Weibull distribution for assessments above 0.7 (O'Hagan, 2006d). The type of distribution used in this research was not critical because it was only used for assessing data distribution, without interest in eliciting the parameters. Also, the exercise was not for eliciting parameters for an algorithm, as interest in particular distributions tend to be important in such cases (O'Hagan, 2005b).

The distribution of experts assessments for site 2 are shown in Table 3-16. The statistical distribution of the experts assessments show little differences between experts within each group, except for a few. It is difficult to determine if the experts, whose assessments were very different, could be considered as outliers because there were not reasonably many experts per group. It is assumed that there could possibly have been many within the same range of assessments, were there more experts being assessed. After seeing the evidence, experts tended to review their assessments upwards (lesser condition) or downwards (better condition) according to large or smaller number of corrective maintenance, respectively. This was reflected by the respective shift of the distribution curves to the right or left after experts reviewed their assessments. It is worth noting that the shifts in the distribution curves were not large in most cases, indicating that experts tended to review their opinions by smaller margins rather than larger margins.

As, stated earlier, expert opinions based condition assessments in water utility have tended to only elicit point estimates and with quite large margins of error as experts could only state condition 1 – 5. The results from this research mitigates the problem by introducing uncertainty estimates and hence, allows a reduction in the margin as experts can state estimates between 0 – 1. Other studies in other fields such as nuclear sector have used different versions this method mainly as probability estimates (Barker and Haimes, 2009b). It has, therefore, been proven to be better than point estimates. Water utilities would be improving their assessments for their Capital Planning Framework requirement and better fulfilling their regulatory requirement to the regulator by improving on their asset condition assessments (Lumbers and Heywood, 2005). The Capital Planning Framework and the regulator (Ofwat) require water utilities to continuously improve their asset planning and budgeting for their five-yearly reviews by the regulator.

One of the major limitations considered from the research is that water utilities tend to undertake asset condition assessments only for purposes of regulation. That is, they carry out intensive network-wide asset condition assessments only once in five years for the purpose of submitting their asset investment plans to the regulator. Such assessments are crudely carried out in passing – with the aim of using them to assess asset remaining life. A few assets are assessed per asset group and estimates are made for the whole network. For example, the number of assets in each condition grade is estimated from a sample and then used to estimate the percentage of assets with a specific remaining life. The limit being that asset condition assessment is, therefore, not part of the value-chain and not mainstreamed within the water utility. Therefore, the lack of data to assess asset condition would continue. Making condition assessment part of the maintenance routine would mainstream condition assessment within the organisation over time and, hence, increase the availability of historical performance data over time. Such data would be further used to better assess asset condition by increased availability of evidence data of each asset performance. This thesis has offered a robust and feasible means of undertaking this within the practical constraints of data quality and availability in a water utility.

The use of specific performance indicators for each asset group introduced in this research's condition assessment approach would further enhance the data gathered for each asset group as it would be specific and unique to each. This would lead to a more focussed and, therefore, efficient allocation of maintenance resources and hence defining how condition assessment feeds into both tactical and strategic asset management. Marlow and Burn (2008i) define the importance of asset condition assessment in water utility as defined by International Infrastructure Management Manual (IIMM), a guide to infrastructure management developed in Australia and New Zealand (IPWEA, 2006), and Publicly Available Standards 55 (British Standard Institute, 2004). However, they lament how the definition fails to express how asset condition assessment feeds into tactical and strategic asset management.

6.2.3.4 Aggregation/ pooling of experts condition

Both weighted and un-weighted methods were used to aggregate the experts' condition assessments. Equal weights were first used and then a performance linear weighted aggregation method was used to pool together the experts' opinions. An opinion pool is a method of combining a number of different opinions about some unknown quantity θ to generate a single pooled opinion. The two most widely used opinion pool methods are linear opinion pools and logarithmic opinion pools. If there are *n* experts, and let $p_i(\theta)$ represent expert *i*'s probability distribution for unknown quantity θ, i =1, …, n, and w_i be expert *i*'s weight. Then the combined probability distribution $p(\theta)$ is a weighted linear combination of the experts' probabilities (weighted arithmetic mean model) in a linear opinion pool. On the other hand, $p(\theta)$ in a logarithmic opinion pool is expressed as multiplicative averaging (weighted geometric mean model). Equal weight and performance-based weight were compared between the experts' assessments.

a) Equal weight aggregation

The equal weight aggregation of experts' assessments was used where experts' judgements were given equal weight to the overall asset condition. The results show that, most of the time, experts did not deviate too far from the mean - indicating that the experts generally agreed, with little deviations, on the conditions of the water pump (Table 3 - 8).

The problem of opinion pools generally reduces down to determining the optimal weights *wi* for experts. Various methods for finding the optimal models are explored in several studies, for example, in DeGroot and Mortera (1991). The simplest choice of weights is assigning all experts an equal weight, $wi = 1 / n$. A simple arithmetic averaging of experts' assessments is used in many studies such as a U.S. Nuclear Regulatory Commission (NRC) research on the frequency of accidents at nuclear reactors (NRC 1989). Cook (1991a) discusses that while there are some efforts in compensating such a simplistic method by improving the elicitation procedure itself, such as those witnessed for the NRC document (Honano *et al*. 1990; Wheeler *et al*. 1989), this type of method is less than optimal as it lacks any attempt to evaluate the quality of each expert's estimates.

b) Performance-based weight aggregates

The second approach of combining experts' opinions that was used in the research pooled experts opinions based on the weight of their performance. The weights for the experts were established by calibration as a measure of performance. Calibration of expert indicates how expert's assessment corresponds to a set of performance results. Each expert's contribution to the aggregate was assessed based on the performance on the calibration. Calibration is the assessment of experts' performance based on a test question which answer is known to the analyst and known to the experts post hoc (O' Hagan *et al*, 2006e). The direct calibration results of experts are discussed in Section 6.2.3.4 in this chapter, where the condition assessment results of the water pump are evaluated. This was to determine the significance of each expert's opinion towards the overall aggregate.

The results (Table 3-7) show that most of the experts' individual performance sometimes deviated much from the aggregate assessment for pump 3. The assessments for pump 1 and 2 had larger variations, indicating that experts' performance was not consistent. After the assessments were reviewed in the light of the performance evidence, experts' assessments were reviewed upwards by a maximum of 13%. The larger the number of corrective maintenance, the more experts reviewed their opinions towards the upwards and downwards with fewer corrective maintenance actions**.**

The results from the condition assessment with weighted pooling, as presented in Table 3 – 10, show that the experts did not deviate too far from the mean for pump 3. The deviations for pump 1 and 2 were larger. This shows that the experts were generally not consistent in their performance on the conditions of the water pump assessments. This was the case for both aggregates obtained before and after preventative maintenance evidence was given to experts to enable opinion reviews. The deviations from the mean seem large for the currently used method because it does not allow experts to state their true value of the asset condition.

The significance of the results for the commonly used versus the new condition assessment approach was also investigated. The results (Figure 3 – 3) show that the old and new approach assessments sometimes had an average 50% difference. The significance was not assessed by the standard error approach because each site had a sample of less than 30 assets assessed.

The results indicate that the nature of asset performance data shown to experts could sway their opinions and to the extent that they believe such performance influences the asset condition as reported in a research by Sharp *et al,* (1988). If experts are shown more data on the asset performance, they develop their confidence in the understanding of the current condition of the asset. The condition of that asset, as given by experts would still be very subjective unless experts are aware of major maintenance work, such as refurbishment, carried out within the assessed period. In such a case, an asset can be restored to 'as good as new' through refurbishment. This would be confusing to experts, particularly if the age is recorded as quite old and they expect the asset to be at least over condition grade 4 and the asset appears to be below condition grade 3.

The results suggest that performance data shown to experts should be balanced and consider an asset's key performance history, which is crucial for true experts' assessments. Such data were not presented to experts in this research due to the difficulty of obtaining the data sets. The performance data accessed for the research suffice for demonstrating the value of performance data, which was the objective in this research. It also suggests that performance data can be factored in as it becomes available in the long term and eventually phase away expert elicitation-based asset condition assessments. Introducing the performance data as more is collected would also be a motivating factor to ensure the data is collected because it would be used. There would be more motivation to collect the data if it is used as it becomes available than when it is to be used later after expert elicitation-based condition assessments are phased out. It would also help utilities to consider the different asset performance data they need for each asset group.

Cooke (1991b) proposed a performance-based weighted averaging model using properties of scoring rules, known as the classical model. He emphasizes that the fundamental goal of science is to build rational consensus and, therefore, the process of collecting expert assessments must be subjected to the following five basic principles (Cooke and Goossens 2000a):

1. *Reproducibility*: All results must be reproducible, with calculation models and data being clearly specified and made available.
2. *Accountability*: The source of data (name and institution) must be identified, and data must correspond to the exact source from which the data are elicited.
3. *Empirical Control*: Experts' assessments must be, in principle, physically observable.
4. *Neutrality*: The elicitation process must ensure that the actual beliefs of experts be collected (e.g. no punishment or rewords through a self-rating system).
5. *Fairness*: All experts must be regarded equally before the aggregation process.

There are several practical problems associated with the introduction of scoring rules or weights:

(1) A scoring rule assumes the existence of one 'true' underlying probability distribution in the assessor's mind. Whether such a single distribution really exists, and whether the assessor is always aware of it is highly questionable (Hogarth 1975).

(2) A scoring rule can be effective only to the extent that: (a) the assessors understand exactly how their probability statements are evaluated by the scoring rule, and (b) the assessors are making an attempt to follow and maximize this scoring rule (Friedman, 1983). The first assumption may often not hold, especially when complex scoring rules are concerned. With regard to the second assumption, as it is impossible to validate that assessors are reporting their ' true' subjective probability, it is similarly impossible to validate whether they are indeed employing (and correctly) a given scoring rule.

(3) As pointed out by Fang *et al.* (2010a), although all scoring rules are supposed to encourage 'honesty', some scoring rules may be more likely to encourage honesty than others. This is a natural question for psychological investigation.

(4) The extent to which a scoring rule may encourage careful assessment may depend on the nature of the rule. Fang *et al.* (2010b) suggest that sharper scoring rules are more sensitive since deviations from optimality are more costly. Sherrick (2002a) argues that most scoring rules, at least in the experimental laboratory, suffer from the flat maxima phenomenon implying relatively small differences in payoffs for optimal and non-optimal decisions. How sensitive assessors are with regard to different scoring rules has not yet been established empirically; in any event, researchers are strongly advised to take account of the potential effects of the flat maxima phenomenon in the process of designing and interpreting experiments (as illustrated in Sherrick (2002b).

(5) A scoring rule is a translation of certain goals to be achieved, and thus the assumption is that such goals exist and are well defined. In reality, this assumption may often be invalid. Moreover, frequently there are several goals to be achieved, and if two or more of these goals are conflicting it may be difficult, if not impossible, to transform them into a coherent scoring rule.

With few exceptions, little empirical research has been conducted to investigate the effectiveness of scoring rules. Jensen and Peterson (1973) compared the three most popular rules (log, quadratic, and spherical) and found little differences in the probabilities inferred from each of these three rules. However, probabilities became less extreme with increased steepness in the functions relating score to assessed probability.

In another research, Fischer (1982a) made a direct attempt to evaluate the impact of scoring rules. Based on four different cues, Fischer asked his subjects to predict grade point average (GPA), for several hypothetical freshman students, by assigning probabilities to one of four possible intervals (of GPA). He employed a truncated logarithmic scoring rule that is characterised by 'flatness' for moderate and large values of the probability assigned to the true value, and drops sharply for values lower than 0.25. The major effect of the scoring rule was to deter subjects from using very low probabilities due to the potential heavy penalties associated with such probabilities. No other statistically significant effect was evident though, compared with the control groups, the scoring-rule groups were both less confident and closer to the predictions of a Bayesian classification model (see Fischer (1982b) for details). The effect of the scoring rule in Fischer's research was certainly limited.

Unlike laboratory investigations, real-life situations often carry with them natural scoring rules. For example, in medicine under most circumstances, physicians adopt a payoff matrix that assigns a greater cost to a false negative diagnosis than to a false positive one. However, Griffin and Brenner (2004) warn that all the results in the medical field were obtained under somewhat artificial conditions (where primary attention was given to diagnosis), and question whether these results can be generalized to the real world. An important question from a descriptive viewpoint, and one that has been completely ignored, concerns the natural scoring rules adopted by subjects when such a rule is not given by an external authority. Self-developed scoring rules, though not precisely formulated, may have a larger impact on the assessor's probability judgments compared with artificial scoring rules, and may be less recognised.

The results also show that there is a difference between the results of weighted and equal weight opinion pooling. Table 3 - 10 show the results and the comparison is summarised in Table 3 - 11. The difference is sometimes large. The literature in aggregation of experts opinions does not show any preference in the type of aggregation method used except some prefer the mathematical over behavioural (group consensus) aggregation. Some researchers have referred to the superiority of mathematical aggregation versus group consensus method of aggregation. This research did not venture into exploring and comparing the aggregation methods. Only the advantage of the mathematical weighted average pooling was realised in the research as it allowed each expert to contribute to the final assessment according to their individual performance. The performance based aggregation approach was adopted as better than the equal weight in this research because the experts' performance was reflected. This is the case with most studies as reported in the Dike ring failure frequency research (Cooke and Slijkhuis, 2003)

It is concluded that such weighted aggregation are better in reflecting the asset condition assessment final value than equally pooling the experts' assessments. In turn, it validates the assessment as true experts' opinions are reflected in the overall aggregate.

6.2.4 Heuristics and biases

The analysis also considered heuristics and bias due to anchoring and personal gain was found to be dominant among the experts. Some experts chose asset performance variable based on their experience with that particular site's assets and were not particularly general in their view. This is a heuristic problem of anchoring and availability. Anchoring is a biased opinion from an expert based on his previous or usual experience with that particular asset or issue being explored (Burgman, 2011a). Availability, on the other hand, is a bias that would be caused by basing their opinion on what the most recent experience was with that particular asset (Ouchi, 2004). Importance itself could be subjected to the experts' understanding of what is important in the asset make up and how it relates to other assets in the water distribution network. On the other hand, variable importance rating by an expert could be based on their particular but not typical experience with the asset regarding that variable – which would be a form of anchoring. For example, a particular expert engineer may have recently carried out maintenance on a water pump with persistent rotor problems and he/she then develops a bias toward placing more importance on the pump's rotation speed and vibration rather than other generally more important performance indicators. Studies have shown that overconfidence is the most common form of bias, which includes anchoring and availability (Burgman, 2011b).

Personal gain was stated as one of the major sources of bias among experts in their assessments, particularly of asset condition. The responsibility as maintenance engineers to ensure assets' good condition meant that some experts were motivated by possible maintenance resources allocated to each asset by management in their assessments. For example, some experts agreed they could have been biased because they would want urgent action taken about assets they know had problems. They would rate the condition of such assets as worse than they actually were (Table 3-16). This is supported by a research on organisational reliability of water utilities, where risk level posed by assets was placed at a higher scale for similar purposes (Bradshaw, 2008d). Such biases could be minimised by employing external experts, but the drive to mainstream condition assessment would be defeated as external experts would only be suitable for the once in five years assessments done for only regulatory reporting due to prohibitive costs.

The interesting aspect of most research on heuristics and biases in expert elicitation is that it is usually carried out in social science settings. Whether these biases have the same meaning in engineering settings is debatable and a subject of further investigation. For example, anchoring may be negative on a social science environment, but it may be positive in an asset management (engineering) environment because experience with technology may be good to remember and apply in similar settings where experts are asked about their opinions. Such anchoring may be critical and support health and safety, minimise risk of pollution to the environment, and in the process save the organisation's associated financial resources. If this form of bias is necessarily positive in engineering environments, it would support the case of employing internal experts and hence easily mainstreaming the asset condition assessments within the organisation.

6.2.5 Evaluation of condition assessment opinions

This research explored calibration, coherence and experts' performance weights to validate experts. Confidence intervals were also evaluated to validate the aggregate opinions.

Experts were found to be coherent (Table 3-18), relatively overconfident than under confident (Table 3-17), and were generally well calibrated. Confidence levels were derived from experts' confidence in their opinions (Table 3-21) and their performance weights (Table 3–20).

a) Calibration

Calibration studies are concerned with the appropriateness of assessors' subjective probability estimates, or confidence in their judgments and predictions, and can be categorized in two groups: one that elicits judgments about discrete propositions, and one that attempts to identify probability density functions assessed over continuous variables (e.g., uncertain numerical values). The customary definition for discrete probability statements is that judgments are well calibrated 'if on the long run, for all propositions assigned a given probability, the proportion that is true is equal to the probability assigned' (Hardman, 2009c). Discrete probability statements can be classified according to the number of possible alternatives the assessor is exposed to, and the corresponding range of the probability scale: in the one alternative *case.* The assessor is required to make a probability judgment with regard to a single event or statement (provided either by the assessor or by someone else). The appropriate probability response in this case ranges between 0 and 1.0. In the two alternatives *case* the assessor has to choose between two alternatives, and then provide a probability judgment for the chosen alternative in the range of 0.5 to 1.0. Finally, in the multiple alternatives case, the assessor is asked to select the most likely response.

The results from experts' performance were assessed against a question whose answer was known to the facilitator and also referred to as the seed variable. It is assumed that all experts should know the assessment value if they are 'good'. Deviation from the seed variable is analysed (Table 3 - 17).

A common way of analysing probability judgements and confidence ratings is via the use of a calibration curve in which it is plotted on the ordinate for each confidence response. It is customary to group all responses in the range 0.50-0.59, 0.60-0.69,..., 0.90-0.99, and 1.0. The mean percentage correct for each response group is then plotted against the corresponding mean probability assessment for that category. The 45 degree line represents perfect calibration. Any point below this line is interpreted as reflecting overconfidence, and any point above it represents under-confidence. Under- or overconfidence can be further assessed by the weighted mean (over response groups) of the differences between the mean of the probability responses and the corresponding proportion correct for each category.

Calibration regarding uncertain continuous quantities can be assessed by estimating the probability distribution with the use of different fractiles. Roughly, calibration is intended to measure the extent to which a set of probability density functions 'corresponds to reality'. Over or under-confidence are usually measured by the interquartile index, and the surprise index. The former is the percentage of items for which the true value (actual outcome) falls inside the interquartile range (between the 0.25 and the 0.75 fractiles), and perfect calibration is indicated by an index of 50. Any value lower than 50 would imply over-confidence, and values above 50 are interpreted as under-confidence. The surprise index represents the percentage of true values falling outside the most extreme fractiles assessed. For instance, a surprise index of 2% refers to the extreme values that fall below 0.01 and above the 0.99 fractiles. Ideal calibration would lead to a surprise index of 2, and any value above it would represent overconfidence. Frequently, the relative frequency of true values falling below the assessed medians is also computed (Vescio and Thompson, 2001).

Two major consistent themes emerge from calibration studies. One is that there is a pervasive tendency of overconfidence, in particular tasks (but not restricted to) that use general-knowledge questions. The second main finding is that the degree of overconfidence (when it exists) depends on the difficulty of the task as measured by of correct responses or predictions. Usually, the more difficult the task the larger the degree of overconfidence as indicated by the traditional measures.

One question, of particular interest, is whether experts (in any given field) are better calibrated compared with lay people or is good calibration a necessary attribute of expertise? The answer to this question is not unequivocal: some studies reported high overconfidence, especially for different types of diagnosis in the medical field. For example, Griffin and Brenner (2004b) and Chan (1982) reviewed various studies with experts and suggested that in several cases, experts' probability assessments were not better than those of lay persons. In contrast, other studies in different fields resulted in good calibration, showing little overconfidence (occasionally even some under confidence). This was true for weather forecasters, accountants (Tomassini *et al.* 1982), professional bridge players (Keren 1987), and students predicting their course grade. Manger and Teigen (1988) reported a high level of overconfidence of students predicting their grades, under different time horizons (eight and two months before their final exam).

These mixed results raise several questions: What is the source of these large differences between experts in making appropriate probability judgments? The question is; is there a general skill involved in making well-calibrated probability judgments? Or substantive knowledge is the decisive factor. If the latter is the case, why are experts in some domains better calibrated than experts in other domains? The question may be raised whether the nature of stimulus material and characteristics of the task may account for the different performance of different expert groups. These are main theoretical questions for which current studies provide only partial answers.

According to this explication, people's poor calibration is just a question of scaling (Levin *et al,* 2006). In light of such an interpretation, the validity of over-confidence phenomenon becomes questionable, and suggested explanations to account for it should be re-examined. For instance, the finding that the degree of overconfidence is positively correlated with difficulty of the task implies, under this interpretation, that the more difficult the task the more difficult is the discrimination between more and less likely events, resulting in a relative flat calibration curve. According to such an account overconfidence should not necessarily be inferred from a flat calibration curve. The view in this research is that over and under-confidence are obviously heuristics and biases issues. As discussed earlier (section 6.2.3), such issues may not be exactly the same as viewed by social science – where experience regarding a particular subject in question could bring negative bias. Over or under-confidence in engineering situations may have different meanings in terms of being negative in value of contribution to the elicitation exercise.

In summary, calibration is supposed to measure the accuracy of probability assessments, but the question still remains, ‘accuracy in what sense’? The strict view conceives the ‘true’ probability to be reflected by relative frequencies measures. But what is a ‘true’ probability? Davey *et al,* (2010) correctly pointed out that such a ‘true’ or ‘objective’ probability often does not exist, and that a probability cannot be right or wrong.

Calibration then is at best one possible way to assess the validity of probability judgments under certain circumstances. The question I;s what are adequate probabilities. Since any probability statement is meant to convey information, it should be accurate as far as possible. However, the criterion for accuracy when applied to probability judgments is often ambiguous. Moreover, the information contained in a probability statement should be evaluated not by precision only, but also by amount and quality as offered by the measure of resolution.

b) Coherence requirements

The collection of consistent condition and performance data facilitates analysis and interpretation, and also allows preparation of deterioration curves that permit prediction of either the probability of failure, or the remaining life of assets or components. It is thus important to develop formal assessment techniques that give repeatable and objective assessments and apply these consistently over time.

The results show that the experts were coherent in their opinions. Experts' responses show that all the experts were coherent is their responses (Table 3-18), except 1 expert from site 3. The reason for this, though experts were not asked specificity, could be that has less work experience and therefore, lacks confidence (Table 3-21).

The coherence criterion, as proposed by Sieck (2003) for evaluating probability assessments, is what they termed *syntactic rules.* The essence of these criteria is to assure that the relations between assessments should be governed by the laws of probability. Yates (1982) termed it internal consistency, to be distinguished from external correspondence, which refers to the degree of correspondence between probability assessments and reality.

According to (Monti and Carenini (2000), coherence is a key concept for the subjectivist viewpoint A set of probabilities is said to be coherent if no gambles can be constructed from such a set that would yield a certain loss independent of the observed outcome (Kadane and Lichtenstein 1982c). Formal treatments (but not empirical) by advocates of the subjectivist school suggest that a person with coherent assessments is expected to be well calibrated (Lad 1984a). According to Lad (1984b), calibration is a concept that can be applied only to all probability assessments made by a given person, and similarly coherence applies to the composite of all probabilities specified. He even goes as far as suggesting that when calibration is considered as a global property of the entire belief distribution, then every coherent specified assessment has been shown to be well calibrated. As with calibration, coherence tests cannot be meaningfully applied to events that are unrelated and are thus essentially unique. Since this research did not involve prediction requirements for experts, the coherence level was accepted as a true indicator of the experts' coherence level.

It is important to point out that empirical calibration studies suggest that people's probability judgments satisfy a primary aspect of coherence: virtually all calibration curves reported in the experimental literature are strictly monotonically increasing. ' The few exceptions in which this rule is violated can be accounted for by chance factors, resulting from an insufficient number of observations for estimating a particular point – meaning that the number of observations for estimating each point on the curve should be explicitly presented.

c) Experts overall contribution weights

The experts' opinions aggregates were summarized and each expert's aggregate removed from the total aggregate in order to assess the value to the overall assessment. An expert's major contribution (above fifty percent is considered an outlier in the experts data). It was found that there were no outliers as experts' contribution were less than 50% across the aggregates (Table 3-10). The reason could be the use of internal experts. The results could have been different when using external experts as they would not be familiar with the assets that were assessed and could have extreme values.

d) Confidence

The overall confidence experts had on their opinions was used to assess the confidence levels on the experts' assessments. For individual experts' opinions, the confidence was determined by their performance weights.

Experts were also asked for their confidence levels in their assessments (Table 3-21). The experts' confidence was quite high, 95% maximum. The results could reflect the over-confidence revealed in the calibration of experts (Table 3-17). If experts are over-confident most of the time, they are expected to give high confidence in assessing their performance.

Two observations were drawn from the above research: one being that there was a large difference between the confidence levels for individual assessments (as determined by personal assessments) and that of the aggregate (as determined by experts' performance). Some experts performed at levels close to their personal confidence level and some did not. The second observation was the fact that experts assigned higher confidence to their assessments than their performance weights reveal. This supports the studies that have shown that experts tend to be more over-confident in their assessments (Todd and Gigerenzer, 2000). Since the confidence level used to evaluate the aggregate was derived from assessments showing some form of overconfidence for some of the experts, the weighted aggregate evaluation can be said to contain some level of over-confidence.

6.2.6 Benefits of condition assessment

This research and thesis offers a practical, robust and implementable approach to condition assessment for situations when data are sparse. There are tremendous benefits attending performing an effective condition assessment programme and these range from improved research planning to implementation, with improved regulatory compliance. Some of the benefits of condition assessment include:

- More accurate capital planning and budgeting,
- Improved regulatory compliance,
- Extension of asset life and capital deferment,
- Improved ability to prepare works program and effective works prioritization
- The ability to generate deterioration curves, to predict probability of failures and/or remaining life,
- Improved risk management,
- Reduced direct costs (through more effective operations and maintenance),
- Reduced risk-cost associated with asset failure, including social and environmental impacts,
- Improved levels of service to customers,
- Demonstration of asset stewardship,
- Improved financial/credit ratings,
- Regulatory compliance, and
- The ability to adopt more favourable financial reporting approaches.

Some of the benefits of condition assessment are discussed below.

6.2.6.1 Improved capital planning and budgeting

By determining the condition of assets, utilities can assess asset value and better understand remaining useful life. Understanding remaining life enables the timing of asset replacement to be forecast more effectively. Knowing the value of the asset allows more accurate budgeting for maintenance, rehabilitation, renewal, and replacement. Armed with this information, utilities can now research future expenditure more accurately and better justify spending to external stakeholders such as governing bodies or boards. In contrast, not understanding the condition of assets can lead to the unplanned failure. This failure usually incurs additional costs and can lead to reactive and unplanned replacement of the asset, which is often the most expensive option.

6.2.6.2 Management of risk

Not all assets are the same; some assets are more important than others and therefore should be treated differently. One way to determine the importance of an asset is to evaluate the risk of its failure. Risk is determined by taking into account both the probability (likelihood) and consequence (severity) of asset failure. The maintenance strategy adopted for a given asset can depend on the assessed level of risk. Condition assessment is generally associated with higher risk assets. However, assessment of lower risk assets are sometimes undertaken for asset stewardship purposes, capital planning, or regulatory reporting. This research validates the need for asset condition assessments to be carried out at all levels and to be adopted as a standard routine in asset management.

The results of condition assessment will indicate which assets are more at risk in the distribution network. Condition assessment, therefore, directly or indirectly supports asset risk management. Each condition grade given by experts can be linked to a certain level of risk of failure by a standard procedure or experts can be asked to give their opinion of the risk level they associate the asset condition with. Many water utilities already have risk assessment tools or programmes and the condition assessment results can be easily linked to these asset risk assessment programmes.

Condition assessment results can then be used to prioritise maintenance resources for those assets in poor condition and or linked to high risk of failure. The risk level would be linked to asset importance in the network in prioritising the asset for maintenance resources, placing condition assessment at the centre of maintenance programmes.

6.2.6.3 Performance, asset condition then impacts on asset failure.

The *consequence* of an asset failure generally remains relatively constant over time. In contrast, the *probability* of failure does not; as the asset deteriorates and ages, the likelihood of asset failure generally increases. Asset management seeks to optimize a utility's expenditure by determining the most appropriate time to intervene in this deterioration process, and the most appropriate intervention (such as replacement, rehabilitation or increased maintenance).

These factors have important implications for establishing a condition assessment program. Except where it is required for regulatory or financial reporting purposes, condition assessment is only warranted when it allows risk to be reduced sufficiently to justify the cost of the assessments. Since the consequence of failure is not affected, condition assessment is generally undertaken in an attempt to manage the probability of asset failure. The benefit derived is equal to the change in probability of failure multiplied by the expected consequence. It is this benefit that must be balanced against the cost of undertaking the assessment and subsequent interventions. A utility would therefore, initially target its condition assessment program on its more critical (higher consequence of failure) assets and progressively move to lower criticality assets over time, as resources allow.

6.2.6.4 Establishing the probability of failure

The probability of failure of an asset increases as its condition deteriorates over time. The output from condition assessment programmes would be a measurement of failure probability, which corresponds directly to the level of asset-deterioration. In combination with assessment of failure consequence, condition assessment would then allow the utility to quantify risk. Given an understanding of risk, the water utility would be able to determine appropriate operational, capital maintenance, and other asset management strategies.

In reality, it could be difficult to derive an estimate of failure probability from a single condition assessment. It may be more feasible to specify thresholds of the asset condition where interventions must occur, and determine if a given asset is above that condition threshold. It is also possible to use the data from condition assessment programmes to produce deterioration curves for modelling/assessing the probability of asset failure, which can then be used in asset management planning.

6.2.6.5 Estimating asset life

Data from condition assessments can be further used to develop deterioration or asset remaining life curves that help manage the risk of failure. Such curves allow the utility to predict time to failure – with failure meaning either: limit of asset capacity; physical end of life; or minimum level of acceptable service. These are usually developed for assessing the asset remaining life, which is outside the scope of this research. The asset condition deterioration curves will show that as the asset's remaining life decreases, its probability of failure increases.

6.2.7 The price of poor asset condition assessment.

This section discusses approaches to assessing the cost of poor assets condition assessment or misallocation of asset condition grades.

6.2.7.1 Condition misclassification and allocation of resources.

There are several implications to the misallocation of assets condition grades. These could be related to the assets reliability, customer services, environmental impact, regulation and maintenance cost. Only misallocation impact on maintenance cost is explored in this research. This is because cost is always important for profit-making organisations. Table 3-23 presents a cost allocation methodology for CG 1 pumps from the sample.

By using the mathematical aggregation there are 2.3 extra CG 1 equivalents than the behavioural method. This means that the budget allowance application to Ofwat for CG 1 pump maintenance will be lower than it should have been. This is because some of the pumps have gone past CG 1 and need more maintenance than is presented by behavioural methods results.

Condition grade 1 pumps in the case study require £52173 maintenance cost for the five year budget period (Table 3-22). When using the mathematical method, pump 20 is not to be in CG1, leaving 22 pumps in CG1. That means the budget allocation per pump will be (£1200000/ 22) = £54545 instead. As more and more assets are misallocated, the budget is further distorted such that there will be over or under investment in maintenance.

It is also observed that pump 1, 29, 43, 52, 53, 83, 95 conditions are under rated in the behavioural method. This suggests that less maintenance attention will be given to these pumps than they actually require. It would lead to faster deterioration of these pumps – shortening their service life. As this misallocation continues over time, the assets' lives will be shortened and the organisation will not achieve maximum benefit from them.

6.2.7.2 Condition misclassification penalty costs methodology.

The optimum classification of assets' condition grades is important because asset management plans are based on such grades. The amount of maintenance and capital investments for five year asset plans are based on the condition grades assessments, which are used as the basis for forecasting in water utility. Therefore, getting the condition grades right is necessary to ensure sound investment in asset management. Failure to do so could result in poor maintenance or having too much resource invested in maintenance and compromising the utilities' profitability in the short and long-term. A model for condition grades misclassification costs penalty assessment for different scenarios is presented.

A water pump is assessed for its condition grade by experts according to section 3 procedures. In reality, the water pump's condition is grade 2 (CG2). Three scenarios are presented where the pump is wrongly classed as CG1, CG3 or CG4. The cost of each misclassification is assessed based on the following assumptions,

- Each pump condition grade incrementally costs £2000 per year in maintenance.
- The misclassification results from consensus expert opinions.
- The misclassification is only likely for two grades above or below the true grade.

The asset classification results (Table 3–23) show that the lower the grade an asset is misclassified to, the less the maintenance cost incurred. This is because the asset is assumed to be in a better condition than it is actually supposed to be. The higher the grade an asset is misclassified to, the higher the maintenance resources are invested in it. This is because the asset is assumed to be in a worse state than it actually is.

As less maintenance attention is given to lower misclassification, the asset service life is shortened and could lead to an increased number of failures. In the long term, a lower misclassification may be more costly than a higher misclassification. This would be due to cost of repairs and lost earnings due to downtime as the failure rate increases. A higher misclassification may be short-term waste, but the asset may benefit from more than average maintenance. This could lead to increased reliability and an increased service life.

It is worth noting that the CG misallocation would be more detrimental if the asset was in the latter stages of its life (CG 4 or 5). A condition grade 5 asset put under CG 3 would also receive less maintenance investment and attention. Since the asset is already almost at the end of its life, it will be assessed as having longer time remaining before its end of life. On the other hand, it is likely to fail unexpectedly leading to increased downtime, risk of pollution to the environment, risk to human health, and increased maintenance/repair costs as well as possible early replacement costs.

The condition assessment importance misclassification costs is supported by the costs implications reported by McCullouch *et al*. (2005d), where they found that incorporating condition assessments in road maintenance program assessments reduced warranty costs by up to 65%. This indicated that the long-term costs of maintenance are minimised by effective condition assessment programmes.

6.2.7.3 Poor risk assessment

The section discussing some of the benefits of asset condition assessments shows its importance to effective asset management. This is particularly highlighted by condition assessment's link to risk assessments and probability of failure assessments. Poor condition assessments, as may be indicated by condition grade misclassifications, could lead to increased failure rates due to poor risk assessments, resulting to high corrective maintenance costs. Poor risk assessments derived from condition misclassification could also cause accidents, resulting in water pollution, environmental pollution, poor customer services and hence penalties from the water regulator. These further illustrate the importance of efficient and constantly improving asset condition assessment programmes.

6.2.8 Limitations and considerations

The expert opinions data were elicited to use in ascertaining asset performance variables and ascertain their assets condition. It was, therefore, important to ensure high quality data was obtained from experts. It is expected that the higher the quality of the elicited information, the better the precision in decision-making. The first major limitation is that experts' elicited data are subjective by nature.

Secondly, the effects of maintenance are not fully taken into account in the condition assessments. For example, some assets may have parts replaced with new ones and such information is not made available to experts Thirdly, the use of questionnaires to elicit experts' opinions mean that experts have no chance of getting feedback and improving their assessments, which would improve the quality of the results. It is also noted that human errors that cannot be quantified would affect the research's results. For example, an expert may not be aware that they did not understand a question and give his/her opinion based on a false premise. It is hoped that the training helped minimise such misunderstanding.

6.2.9 Summary

One of the objectives of this research was to develop an improved approach to eliciting and presenting experts opinions. Uncertainty in the experts' beliefs about the assets conditions was introduced to the five condition grades. According to Sloman *et al,* (2003), experts usually have little difficulty in presenting their opinions by direct probabilities, although training is recommended. Simplifying questions also helps experts understand what is required (Girotto and Gonzalez, 2002).

The research also explored the performance, adequacy and feasibility of point estimate method and the uncertainty approach to condition assessment. The results show that there are maintenance costs implications to using either of them, which would impact on the long-term reliability and remaining life of the asset due to differences in resource allocation. The point estimate approach is taken as the cost penalty for condition grade misallocation because we conclude that the uncertainty approach is better at presenting the asset condition and has been found to be better than point estimate in line with the findings of Cooke and Goosen (2000b).

Probabilities are a natural medium for expressing uncertainty and can be easy for experts to understand. This makes them particularly attractive in this research. Rationality and traceability of judgements are important considerations for auditing and it is anticipated that these will become increasingly important during the review of a water distribution licence as well as five year asset planning by the regulator. Mainstreaming condition assessment is crucial for utilities because it is important to retain the results of individual experts in order to permit the regulator to examine the diversity of opinions leading to the basis for the given value of uncertainty regarding a given quantity or condition of the asset. This research presents an asset condition assessment approach that minimises the error range derived from experts' opinions. It is, therefore, important to use methods that incorporate uncertainty in asset condition assessment. The condition assessment methods should be justifiable and line with the capital asset planning framework - it should reflect the capability to continuously improve.

6.2.10 Contributions of the research

Both industrial and academic contributions were considered.

a) Academic contributions

Key contributions for asset condition assessment where there is sparse data include;

- Application of uncertainty measures in asset condition assessment in water utility is an improvement on the current condition grade methods. Probabilistic measures are currently used mainly for assessing asset risk of failure and not overall asset condition assessment. Most models that have been applied in water asset condition assessments tend to be specifically tailored to pipe assessments and instruments such as leak detectors are sometimes used to assess pipe condition (Agarwal, 2010).The new condition assessment approach evaluates not just precision, but also the quality, as measured by resolution capability of the new approach.
- The approach shows that evidence (historical data) can be gradually integrated into expert elicitation approaches as performance data become available. Expert elicitation can be eventually phased out as all asset performance data become available to assess asset condition.

b) Industrial contributions

The following contributions are made by this research that water utilities can adhere to;

- The developed tool offers an improved method for eliciting and analysing expert opinions and hence, better condition assessment in water utility.
- Since not all assets fail due to poor condition, condition assessment needs to incorporate performance variables to assess the condition of assets.
- It would be effective to mainstream condition assessment for improved asset risk management and not only for legally required reporting purposes. The

asset groups would also have an established historical data over time for reference.

- Asset-specific performance indicators are important as assets condition is affected by different performance variables for different asset groups.

6.3 Assessing the effects of maintenance

6.3.1 Introduction and rationale

Chapter 4 of the thesis developed a model for supporting managers in evaluating the effectiveness or quality of maintenance when they do not have or have very limited data to support their decisions.

Assessing maintenance effectiveness was found to be important and the literature showed there are developments in methods applying full data and not much work has been done to develop methods for limited or no data situations. Water utilities were found to have very limited data to assess maintenance effectiveness. None of the formal maintenance effectiveness techniques is based on expert elicitation, creating an opportunity to apply and test it. The assessment approach adopts expert elicitation techniques to assess maintenance effectiveness.

The precision in maintenance effectiveness assessments is important because decisions such as reviews of maintenance regimes are made from the results. Maintenance regimes would be ineffectively reviewed based on poor assessments of maintenance effectiveness. Maintenance resources would not be allocated effectively – leading to poor asset management contributions to the overall performance of the organisation in customer services as poor maintenance may increase asset failure. Asset failure could lead to increased customer incidents. Secondly, poor maintenance resource allocation could lead to poor business performance due to increased asset operating and replacement costs.

6.3.2 Research approach

The approach used to assess maintenance effectiveness in this research was to develop a method that would use expert elicited data. Developing a new approach was based on findings that there was no approach found to assess maintenance effectiveness where there is limited or no data. Most of the methods used to assess the effects of maintenance assume full data. It was found that tools used in the literature to assess maintenance effects assume full data availability (Canfield, 1988; Kijima, 1989; Crocker, 2010; Wu and Zuo, 2010). As stated in earlier sections, there is prevalence of limited data in water utilities.

Experts were selected in line with the condition assessment approach, following the steps of variable selection, elicitation of maintenance effects, aggregation of opinions and validation. The method follows from the condition assessment steps; training, variable selection, elicitation of expert opinions regarding assets condition, combining experts' opinions and assessing the effects of maintenance. The results are discussed in the following section.

Variable selection

The set of variables to be considered for each group of assets in assessing their condition and assessing maintenance effectiveness can be large. Variable selection is an important challenge. It is critical to determine the set of variables that provide a relevant representation of the phenomenon under research. There are many different procedures for selecting relevant or *significant* variables, from statistical correlation (Salvador-Carulla *et al,* 2007b) through multivariate analysis to artificial intelligence techniques (Gibert *et al,* 2006). Variables selection using experts' opinions is limited (Garthwaite and Dickey, 1996b; Garthwaite, 1983b). There is a need to employ variable selection in reliability analysis because a large number of variables contribute to item performance, failure or condition. An expert elicitation approach to variable selection might consider only the variable set that the expert proposes to be important in asset condition assessment. The same important variables that were used in the condition assessment were also used to assess the maintenance effects for the same water pump asset group.

When asked, the experts did not change the type of performance variables when assessing water pump maintenance effectiveness. The variables that were used in assessing asset condition were further used to assess maintenance effectiveness. The important variables remained the same. Experts from the other sites agreed with the three variables rated with highest importance by the first two groups of experts (Table 3-5). The chosen performance parameters were rotation, vibration and corrosion.

6.3.3 Effects of maintenance assessment

Maintenance effectiveness was assessed by inviting experts who were asked to assess a water pump's condition before a planned maintenance action. The experts were asked to estimate the asset condition after the maintenance action as well. The difference between the condition before and after the maintenance action is the maintenance effectiveness value (Equation 4-1). In qualitative terms, the asset could be 'as bad as before', 'better than before', or 'worse than before' the maintenance action was carried out. The results followed a survey carried out where groups of experts gave their opinions on a selection of the water pump important performance indicators to grade its condition. The maintenance effectiveness is, therefore, given by;

$$ME_{IJ} = af \sum_{i=1}^{N^e} \sum_{j=1}^{M^f} S_{ij} C_{ij} - bf \sum_{i=1}^{N^e} \sum_{j=1}^{M^f} S_{ij} C_{ij} \quad (4\text{-}1)$$

Where;

ME_{IJ} = represents the maintenance effectiveness value

af = represents the condition value after a maintenance action and

bf = represents the condition value before the maintenance action.

The results show that experts found all maintenance actions positive or of no significant improvement in their impact on the asset condition. None of the experts found any maintenance effects to be negative or a worse condition than the asset was before the maintenance as assessed according to Equation 4-1 (Table 4-2). This could be due to bias on the experts' part based on their experience than actual observation of the maintenance quality. If their experience is such that most preventative maintenance actions they have done improved the pump condition, they would always rate the condition positively. This is referred to as 'anchoring' one's current assessment based on previous experience. Anchoring is viewed as a negative practice (Soll and Klayman, 2004). Whether anchoring in this case is a negative is subjective because it could rather have contributed to the expert's expertise. In assessing events where previous conditions do not affect the outcome of current conditions, such as weather forecasts, anchoring could be negative. But in engineering cases, it could be positive because a component condition could be highly impacted by previous conditions. This was evident in the research where experts were shown data detailing the number of corrective maintenance in the past twelve months (as discussed in Chapter 3 and Section 6.3). Experts reviewed their condition classification. Such corrective maintenance could have been performed by one of the experts (experts were internal engineers working for the water utility). If the expert remembers that corrective maintenance experience and anchor his judgement of the pump's current condition on that, it would enhance the quality of his judgement. He/she could even remember another pump from a different site and observe similarities with the one he would be assessing. Giving a condition judgement based on that would enhance the quality of his judgement.

Methods applying expert elicitation to assess maintenance effectiveness were not found in the literature. Studies assessing maintenance quality assume full data availability within organisations and mix cost and other indicators than specifically maintenance (Freimut and Briand, 2005). These studies were not found to be applied in practice as the methods were not tested real organisation asset maintenance settings.

6.3.3.1 Experts aggregates

The results showed that the experts agreed easily when asked on a consensus value of the effectiveness as a group. The minimum and maximum effectiveness values differed by 5% on average. The average effectiveness was 10% from the group consensus effectiveness value and 7% for the individual assessments (Table 4-4). This shows that eliciting individual opinions helps reveal the disparity between experts and gives the decision maker the option to consider these differences. It therefore, also improves the quality of the assessments as the different experts can be given different weights according to their performance. The quality of the assessment improves with individual probability scores as the group consensus does not allow for the weighting of experts.

Experts' assessments of maintenance were more effective when using the new asset condition assessment method because experts found the method allowed them to express their true beliefs and stated that they were more confident when using the approach. This follows from the improved condition assessment approach, which enabled experts to state their maintenance effectiveness value even when it was small within the 0 to 1 scale unlike the condition grade values (as discussed in Section 6.3). It provides for the smallest realised improvements in the condition of the asset after a planned maintenance to be recognised. It also provides for the maintenance effectiveness assessment to mimic a purely qualitative one, where quality improvements of any value can be recorded (Chu and Durango-Cohen, 2008).

6.3.3.2 Heuristics and bias

Biases in expert opinions were also explored. Bias in expert opinions and human errors can occur even when all maintenance programmes are performed according to procedure and the most reliable methods of eliciting experts' opinions are used. The results from the elicitation exercise show that some experts were influenced by organisational 'politics' in their assessments. For example, politics was likely to influence engineers judgement if they regarded an asset as having too many failures and wanted management to invest more money in either refurbishing it or replacing it (Table 3-15). About 80% of experts said they sometimes rate the condition worse than their true belief in order to influence management decision. Measures should be in place to respond to these possibilities by making policies that are beneficial to maintenance effectiveness assessment. Awareness also means that provision for errors caused by biases would be provided for.

Other sources of bias could be more subtle than those discussed in this research. Many general-knowledge tasks contain some items that can be termed 'misleading'. Such items are characterised by a percentage of correct responses that is significantly below chance level. For example, in a research by Keren (1988), subjects were asked which country has a larger population: Israel or Nepal? 87% of the subjects believed that Israel has a larger population and assigned a mean confidence of 0.70 for responding correct. In fact, the population of Nepal was almost three times as large as that of Israel. Supposedly, since Israel is continually mentioned in the news, subjects may have considered this fact as a useful cue which, in this particular case, was not. In engineering, as mentioned earlier, such availability could be positive – unlike in social science and general knowledge case studies.

The concern, from this example and similar others, was not that subjects are using fundamentally wrong inferences. It is probable that a positive correlation exists between country size and media exposure. Subjects, however, did not realize that the inference were probabilistic (error prone), and failed to discount their confidence ratings accordingly. More important for the present context is the existence of misleading standards creating an experimental bias for producing overconfidence, since even on items that are scored at significantly low levels, subjects are not allowed to provide confidence ratings below 50%. This means that high confidence levels from other studies may be very subjective when used to compare one's results.

An example of misleading confidence levels are reported in Wagenaar and Keren (1986), where they thesis an eyewitness research in which subjects were shown slides presenting a car-pedestrian accident. Later, subjects were presented with picture pairs and asked which one they had seen before and how certain they were in their choice. On 5 out of the 15 test trials, accuracy was less than 50% and the scores for the two worst items were 18% and 21%. Evidently, when subjects failed to remember, they were still over-confident and biased in their opinions.

6.3.3.3 Evaluation of maintenance effects

Calibration was used to evaluate the maintenance assessments by experts. The deviation from the mean was only large for sites 3 and the other sites did not deviate much from the mean (Table 4-4). The deviation from the mean shows that the experts were not very well calibrated at the sites 3 and better calibrated at all other surveyed sites. The confidence in the results from the sites with less deviation from the calibration mean would be, therefore, higher when using the results for supporting maintenance decision-making. The experts from the sites with better calibration tend to be the ones with higher working experience, as summarised in Table 3-20. This suggests that maintenance managers could consider using work experience as a criterion for choosing the engineers to use when doing condition assessments and maintenance effectiveness exercises.

The uncertainty approach of eliciting the opinions of experts ensures better precision in the experts' opinions because it allowed experts to state whatever smallest effectiveness value they believed was achieved by the maintenance action. The method employed by the organisation would not allow such quality assessments of the maintenance effects and hence minimisation of costs through better maintenance resource allocation. The Common Framework also requires a consideration of costs (capital, resulting changes in operational costs, net of cost savings gained by avoiding asset failure) and quantified service benefits for the evaluation of a maintenance strategy (UKWIR, 2002g).

The results (Table 4-2 and 4-3) show that introducing uncertainty allowed experts to better assess the level of maintenance effectiveness. This is particularly clear where the effectiveness of maintenance is small. The comparisons of the values in the uncertainty allowance are presented in Table 4-4. The mean values differ between the approaches and the deviations also support the value of allowing for uncertainty in assessing maintenance effectiveness and in eliciting experts' opinions.

Werey *et al,* (2008) explore an expert elicitation approach for assessing wastewater pipe condition. They use predetermined dysfunction or performance indicators, which indicate fixed condition grades of the pipes. The advantage of the approach developed in this research is that it does not limit experts' assessment of the asset condition by only presenting fixed predetermined values. Experts relate each asset performance variable to the asset condition before giving an overall condition score. This allows for the contribution of each variable to the condition to be assessed separately, thereby recognising that not all the variables contribute in the same measure to the asset condition. Wang and Zhang (2008b)'s approach present a similar limitation in that asset condition is generic and does not recognise individual performance variables' different contribution to the asset condition. Similar limitations are observed in other sectors' expert-based condition assessments, such as in bridge management (e.g. Wang and Zhang, 2008) and flood defence management (Flikweert and Simm, 2009).

6.3.4 Considerations and limitations

There is heavy dependence on the condition assessment methodology and therefore, its limitations impact on the maintenance effectiveness assessment. Developing better asset condition assessment approaches mean better maintenance effectiveness assessment. The advantage is that the approach limits time spent by experts on the assessment because become familiar with the elicitation exercise as it is identical to the condition assessment exercise.

The criterion for assessing the effects of maintenance is limited in that not all performance indicators for each asset group can be used when eliciting from experts because the exercise would require a lot of time. Even computerised quantitative methods of tend to limit the number of performance indicators used.

6.3.5 Summary

Water utilities are under pressure to produce and deliver more at lower costs by regulatory requirements and other stakeholders. The proposed maintenance effectiveness measurement method provides a decision-making support tool that prioritises the allocation of maintenance resources in the general drive to minimise maintenance costs. It shows how structured expert judgement can be a useful tool in reliability analysis – contributing positively to rational agreement where uncertainty exists. Experts give coherent judgements on important performance variables, experts' reliability, condition classifications, and maintenance effectiveness related to various asset groups and their performance indicators. The behavioural method is defined, which is used to quantify the experts' judgements. The maintenance effectiveness measure method supports the definition of maintenance effectiveness strategy formulated by;

- a variable selection method;

- aggregating experts with a group discussion in order to merge the differences in experts' views;
- eliciting values associated with the condition of an asset;
- eliciting values associated with the effectiveness of a maintenance action; and
- possible costs associated with experts' failure to rate assets into correct condition.

Since the goal of applying structured expert judgement is to enhance rational agreement, the proposed method ensures accountability, empirical control, neutrality and fairness in asset management decision support. The tool can yield results that can be used in deciding;

- where to invest more maintenance human resources;
- which maintenance need is prioritised as most urgent;
- how to prioritise the allocation of maintenance resources at the budgeting stage; and
- how to modify or develop a maintenance strategy.

Water utilities would benefit from expert elicitation approaches to assess maintenance quality because they have limited data and in some cases no data. As they develop rich databases, they would gradually upgrade to the use of techniques that apply data. Other emerging asset-intensive industries with limited data, such as waste management organisations could adopt such expert elicitation based techniques to assess their maintenance effectiveness whilst they build their databases.

It is critical to have good condition assessment techniques because maintenance effectiveness techniques are developed based on the condition assessment techniques. Maintenance policy can then be evaluated based on the maintenance effectiveness value obtained for each asset. For example, preventative maintenance schedules may be reviewed according to the maintenance effectiveness values. As Marlow and Burn (2008j) elaborate, financial resources allocated to asset management activities are also influenced by maintenance effectiveness results. Preventative maintenance intervals may be extended where the maintenance effectiveness is observed to be very low or negligible for a group of assets and vice versa.

Eliciting from multiple experts helps minimise the error and subjectivity of the experts' opinions. Since the engineers who carry out the maintenance are the experts who assess the assets condition, there is more confidence in the results. Firstly, this is because the engineers are familiar with assets as they service them routinely. Secondly, the engineers have the opportunity to examine all components of the asset in its dismantled state during maintenance, unlike external experts who do not have the opportunity to dismantle the assets. As Cooke and Slijkhuis (2003c) state, the costs and effort involved in expert opinion exercises tend to put off some organisations. However, the proposed approach in this research ensures minimum costs because in-house expertise is sought.

6.3.6 Contributions of the research

Both industrial and academic contributions were considered.

a) Academic contributions

The introduction uncertainty and probabilistic measure in the condition assessment of assets allowed experts to better assess the level of maintenance effectiveness. This is particularly clear where the effectiveness of maintenance is small. Whilst the approach contributes a new approach to assessing maintenance quality, it would not be possible to implement without the developed condition assessment approach. The capability to state any value of maintenance effects makes the approach valuable where no data exists to measure maintenance quality. This is because the precision of the maintenance effectiveness is finer.

b) Industrial contributions

As stated earlier, the Asset Capital Planning Framework (APCF) requires a consideration of costs (capital, resulting changes in operational costs, net of cost savings gained by avoiding asset failure). Quantified service benefits from the evaluation of a maintenance regime are also required to be considered. The maintenance effectiveness approach developed in this research significantly contributes towards the APCF requirement. Avoiding asset failure and associated net cost savings can be realised by proactive asset condition assessment and maintenance quality evaluations. Such proactive approaches are highly enhanced by the tools developed in this research. Condition assessment contributes to better targeted allocation of resources and thereby ensuring cost savings, better customer service and environmental protection through minimised asset failure.

6.4 Selection of maintenance regime

6.4.1 Introduction

The objective of the research in this section, as outlined in Chapter 5, was to develop a decision support tool for selecting a maintenance regime where there is no data. The assets could be new and databases being developed or there could be poor quality data. The theme method throughout the research is the use of expert elicitation methodology to support maintenance decision making where there is no data, as the basic background that decisions have to be made by asset managers when no data exists to support those decisions.

Almeida and Bohoris (1995) discuss the application of decision making theory to maintenance with particular attention to multi-attribute utility theory. Triantaphyllou *et al.* (1997) suggest the use of Analytical Hierarchy Process (AHP) considering only four maintenance criteria: cost, reparability, reliability and availability. The Reliability Centred Maintenance (RCM) methodology (Fynn *et al,* 2006) is probably the most widely used technique. RCM represents a method for preserving functional integrity and is designed to minimise maintenance costs by balancing the higher cost of corrective maintenance against the cost of preventative maintenance, taking into account the loss of potential life of the unit in question (Crocker and Kumar, 2000).

Expert elicitation and the analytical hierarchy process (AHP) methods were used in designing a model for selecting a maintenance regime where no data exists within an organisation. The AHP is an approach to decision making that involves structuring multiple choice criteria into a hierarchy, assessing the relative importance of these criteria, comparing alternatives for each criterion, and determining an overall ranking of the alternatives (Cho and Wedley, 2004). Experts were employed to give their opinions on the ranking of alternatives in the AHP.

6.4.2 Maintenance regime selection approach

Data was collected by using expert elicitation and the analytical hierarchy process used to analyse the elicited data. The reason for using the AHP is because it is very useful when the decision-making process is complex, for instance, by being unstructured and requires the use of multiple criteria (Figueira, *et al.* 2005; Saaty, 1980d). The idea being to use a multi-criteria approach as proven to be ideal in circumstance where no data exists (Al-Najjar and Alsyouf, 2003d). When the decision cycle involves taking into account a variety of multiple criteria which rating is based on a multiple-value choice, AHP splits the overall problem to solve into as many evaluations of lesser importance, while keeping at the same time their part in the global decision.

The AHP process establishes a top down approach to problem solving. A preference matrix between alternatives is iterated from top (the more general) to bottom (the more specific), split the problem, which is unstructured at this step, into sub-modules that will become sub-hierarchies. Navigating through the hierarchy from top to bottom, the AHP structure comprises goals (systematic branches and nodes), criteria (evaluation parameters) and alternative ratings (measuring the adequacy of the solution for the criterion). Each branch is then further divided into an appropriate level of detail. At the end, the iteration process transforms the unstructured problem into a manageable problem organized both vertically and horizontally under the form of a hierarchy of weighted criteria.

Experts were invited to give their opinions where they evaluated different asset management regimes and gave their weighting of importance on a pair wise comparison. The experts were maintenance and operations engineers from a water utility. Drawing from their experience in managing assets, they helped develop the matrix, which was then used in the analytical hierarchy process. The AHP was used to further process the data elicited from experts.

Since the objective was to choose a suitable maintenance regime for a group of assets, different maintenance regimes were defined as the criteria and alternatives were established. The five (Table 5-2) alternatives and criteria were given to experts and they pertain to above ground active assets (in this case, water pumps) maintenance. The results of the research are discussed in line with the procedure followed in collecting and analysing the data. This involved decomposition of the alternatives and criteria importance, experts' judgements of criteria and alternatives, evaluation of experts' opinions, and selecting the best maintenance regime.

The literature particularly does not record experts' involvement in criteria (variable) selection. The AHP was effective in summarizing elicited experts' opinions and weighing alternatives maintenance regimes.

Very few experts did not agree with some of the criteria as they thought others were more relevant to water pump maintenance than the ones used across all sites. Table 5-1 presents the used alternatives and the criteria are presented in Table 5-2.

6.4.3 Decomposing of the criteria and alternatives hierarchy

Iterating from top (the more general) to bottom (the more specific), split the problem, which is unstructured at this step, into sub-modules that will become sub-hierarchies. Navigating through the hierarchy from top to bottom, the AHP structure comprises goals (systematic branches and nodes), criteria (evaluation parameters) and alternative ratings (measuring the adequacy of the solution for the criterion).

Each branch is then further divided into an appropriate level of detail. At the end, the iteration process transforms the unstructured problem into a manageable problem. It is organized both vertically and horizontally under the form of a hierarchy of weighted criteria. By increasing the number of criteria, the importance of each criterion is thus diluted, which is compensated for by assigning a weight to each criterion. In decomposing or structuring the problem, which is iterating from top (the more general) to bottom (the more specific), the problem is split and structured.

6.4.3.1 Criteria

The criteria presented below are derived from experts who select the most important parameters that contribute to maintenance regime suitability for different asset groups. Five criteria are considered by the experts for each maintenance regime;

- Asset importance for the process (C_1)
- Spare parts availability/ obsolescence (C_2)
- Maintenance cost (C_3)
- In-house maintenance capability (C_4)
- Asset type (active or passive) (C_5)

Whether it is necessary to involve experts in the selection of objective and criteria type could be a matter of choice. Time constraints may limit experts' involvement at this stage. It is also generally assumed that the decision maker already has specific options and needs to choose the best option in the given circumstance when using the AHP. Previous research seems not to favour either and there was no expert involvement in the criteria selection and alternative options found in the literature of basic AHP studies (Saaty, 2006c and Saaty, 1994c).

Since experts expressed their opinions in passing about the list of alternative, it may be beneficial to involve them in the initial stage of deciding on alternatives. This could be particularly true for very important decisions that would have impact on people's health, safety or the environment. This could be the case or water assets that are more critically placed to affect people's health, safety or the environment when something goes wrong.

6.4.3.2 Alternatives

Three alternative maintenance regimes were evaluated in this case study. It was assumed that managers had used the three maintenance regimes in the past and they needed to assess the regime suitable for each asset group. Briefly, they are;

- *Corrective maintenance (CM),* The maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function (BSI, 1993b).
- *Condition-based maintenance (CBM*), A method to sustain a desired quality of service by the systematic application of analysis techniques using centralized supervisory facilities and/or sampling to minimize preventative maintenance and to reduce corrective maintenance (BSI, 1993c).
- *Preventative maintenance (PM),* The maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item (BSI, 1993d).

All experts agreed the maintenance regimes were the major ones to consider for water pump maintenance. Paired comparison matrices were developed for the three maintenance regimes. A three maintenance regime mix is favoured by management, which includes preventative maintenance (PM), corrective maintenance (CM) and condition-based maintenance (CBM). Five of the regime matrices were developed from expert preference with respect to criteria C1, C2, C3, C4 and C5. The problem was decomposed or structured, which is iterating from top (the more general) to bottom (the more specific), split the problem.

Paired comparison matrices were developed for the three maintenance regimes. A three maintenance regime mix was chosen because the organisation already used these maintenance regimes in one form or another. It was believed experts would, therefore, easily understand the selected regimes. These were explained to experts during training and they are preventative maintenance (PM), corrective maintenance (CM) and condition-based maintenance (CBM). The regime matrices were developed from expert preference with respect to criteria C1, C2, C3, C4 and C5. Table 5-3 presents the experts preferences with respect to each criterion for site 1.

6.4.3.3 Importance of criteria

A relative weight was assigned to each criterion, based on its importance within the node to which it belongs. The sum of all the criteria belonging to a common direct parent criterion in the same hierarchy level must equal 100% or 1. A global priority is computed that quantifies the relative importance of a criterion within the overall decision model.

The importance of each criterion contribution to the decision was assessed. The criteria were weighted as equal. The impact of that is that it does not recognise the contribution difference that each criterion has on the overall value of the maintenance effectiveness. The maintenance effectiveness is important in selecting a suitable maintenance regime – as illustrated in section 6.4 and in chapter 4 of the research.

6.4.4 Experts' judgements of criteria and alternatives

Results from experts' opinions of weighting the criteria are presented in (Table 5 –4). The difference was the number of experts evaluating the weights of each criterion and alternative against each other in different sites. The limitation would have been results from small and larger number of experts would vary in quality. The larger the number of experts, the more credible the results are expected to be because fewer experts reduce the confidence level of the opinions (O'hagan *et al*, 2005c). Therefore, there is more confidence in the matrices from site 1, 2, 5 and 7 since they had more experts.

Each alternative was scored in comparison with other alternatives. Using AHP, a relative score for each alternative was assigned to each leaf within the hierarchy. At the top of the hierarchy, an overall score was computed from each branch. Experts allocated the score values for their preferences in paired comparisons and a matrix was developed (Table 5-5). After having the comparison matrices, the priority vectors, which are the normalized eigenvector of the matrix, were computed in order to determine the preference scores. Sums of each column of the reciprocal matrix were obtained. Each element of the matrix was divided by the sum of its column to get the normalized relative weight. The normalized principal eigenvector was obtained by averaging across the rows. The normalized principal eigen or **priority vector** shows relative weights among the compared items (Teknomo, 2007b).

Table 5-8 presents the weights, normalised eigenvectors and the normalised preference scores derived from the matrices. From the overall results for site 2, the highest eigenvalue is the best preferred criterion and the smallest value is the least preferred criterion. The criteria (C1 – C3) were preferred with relatively similar weights. On the other hand, criteria C4 is highly preferred, with high magnitude of the difference from the other criteria. Criterion C5 was also highly preferred, although lower than C4. Preference scores for other sites are presented in Appendix 5.

6.4.5 Evaluating experts' assessments

To validate the experts' scores, consistency ratios (CR) were used to measure how consistent the judgements were. If the CR is much in excess of 0.1, the judgements cannot be relied upon. There was less variation in the consistency evaluation between surveyed sites as they were below of 0.1. Only two sites were slightly above (0.1), which is not a significant deviation either and can be accepted as consistent. Consistency ratios results (Table 5-14) show that the experts were generally consistent in their opinions. The results show that the consistency ratios for the each site were 0.05, 0.03, 0.01, 0.11, 0.02, 0.07 and 0.11, respectively. Sites 4 and 7 were slightly above 0.1 and, therefore, accepted as consistent with the other sites that were below 0.1 because the deviation from 0.1 was only 10%. The consistency is in line with Pelez and Lamata (2003) findings where all matrices were found to be consistent when measured by the consistency ratio.

What-if analysis or sensitivity analysis was also done. The results show that the CR can be very sensitive to any changes in the initial matrix. For example, changing only one matrix entry and alternating it with its opposite value significantly changed the CR. The matrices became very inconsistent or consistent. The sensitivity effect supports the findings by Ji and Jiang (2003) that the matrices can be very sensitive to changes and can therefore be manipulated to achieve certain results.

6.4.6 Selecting the best maintenance regime for each asset group

Table 5-10 presents the normalised preference score for each regime with respect to the criteria. The results also show that PM was the most preferred maintenance regime with respect to C1 (asset importance for the process). The experts normalised preference score these highly – given the nature of the operation process whose assets they give opinion about.

The results show that corrective maintenance is important for all water pumps. Preventative maintenance is important for all but C2. CBM is the least preferred maintenance regime for pump maintenance, except for C2. Where the condition based maintenance is applied, it may be sound to suggest that preventative maintenance may not be a priority because CBM offers some form of preventative maintenance. Figure 5-5 values show that CBM was the selected maintenance regime for site 2. After comparing alternatives and criteria, the best maintenance regime was selected. The best maintenance regime for each site is presented in (Table 5-12) - following Figures 5-5 results. The maintenance regime overall hierarchy for each site showed that CBM and PM were chosen as the best regime (Tables 5–13). The combined regime overall hierarchy for all sites showed that CBM was also the overall best regime.

The research carried by Bevilacqua and Braglia (2000b) show different results in terms of the best maintenance regime. The difference in the research is that the pair-wise comparison was derived from experts who did not carry any maintenance work on the assets they were comparing the criteria and alternative for. The research was for recommending a maintenance strategy whilst the asset was at its design stage. The experts did not have maintenance experience with the assets (oil refinery) they were assessing. Therefore, the results from this research are expected to be less theoretical because the experts had experience with applying the different maintenance regimes with the assets they were assessing.

The organisation then selects the ideal maintenance regime for the water pumps by considering the maintenance regime normalised preference scores order and the criteria normalised preference scores. Managers do not have to strictly follow the normalised preference scores order, but the results provide a tool for assisting in the decision making for selecting the maintenance regime. For example, a maintenance regime could be chosen for theoretical reasons such as possible severe regulatory penalties of asset failure - even when the risk of failure is very low. On the other hand, the results provide a rational and valuable tool for maintenance decision-making support. Management can discuss and choose a maintenance regime that did come out as the best in the AHP analysis for other theoretical reasons (Ho, 2008; Brugha, 2004). For example, the asset may have exceeded its life and ready for replacement. It can be decided that only corrective maintenance is suitable for such an asset as it will be replaced on a planned date.

6.4.7 Limitations of the research

The research has the following limitations;

- Different results of the normalised preference scores could be achieved when using the same criteria due to differing experts' opinions.
- Different results of the normalised preference scores could be achieved when using the same criteria due to differing experts' opinions aggregation methods.
- Experts' opinions are subjective by nature and are subject to biases.
- The number of alternatives could be large and the number of comparisons required too large. This could reduce the efficiency of the experts as they may lose focus when making judgements, hence reducing the results obtained as supported by results (Oslon *et al*, 1995).

Another limitation is that there are several methods of obtaining the approximation to the normalised preference score and it may be subjective to say which one is the best (Ishizaka and Labib, 2009). Another limitation is that dependencies between the criteria are not considered. For example, in-house capability (C_2) may be influenced by maintenance costs (C_3) and spare parts availability (C_5).

6.4.8 Summary

A summary from the research results are;

- The maintenance selection approach was developed by applying expert elicitation for data collection and using the AHP to compute and determine the choice.
- The multi-criteria aspect of the model enhances the the quality of the process because several asset specific key performance indicators (referred to as alternative) were considered.

- The AHP integrates both qualitative and quantitative information as a decision support tool.. The method catered for multi-criteria assessments before a decision was reached.
- Validation of the method was assessed as the AHP measure the consistency of the decision maker.
- By organizing and assessing alternatives against a hierarchy of multifaceted objectives, the AHP provided a proven, effective means to deal with complex decision making. It is an easier and more efficient way for identification and selection of criteria, their weighting and analysis – whilst keeping the decision cycle in check.
- The application of a combination of experts' opinions and AHP in water utility asset management can be very effective in decision support, due to the prevalence of lack of data. It provides a coherent and verifiable tool to support decision making in such cases and can be applied with different alternatives for different asset groups.

6.4.9 Contributions of the research

Both industrial and academic contributions related to a selection of maintenance regimes were considered. The research contributes to the body of work in both asset management and the AHP approach in that;

a) Academic contribution;

Academic contributions include;

- The AHP methodology is varied to include expert opinions at different levels. The literature particularly does not record experts' involvement in criteria (variable) selection.
- The application of the AHP approach to maintenance selection at operation level of the asset life gives a new perspective to the approach. It has been applied at asset design level, without practical understanding of the alternatives and experience of actual operation engineers.
- Experts may also introduce the latest developments in the problem as they are usually aware of issues affecting the industry. This may be further utilised

to enhance the organisation's criteria when selecting or evaluating a maintenance regime.

b) Industrial contribution;

The contributions to industry include;

- AHP application after a maintenance management year end provides hindsight for better understanding of the list of criteria by both management and experts.
- The application of a combination of experts' opinions and AHP in water utility asset management is relevant due to the prevalence of lack of data (Brint, 2009b; Barker and Haimes, 2009). It provides a coherent and verifiable tool to support decision making in such cases and can be applied in different decision making scenarios.
- The tool can be tailored to select a maintenance strategy for different types of assets. The criteria rating by experts would differ for each asset group due to different factors such as operating modes, design and usage intensity.
- The approach provides an easy to use tool, using elicited judgements of experts to ensure verifiable and coherent decision support for maintenance regime selection. Rule-of-thumb approaches are currently used to decide on asset maintenance regimes.

6.5 Combined research maintenance decision-support tools framework

6.5.1 Risk management research framework

Asset condition assessment, maintenance effectiveness and maintenance regime were integrated into the risk management process framework. The decision support tools developed in this research fit in the asset risk management process was determined. This indicates the approaches' value as decision support tools at strategic level of asset management as well as in managing asset risk in routine asset management. The risk assessment link of the three maintenance aspects been clearly established and applied in water asset management before (Figure 6-1 and 6-2).

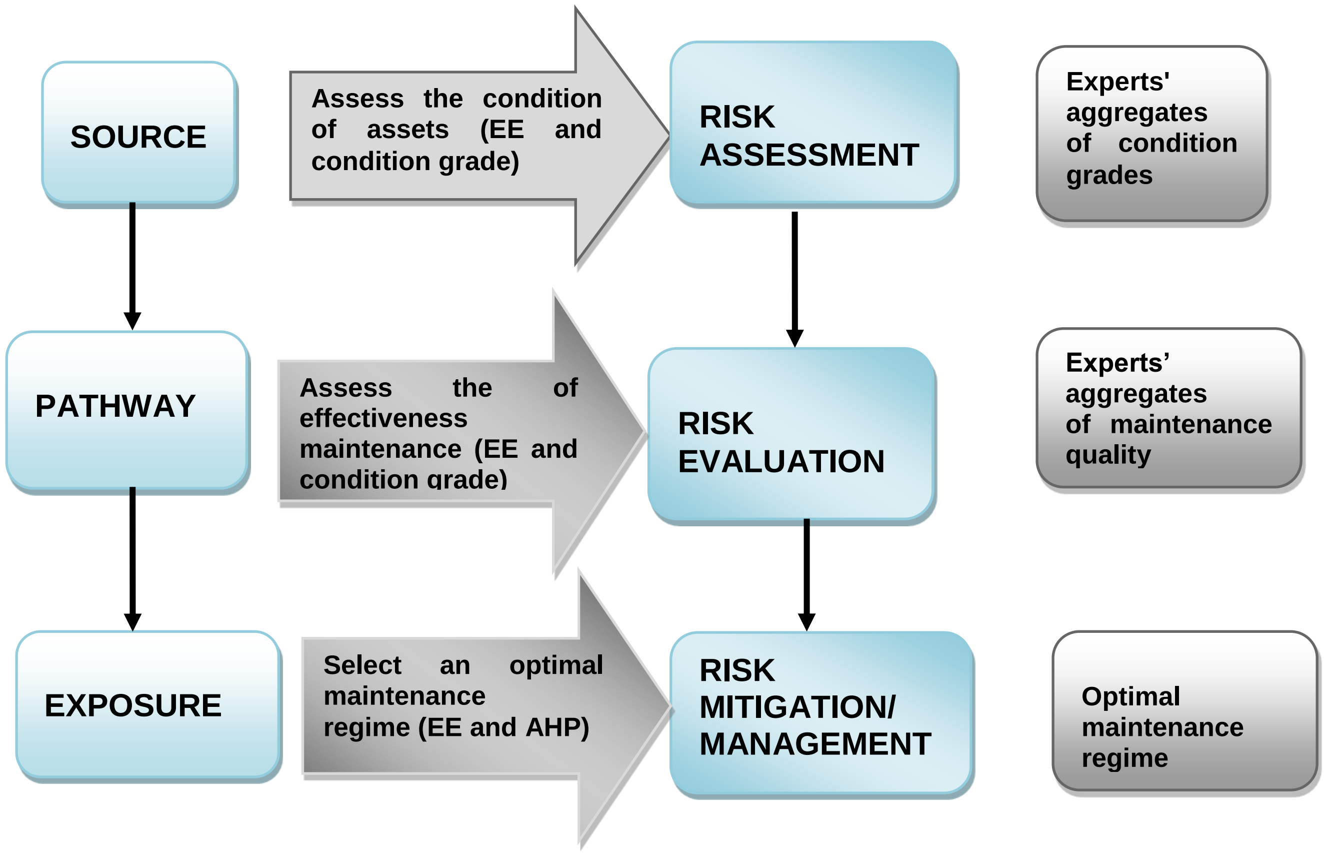


Figure 6-1: Summary of maintenance decision support tools in the risk model

Many water utilities and other companies operate a risk-based asset management strategy, but the formal asset management aspects have not been formally integrated into the process of risk assessment. Formal asset management practices, such as maintenance effectiveness assessments and maintenance regime quality assessments have not been directly or formally integrated into the risk assessment process in asset management. Figure 6-2 also presents the framework of these asset maintenance disciplines in the asset risk assessment process.

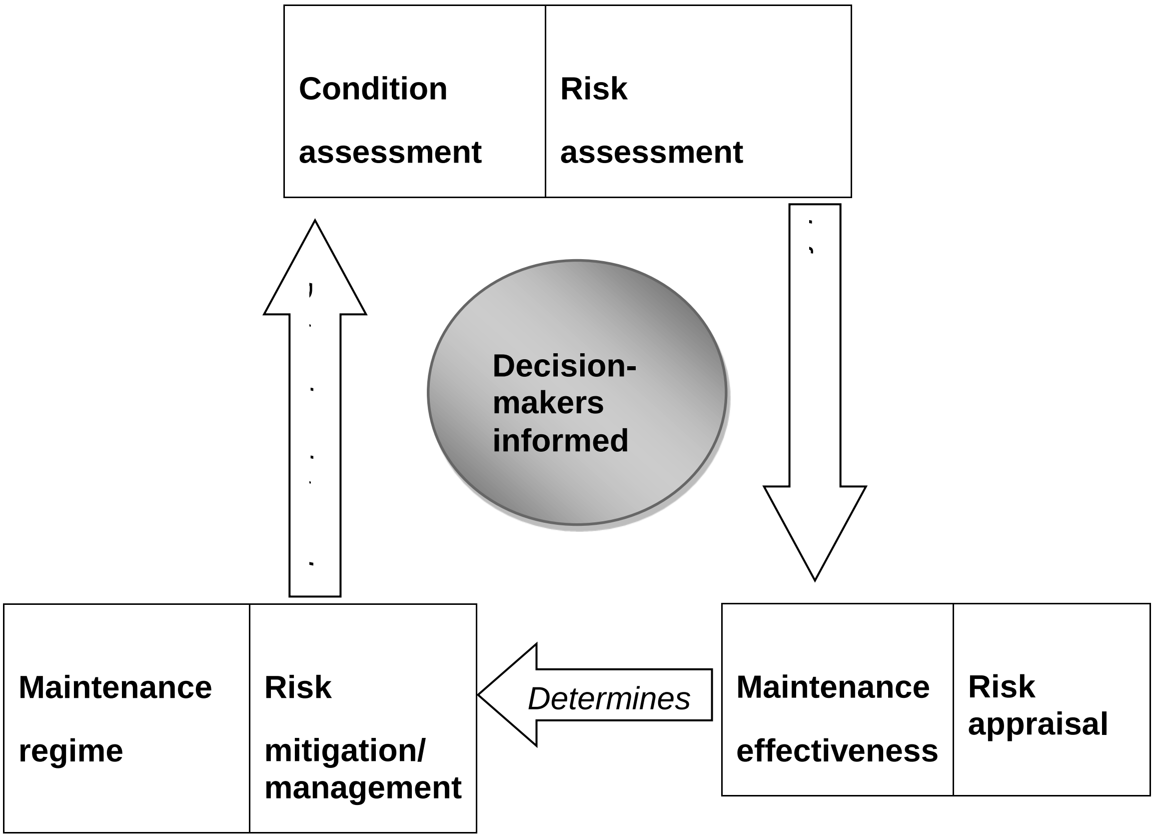


Figure 6-2: Research combined approaches summary

Studies in asset risk assessment have focused on asset performance levels, particularly assessing the immediate risk of failure (Marlow *et al*, 2012). This is without linking such risk to the different aspects of maintenance, such as the asset maintenance quality. This study introduces these different maintenance functions to the risk assessment process, and therefore enriches it into a more holistic process.

The risk framework was not investigated in detail to determine how it would be applied practice in determining real levels of asset risk and linking them to real maintenance functions.

6.5.2 Feasibility of the developed decision-support tools

Figure 6-3 illustrates how the research areas inter-relate in the asset management cycle context. Each of the research objectives fits into the framework of the asset management cycle.

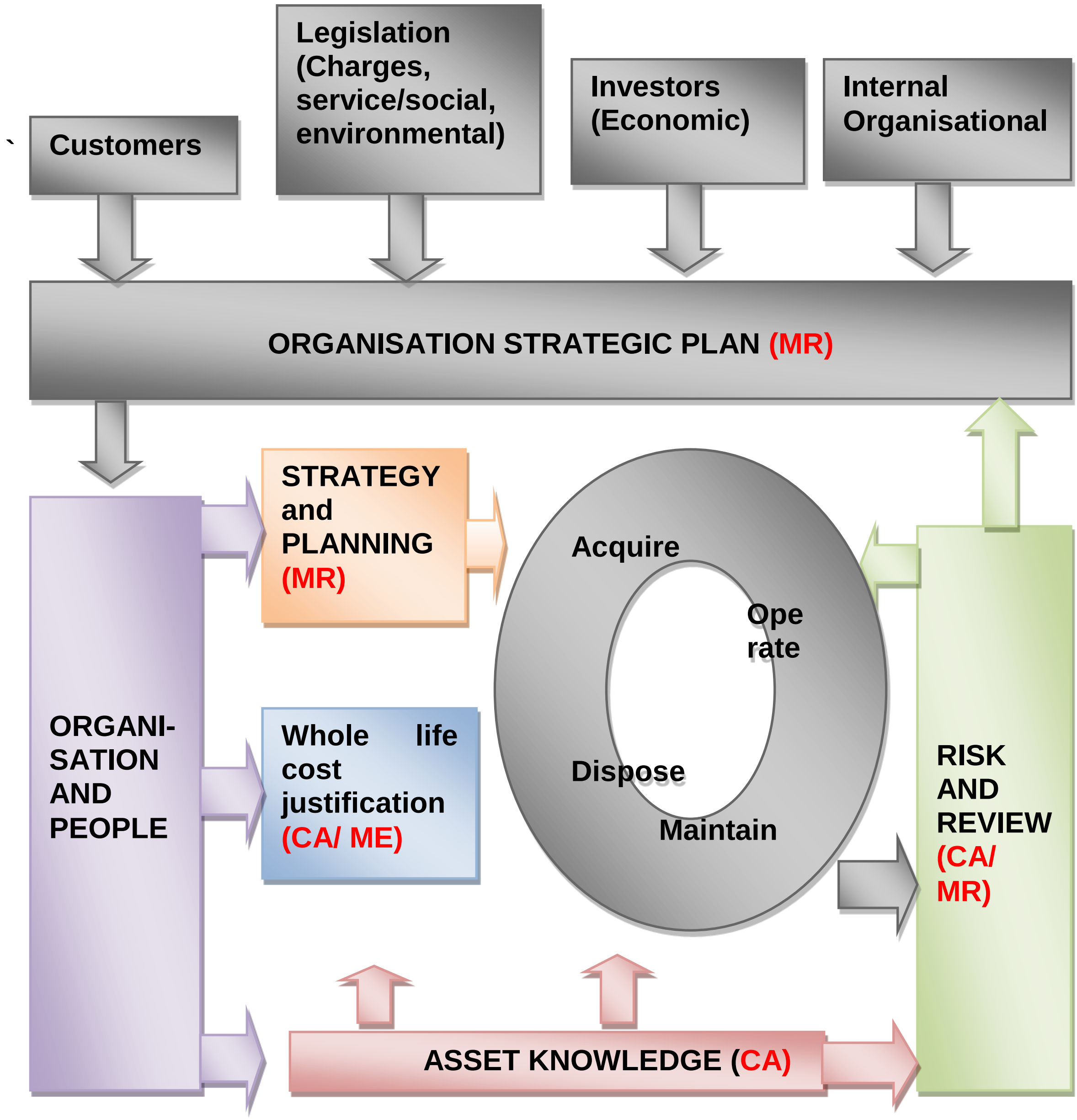


Figure 6- 3: Asset management cycle and research fit

Where; CA = Condition assessment
ME = Maintenance effectiveness
MR = Maintenance regime

The research contributes to the asset management cycle (Figure 6-3) water asset management by clearly defining the strategic fit of asset condition assessment, maintenance effectiveness and maintenance regime quality. Methods of assessing these where there is limited data were developed. The research clarifies how these are interconnected at both strategic decision making and routine risk management levels and therefore helping organisations to;

- Follow best practice, as required by the asset planning common framework by supporting asset management strategy decision making (MR as indicated at strategic level.
- Identify and prioritise critical assets as condition assessment is mainstreamed within water utilities value chain (CA as indicated in asset knowledge, risk and review and while life cost justification).
- Identify and manage the risk of asset failure through condition assessment programmes (CA as indicated in risk and review).
- Identify indicators of failure to monitor the critical items as supported by variable selection approaches in the research and link three research maintenance aspects to risk assessment.
- Identify priorities for cost effective maintenance solutions as presented by the maintenance regime selection method, whilst identifying assets to dispose or maintain through condition assessments (MR as indicated in strategy and planning, as well as risk and review).

6.6 Are water utilities effective in employing decision support tools for their asset management decisions?

Water utilities in the UK widely use expert elicitation for their asset condition assessment. Garthwaite and O’Hagan (2000a) summarized some of the approaches used by water utilities to elicit experts’ opinions by water utilities. Seeking experts’ opinions is, therefore, common in the water utility sector. Utilities employ experts to give opinions on a variety of management areas and asset management is one of them. This is mainly due to newly established maintenance databases still being developed. The methods employed in eliciting experts' opinions have been found to be very good, particularly where they invite an elicitation expert to manage the exercises. Such cases are not common, but limited to non-routine studies that are usually more academically suited than tailored for internal routine asset management. Garthwaite and O'Hagan (2000b) also did a research with several major UK water utilities – estimating underground length of buried water distribution infrastructure. On the other hand water utilities widely use expert elicitation for assessing their asset conditions and reporting to their five year asset plan strategies to the water regulator, Ofwat. The routine use of expert elicitation and the business planning strategic level at which the results are used require higher standards of expert elicitation practice, which needs improvement in water utilities, particularly the precision ranges (Marlow et al, 2007 and Ofwat, 2004).

Analysis of other approaches of condition assessments in water utilities

a) Some water utilities use probabilistic models and statistical inferences for asset condition assessment. Assets are first divided into two categories i.e. those which would be sampled (local distribution network) and those which would be investigated (dams and raw water systems). Sampling units including zones are defined and classified based on the number of connections, type of supply (rural/ urban/ mainly rural/ mainly urban) and the number of water service problems per connection. These zones are then sorted into different strata depending on the type of supply and the identified problems per connection. Random samples are collected from each stratum. The number of samples collected being proportional to the number of connections. Costs of the required renewal work for the selected zones were calculated and then the cost for the entire strata is estimated and is deemed to reflect on the condition of the assets. The calculation of the renewal investment requirement was made from unit cost data obtained from national data on unit costs or other past records.

The shortcoming of the sampling and condition assessment approach is the lack of ability to prioritise because the utility could not be certain which zones are in the worst condition and where renewal works were needed the most (Metcalfe, 1991).

There is less emphasis on the condition assessment but cost of replacement. Since cost is a volatile variable, the condition of the asset it reflects can be very subjective.

b) Another company adopted a step-by-step approach to condition assessment. After the objectives were defined, they collected data about the assets in their possession by developing an inventory of their assets. Next, data on condition and performance of these assets was gathered from past records. Data was also collected from repair works on bursts and other repair work. Information about the mains pressure survey was gathered. Random water quality sampling exercises were undertaken to assess the condition and performance of the assets.

After the data was collected reports for each zone were prepared using all the gathered information in a specified consistent format for the purpose of comparison. Each zone was assigned a rank based on a two-tier ranking system. Tier I was based on the water service data available and Tier II was based on the results of surveys. On the basis of these reports investment estimates for rehabilitation were prepared for each zone. The criterion for prioritisation of rehabilitation work was that zones suffering from poorest service were to be resolved first and all the works in one zone were to be taken up together.

The condition assessment strategy ensured uniformity of approach throughout a large organisation having many operational districts and management teams (Pearson and Dewhurst, 1989). There is less emphasis on the condition assessment because data that are not asset specific are incorporated and the true condition of the asset is diluted. The quality of the asset condition is compromised as it is not asset specific and includes performance variables that are not directly related to the asset.

c) Lindley (1992a) describes the asset condition assessment process of an unnamed water utility. The water utility initially stated that its objective to carry out asset condition assessments was customer satisfaction. As no statutory standards were available on pressure or flow, the next step was to define standards of service and then monitor the performance of the existing system relative to the defined standard of service. Stratified random sampling was carried out. The strata were classified on the basis of types of water being supplied (soft/ medium/ hard), the type of network (rural/urban/semi-rural) and the age of the network (pre-1918, 1918-1945, post 1945).

Research units were selected from these strata and desk studies and field work were undertaken to make an inventory of the system and measure performance relative to the specified standards of service. The local knowledge of problem areas was the basis on which pressure loggings in key areas were employed for research of pressure and flow as network models were not available. Water quality modelling was achieved through using the water quality data and referring to the archives where customer complaints were stored. It was realised that water quality modelling was essential to establish the cause of the problem because it could be a result of poor water treatment, the existing network conditions or other unknown causes.

Further investigations were undertaken for monitoring and assessing the continuity of water supply. Main burst data was studied against the acceptable predefined standard rate of one per year. More than one per year was taken to be unacceptable. A need for structural sampling of sections of mains was identified as an essential requirement to support and augment the desk research of main burst records. Unit costs are used for costing of the renewal programme. The above parameters and the information collected were analysed and employed to assist the water utility in assessing assets condition in order to achieve their stated objective of customer satisfaction (Lindley, 1992b).

There is less emphasis on the condition assessment but on customer satisfaction. The lack of focus on condition assessment means that less interest is particularly placed on the quality of the condition assessment of assets. Customer satisfaction is very subjective as a measure of condition because customers can thesis satisfaction when the assets are not particularly in good condition and vice versa.

d) Another water utility adopted an approach of calculating the condition of each asset/asset category as a product of condition grade and performance grade. For surface assets, condition grades were assigned after visual inspection, and for underground assets statistical analysis was undertaken to estimate the condition grade. Performance grades were assigned from performance records of the assets held by the company. The overall condition grades are then cross-checked with maintenance records. Assets with good condition grades but poor maintenance records warranted further investigations to check if there was any design defect so that pre-emptive action could be taken. A priority matrix for renewal is then prepared for Electrical and Mechanical equipment (Banyard, 1996).

Parsons (1999) reported that the method employed is used when the focus of the asset management planning is leakage control. Each company had their own declared 'Economic level of leakage' (ELL) required by regulator Ofwat, and the utility's ELL was approximately 330 million litres per day (MLD). District Metering Areas (DMAs) were grouped into four levels of unaccounted for water (UFW) relative to the company average. Specific assets responsible for UFW and their condition grades were identified from the main burst data and other asset performance records available within the utility. For all condition grades ranging from 1 (good) to 5 (awful), percentages of assets were computed. It was found that 70% of the main bursts were in condition grade 3, 4 and 5 and 50% of the assets responsible for UFW were in condition grade 3, 4 and 5. These two together represented 15% of the total assets of the DMA.

The identification of these specific assets and knowledge regarding their condition are utilised to prepare asset management plans to plan future capital maintenance investments. The focus of this condition assessment approach seems to be a passive means to an end (leakage control). There is less emphasis on the condition assessment but only done for regulatory reporting of leakage. The lack of focus on condition assessment means fewer resources may be allocated to the asset and minimum maintenance standards achieved.

Expert elicitation protocol was found to be disregarded when carrying out elicitation exercises. This seemed not to be deliberate because they seemed not to know what the elicitation protocol was. This suggests that, when employing external expert elicitation experts, the organisation does not have systems in place to acquire knowledge from the expert and transfer it into the organisation's practice. The lack of knowledge of elicitation standards, such as the elicitation protocol, is important as it leads to poor elicitation results and compromise the value of decisions and conclusions made from the elicitation results.

Experts' biases were found not to be considered in determining the confidence level of the results derived from expert elicitation. Traditional decision theories have assumed that people integrate all available information to rationally determine the utility of decision outcomes. However, research in psychology, economics, and related fields has shown that real decision makers often deviate systematically and predictably from normative standards of rational decision-making (Camerer and Thaler, 1995). For example, people tend to be risk-seeking when a decision problem is described as a choice between two losses but risk-averse when the same problem is described as a choice between two gains. Instead of attending solely to future risks and rewards, people tend to be affected by their past experiences when, for example, allocating resources (Arkes and Blumer, 1985). Despite these biases, people are often overconfident of their decision-making abilities (Gilovich *et al*, 2002).

On the surface, such deviations from rational decision-making appear alarmingly common. Yet examining individual differences may reveal a different picture. Specifically, such personality factors as *need for recognition,* or the extent to which people engage in and enjoy effortful cognitive activities may moderate susceptibility to decision biases (Smith and Levin, 1996; Stanovich and West, 1999). In this research, training was found to have made experts aware of the issue of possible biases and hopefully minimised them.

The background of the research was based on decision support in situations of lack of data in water utilities, which are faced with the need to justify and support their decisions to regulators and other stakeholders, whilst a confident basis for internal decision-making is necessary as well. The lack of data makes the need for such decision support tools necessary. It was found that water utilities make asset management decisions all the time and there are many instances where there is no data to support those decisions. Expert opinions are therefore, widely sought in such cases. The overall expert elicitation process currently used was found to fall short of the standard. This was mainly due to the limited application of the elicitation protocol when eliciting opinions from experts. Failure to apply the elicitation protocol compromises the quality of the results. For example, failure to train experts could mean they are giving opinions without proper understanding of the exercise and the variables being sought. Lack of understanding of different approaches, for example, of aggregation and validation of expert opinions would also compromise the quality of the results from experts.

The developed approached in this research adhere to elicitation protocol and caters for experts uncertainty in their judgements, which ensured experts stated their true opinions better.

6.7 Lessons learnt

6.7.1 Emerging asset intensive organisations

Some of the results from the research could be utilised by different sectors for their asset management programmes. The approaches for asset condition and maintenance effectiveness assessment would be useful for sectors.

Emerging asset intensive sectors, such as waste management installations and equipment, carbon capture storage installations and others could learn from water utility experience. Since such sectors are new, they have limited data for their asset performance and could adopt these condition and maintenance quality assessment approaches whilst they establish their asset maintenance databases.

6.7.2 Asset management in organisations value chain

The need to embed asset reliability assessments and condition assessments in utilities value chain is another lesson learnt from this research. It emerged that a better approach would be to make maintenance quality and condition assessments part of the organisations’ routine operations and not only for regulatory reporting purposes, but to ensure that they are effective and sustainable.

6.7.3 Protocol

There is need for a protocol and adopting it into a standard for condition assessment. A research was carried out by UKWIR to assess the possibility of developing protocols for assessing the condition and performance of water and wastewater assets. The condition assessment protocol research covered a range of important issues necessary for good practice. There was an obvious lack of attention paid to cases where utilities have no data. Too much emphasis was given to underground assets (UKWIR, 2002). The findings from this research point to the need to further consider and develop multi-criteria approaches for condition assessment and maintenance quality assessments where utilities lack data, such as the expert elicitation approach used here.

7 CONCLUSIONS AND FURTHER WORK

7.1 Condition assessment

The findings reveal that by-and-large, lack of methodical analysis is a major weakness of application of expert elicitation in water utility. Still some rule-of-thumb based decisions are made in asset management. Case studies which have been conducted, and one that has been briefly reported here, also support this conclusion. The methodology of the research includes literature review, surveys and case studies in a water utility.

One of the objectives of the research was to develop an improved approach to eliciting and presenting experts opinions. Rationality and traceability of judgements are important considerations for auditing and it is anticipated that these will become increasingly important during the review of a water distribution licence as well as 5 year asset planning by the regulator. It is important to retain the results of individual experts in order to permit the regulator to examine the diversity of opinions leading to the basis for the given value of uncertainty regarding a given quantity or condition of the asset. It is therefore, important to use methods that incorporate uncertainty in asset condition assessment by experts. The condition assessment methods should be justifiable and in line with the capital asset planning framework requirements.

The literature showed that there is a large scope for improvement in condition assessment approaches in the water sector, especially for above ground assets. The conclusions drawn from the research include;

7.1.1 Primary conclusions

The results from the research show that there is a large scope for improvement in increasing the precision for assets condition assessment. In some cases, the results from the research show the error bands for the old approach were more than fifty per cent between condition grades (Table 3-13 and Figure 3-4). The research therefore, provides a base for water utilities to improve their approaches in order to continuously improve the precision in their asset condition assessments because it reduces the misclassification of assets' CG.

- Continuous improvements in condition assessments contribute to better allocation of asset maintenance resources.
- Expert elicitation protocol should be followed or they will produce poor results in their asset condition assessments. For example, experts expressed that training was helpful for them (Table 3-1).
- Evidence from asset performance data can improve the results of expert-elicited information. Introduction of evidence about the asset performance was found helpful in refining experts' assessment of the assets condition (Figure 3-5 and Table 3-14a). Experts reviewed their opinions after being shown the number of reactive maintenance carried out in the previous twelve months for each water pump. The results show that the more the number of corrective maintenance calls each water pump had, the more the experts reviewed their assessments to a lesser condition grade and vice versa.

Another aspect of the research explored the costs and resource allocation implications of classifying assets into wrong condition grades. From the condition misclassification assessment research, it was concluded that there is a need to consider that imprecision in assessing asset conditions because they lead to misclassification of the condition grade. Misclassification of the assets condition would further lead to misallocation of resources which results from the number of assets in each condition being exaggerated or understated, as illustrated in Table 3-22 and 2-23. A vicious cycle is inventible, resulting from misallocation of resources, as an asset life is unnecessarily enhanced or diminished – leading to poor organisational performance at both an operational and strategic level.

7.1.2 Secondary conclusions

- Variable selection is important because it ensure that only the important variables before asset conditions are assessed. This is because not all variables can be used, particularly if there are many of them.

- Human judgements are subject to biases and utilities need to be aware when eliciting opinions. Table 3-15 shows some of the biases the experts were aware of.
- Very few experts were not coherent in expressing their opinions, perhaps indicating the value of training the experts (Table 3-18).
- Asset managers need to consider experts' work experience in choosing experts as their performance was positively correlated to their calibration performance (Table 3-19 and 3-20).

7.1.3 Further work

It is established that condition assessment output can be used in modelling an asset remaining life. Further work can be explored by using results from the research to assess asset life.

Further work can be also explored by increasing the number of experts. This is important because the value each expert contributes to the overall condition value would be reduced as the number of experts increase.

7.2 Maintenance effectiveness

As detailed in Chapter 4, the research shows that measuring maintenance effectiveness is essential for developing an optimum asset maintenance strategy. Assessing maintenance effectiveness can be complex and requires the commitment of both financial and human resources. Developing maintenance databases is also necessary in order to capture and store asset performance or operational data, which is necessary to effectively assess maintenance effectiveness. The conclusions from the research on assessing maintenance effectiveness include;

7.2.1 Primary conclusions

Experts' opinions can be invaluable for assessing maintenance effectiveness where such data are not available. Expert elicitation offers a consistent and verifiable consensus for assessing maintenance quality for management decision support. Expert opinions should ensure accountability, empirical control, neutrality and fairness. From the research, it was concluded that;

- Experts found all maintenance actions positive or of no significant improvement in their impact on the asset condition. None of the experts found any maintenance effects to lead to a worse condition than the asset was before the maintenance was carried out (Table 4-4). This indicates the positive value of most maintenance work.
- Experts assessments of maintenance was more effective when using the new method as experts said they found the new method had scope to express their true beliefs better. The results can then be used to review and improve different asset groups' maintenance regime.

7.2.2 Secondary conclusions

- Some of the practices referred to as bias in behavioural sciences may not be considered bad elicitation practice in some areas of engineering. For example, it could be helpful for an engineer to give their answer by basing it on recent experience in maintaining an asset. Such answer may be necessary to prevent an asset failure and risk to the customer and the environment.
- Experts' confidence in the reliability of their opinions slightly improved from the confidence stated in assessing condition grade (Table 4-6). This could be due to the confidence gained from the experience of eliciting condition grades from the same experts. This indicates that experts may improve with experience in the elicitation exercise.

7.2.3 Further work

The research can be extended further to explore and improve the elicitation of information about asset condition in water utility. Further data can be elicited about asset condition to further analyse the subjectivity and uncertainty in assets condition grading and experts' beliefs. This would help to further improve precision in the assessments and help improve maintenances resource allocation in water utilities.

The research can also be extended to investigate the feasibility of the actual application of the link of the three maintenance aspects into the actual asset risk assessment processes used by water utilities (Figure 6-2). The research can investigate the maintenance aspects integration to the actual asset risk assessment process to assess actual asset risk levels. Maintenance strategies would then be linked to asset risk levels, for example of failure and optimal maintenance strategies determined.

7.3 Maintenance regime selection

The AHP methodology is used and varied to include expert opinions at both variable selection and maintenance regime preference scoring. The advantages of the AHP can be utilised in asset policy decision-making when there is no data, including that; it is a multi-criteria decision method as it takes several factors into account, it can take into account as many possible alternative factors, and it integrates both qualitative and quantitative information. Overall, the approach presented would increase confidence in decision making where there is reliance on expert opinions. From the results, it is concluded that;

7.3.1 Primary conclusions

- The application of a combination of experts' opinions and AHP in water utility asset management was useful due to limited data for use to develop full data models. The approach provides a coherent and verifiable tool to support decision making in such cases and can be applied in different decision making scenarios. The preference scores provide clear method for selecting a maintenance regime (Table 5-12 and Figure 5-5).
- The tool can be tailored to select a maintenance strategy for different types of assets. The criteria (Table 5-2) would differ for each asset group due to different operating modes, design and usage intensity.
- AHP application, with historical perspective in asset management, provides for better understanding of the list of criteria by both management and experts. This is because they have had experience with managing the assets.

7.3.2 Secondary conclusion

- Some experts expressed their opinions in passing about the list of alternatives and it could be beneficial to involve them in the initial stage of deciding on criteria. This could be particularly the case for water assets that are more critically placed to affect people's health, safety or the environment when something goes wrong.
- Experts and elicited matrix consistency seems to be ensured if training is provided. There was little variation in the consistency evaluation between surveyed sites, and they were all within the meaningful of 0.1. Only one site was above (0.12), which is not significant either.

7.3.3 Further work

Additional or fewer criteria variables than are currently used can be explored further to determine the difference.
Other maintenance regime importance rating methods could be explored to determine the difference in the results of the expert's opinions, if any.

The tool can be tailored to select a maintenance strategy for different types of assets. The criteria variables would differ for each asset group due to different operating modes, design, usage intensity and others.

Overall, the presented approach would increase confidence in decision making where there is reliance on expert opinions for maintenance regime selection. Though the surveyed sample did not include strategic management level staff, involving them in the survey could be incorporated.

7.4 Overall summary

In summary, the three sections of the research contribute towards developing knowledge behind the management of health and safety risks, asset maintenance, customer service confidence and effective maintenance resource allocation in the water supply system. In addition to increasing regulatory reporting confidence for water supplies, the potential benefits from the research include:

Economic - uncertainty in financial resource allocation is minimised and other maintenance resources are better focused according to need as condition assessment is with better precision and condition misclassification is minimised. At strategic level, the organisation minimises unnecessary expenditure in replacements and repairs. Assessing maintenance effectiveness also contributes to improved maintenance quality, as well as selecting the best maintenance regime for each asset group.

Asset failure and risk management – purely risk based methods have contributed to water asset management. Incorporating improved condition assessment to risk assessment adds to the quality and confidence in the risk assigned to each asset.

Health / safety and environmental risk management - adoption of these practices contribute to risk minimisation to both human health and the environment as assets conditions are improved and failure risk minimised.

7.5 Recommendations

Recommendations are formulated for each section of the research on how water utilities could adopt some of the results from the research to enhance their water distribution assets management.

First, it is recommended that asset databases should ultimately be established to assess asset condition as standard procedure in utilities and not only for Ofwat reporting purposes. Data availability would also help to determine availability and performance trends and to get a clearer picture of any long-term risks. An objective assessment of network performance, reliability and availability statistics allows an asset manager to benchmark the asset's performance against the industry standard. This facilitates the process of optimising performance, minimising downtime and efficiently planning maintenance and overall water supply. Where such databases are not available, experts opinions can be used, but utilities should ensure proper elicitation protocol is followed in order to get quality results.

Secondly, water utilities can effectively evaluate and account for possible failures in their condition assessments by applying the principles of asset condition misclassification costs explored in Chapter 3. This would allow them to introduce mitigation to these errors and effectively account for these in their asset management and maintenance budgets.

Thirdly, the maintenance regime selection approach and maintenance effectiveness tool provide bases to build from for water utilities to effectively justify their maintenance quality and strategies even in the absence of adequate data.

It is recommended that not only visual appearance of assets, but performance standards should be the major factors in the condition rating of assets. This is because performance determines maintenance costs and performance factors differentiate asset groups.

From the regulator's perspective, the asset condition assessment and precision level in classifying assets conditions could provide criteria for assessing commitment by water utilities to continuously improve their asset management.

Because of the importance of condition assessment - as it is further used to forecast assets remaining life and risk of failure, it is recommended that a protocol be established. This could be initiated by the regulator in order to ensure the conditions of water networks presented by utilities under the capital framework plans are credible to a minimum standard.

The regulator could also introduce standards requiring that condition assessments be not wild guesses but be empirically justified. For example, the misclassification costs concept can be based on the level of experts' uncertainty in their assessments

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APPENDIX

APPENDIX 1: CONDITION ASSESSMENTS CA AND MAINTENANCE EFFECTIVENESS (ME) EXPERTS ELICITATION QUESTIONNAIRE

SECTION 1

Table 1: Asset condition grading criteria

	ASSET CONDITION				
CRITERIA	**1=GOOD**	**2=FAIR**	**3=ADEQUATE**	**4=POOR**	**5=AWFUL**
-Corrosion, -Leaking glands -Rotation -Brush wear status -Pressure -Temperature -Flow	As new/ functioning well	Superficial wear/ functioning fairly well	Significant wear & tear/ not functioning very well	Work required/ functioning obviously poorly	Worn out/ not safe to operate.
REMAINING LIFE EXPECTANCY	As new	Long	Medium	Short	None

1.1 Would you agree the three major pumps performance and condition variables in your experience are vibration, corrosion and rotation speed?

1. Agree with 1
2. Agree with 2
3. Agree with 3
4. Agree with all 3

1.2 Between condition grades 1 – 5, how would you rate the water pumps considering the above 3 performance variables and Table 1;

Asset	**Condition grade**
Pump 1	
Pump 2	
Pump 3	
Pump 4	
Pump 5	

1.3 Consider each pump to have gone past or just about to reach the grade you gave above. By what percentage would you rate the condition of each pump (for above the CG use '+' and for just below the CG use '- ').

Asset	**Condition grade**
Pump 1	
Pump 2	
Pump 3	

1.4 Consider that each of the pumps has had 4 corrective maintenance actions in the past 12 months, how would you rate each condition given this evidence.

Asset	**Condition grade**
Pump 1	
Pump 2	
Pump 3	

1.4 What is the probability that pump1 is in condition grade;

Pump 1	**In CG 1**	**Not in CG 1**
Probability		

1.5 How would you rate the reliability of all the opinions you have given in this questionnaire?

_____________ % reliable

1.6 How many years have you worked in asset maintenance?

____________ years**.**

1.7 Was the training exercise helpful to you?

- Very helpful
- Quite helpful
- Not helpful

SECTION 2

2.1 Consider the last PM you carried out for the pumps, how would you rate the condition of before the planned maintenance activity.

Asset	Condition grade
Pump 1	L- M- U-
Pump 2	L- M- U-
Pump 2	L- M- U-

Key: L - Your answer is 75% likely

M - Your answer is equally (50%) likely

U – Your answer is 75% likely

2.2 Consider the last PM you carried out for the pumps, how would you rate the condition after the same planned maintenance activity.

Asset	Condition grade
Pump 1	L- M- U-
Pump 2	L- M- U-
Pump 2	L- M- U-

Key: L - Your answer is 25% likely

M - Your answer is equally (50%) likely

U – Your answer is 75% likely

2.3 How would you rate the reliability of all the opinions you have given in this questionnaire?

____________ % reliable

2.4 What biases do you think you had in giving your assessments

Bias	Response
1. Subjective motivation to assessments.	
2. Group influence.	
3. Other influences.	

APPENDIX 2: BUILT ENVIRONMENT CONDITION ASSESSMENT EXAMPLE

Table 1-1 shows an example of a condition assessment protocol used in assessing building condition[1], where the first column includes variables selected by a team of experts.

Table 1-1: Building condition assessment example (after Hesa, 2009)

Element	Weight	Grade A (10)	Grade B (6)	Grade C (3)	Grade D (0)
Structure & Fabric	5				
Mechanical Services	3				
Electrical Services	3				
Internal Finishes	3				
Fittings & Equipment	4				
Health & Safety	4				
Statutory Compliance	3				
BUILDING CONDITION		200-250	125-200	75-125	0-75

The buildings condition assessment follows the following steps;

(1) Preparation: development of the condition assessment protocol

Step A. Identification of variables: These variables are structure & fabric, mechanical services, electrical services, internal finishes, fittings & equipment, Health & safety, and statutory compliance;

Step B. Defining the grades of each variable selected in Step A: the grades are defined grade A=10, grade B=6, grade C=3, and grade D=0;

Step C. Weighting the variables: the numbers in the 2nd column are the grades; and

Step D. Combination of the assessment: in the above example,

Building condition = grade A if the summarised score is between 200 and 250;

[1] Adopted from http://www.hesa.ac.uk/dox/datacoll/c09042/EMS_09_10_D20A.pdf

= grade B if the summarised score is between 125 and 200;

= grade C if the summarised score is between 75 and 125;

= grade D if the summarised score is between 0 and 75;

(2) Training experts: training experts on the condition definitions is needed.

(3) Walk-through inspection: the experts will then score each variable defined in Step A in (1). The scores in Table 2 are obtained.

Table 1-2: Scores for building condition assessment

Element	Weight	Grade A (10)	Grade B (6)	Grade C (3)	Grade D (0)
Structure & Fabric	5	✓			
Mechanical Services	3	✓			
Electrical Services	3		✓		
Internal Finishes	3		✓		
Fittings & Equipment	4		✓		
Health & Safety	4		✓		
Statutory Compliance	3			✓	
BUILDING CONDITION		200-250	125-200	75-125	0-75

(4) Aggregation: the scores of the variables assessed in Step C will then be aggregated with the method defined in Step D in (1).

As a result, the building condition investigated with the ticked scores belongs to Grade B (as the total scores are 5×10+3×10+3×6+3×6+4×6+4×6+3×3=**173**).

APPNDIX 3: ASSET CONDITION ASSESSMENT (CA)

APPENDIX 3.1: Site 1- 7 CA equal weight aggregates

Table 3-1: Equal weight aggregates

		Pump 1	Pump 1	Pump 1
Site 1	L	0.19	0.06	0.10
	M	0.28	0.11	0.16
	U	0.34	0.17	0.21
		0.27	0.11	0.16
Site 2	L	0.29	0.18	0.81
	M	0.34	0.22	0.86
	U	0.39	0.26	0.91
		0.34	0.22	0.86
Site3	L	0.25	0.21	0.49
	M	0.29	0.24	0.53
	U	0.32	0.31	0.57
		0.29	0.25	0.53
Site 4	L	0.08	0.15	0.46
	M	0.10	0.19	0.53
	U	0.12	0.22	0.59
		0.10	0.19	0.53
Site 5	L	0.15	0.22	0.23
	M	0.18	0.38	0.28
	U	0.21	0.31	0.33
		0.18	0.31	0.28
Site 6	L	0.48	0.48	0.07
	M	0.55	0.53	0.09
	U	0.06	0.58	0.11
		0.36	0.53	0.09
Site 7	L	0.46	0.07	0.43
	M	0.46	0.05	0.51
	U	0.53	0.08	0.56
		0.48	0.06	0.50

Appendix 3-2: Site 1- 7 CA weighted aggregates

Table 3-2: Weighted aggregates

		Pump 1	Pump 2	Pump 3
Site 1	L	0.20	0.06	0.10
	M	0.24	0.08	0.10
	U	0.12	0.08	0.09
		0.19	0.08	0.10
Site 2	L	0.26	0.18	0.80
	M	0.20	0.09	0.70
	U	0.21	0.07	0.52
		0.22	0.11	0.68
Site 3	L	0.28	0.24	0.54
	M	0.20	0.11	0.32
	U	0.17	0.15	0.29
		0.21	0.16	0.38
Site 4	L	0.11	0.19	0.64
	M	0.05	0.22	0.39
	U	0.07	0.06	0.30
		0.08	0.16	0.44
Site 5	L	0.11	0.31	0.17
	M	0.17	0.21	0.25
	U	0.24	0.07	0.36
		0.17	0.20	0.26
Site 6	L	0.50	0.57	0.08
	M	0.47	0.58	0.10
	U	0.34	0.52	0.08
		0.44	0.56	0.09
Site 7	L	0.49	0.07	0.45
	M	0.26	0.02	0.32
	U	0.11	0.03	0.23
		0.29	0.04	0.33

Appendix 3-3: Experts equally weighted aggregates

Table: Site 1

	Pump 1	Pump 2	Pump 3
	CG	**CG**	**CG**
Group CG	1	1	1
L	0.19	0.06	0.10
M	0.28	0.11	0.16
U	0.34	0.17	0.21
Grade	0.27	0.11	0.16

Table: Site 2

	Pump 1	Pump 2	Pump 3
	CG	**CG**	**CG**
Group CG	1	2	2
L	0.29	0.18	0.81
M	0.34	0.22	0.86
U	0.39	0.26	0.91
Grade	0.34	0.22	0.86

Table: Site 3

	Pump 1	Pump 2	Pump 3
	CG	**CG**	**CG**
Group CG	1	3	2
L	0.25	0.21	0.49
M	0.29	0.24	0.53
U	0.32	0.31	0.57
Grade	0.29	0.25	0.53

Table: Site 4

	Pump 1	Pump 2	Pump 3
	CG	**CG**	**CG**
Group CG	3	2	1
L	0.08	0.15	0.46
M	0.1	0.19	0.53
U	0.12	0.22	0.59
Grade	0.1	0.19	0.53

Table: Site 5

	Pump 1	Pump 2	Pump 3
	CG	**CG**	**CG**
Group CG	2	4	2
L	0.15	0.22	0.23
M	0.18	0.38	0.28
U	0.21	0.31	0.33
Grade	0.18	0.31	0.28

Table: Site 6

	Pump 1	Pump 2	Pump 3
	CG	**CG**	**CG**
Group CG	1	2	1
L	0.48	0.48	0.07
M	0.55	0.53	0.09
U	0.06	0.58	0.11
Grade	0.36	0.53	0.09

Table: Site 7

	Pump 1	Pump 2	Pump 3
	CG	**CG**	**CG**
Group CG	2	2	2
L	0.46	0.07	0.43
M	0.46	0.05	0.51
U	0.53	0.08	0.56
Grade	0.48	0.06	0.5

Appendix 3-4: Experts' weights based on performance

Table 1: Site 1

Experts	Weight
E1	0.32
E2	0.21
E3	0.29
E4	0.18

Table 2: Site 2

Experts	Weight
E1	0.17
E2	0.28
E3	0.31
E4	0.24

Table 3: Site 3

Experts	Weight
E1	0.25
E2	0.28
E3	0.16
E4	0.31

Table 4: Site 4

Experts	Weight
E1	0.33
E2	0.29
E3	0.38
E4	0.33

Table 5: Site 5

Experts	Weight
E1	0.20
E2	0.16
E3	0.28
E4	0.36

Table 6: Site 6

Experts	Weight
E1	0.18
E2	0.31
E3	0.36
E4	0.15

Table 8: Site 7

Experts	Weight
E1	0.24
E2	0.20
E3	0.29
E4	0.27

Table 8: Weights summary, site 1-7

Site 1	**Experts' estimates**	**Weights**	**Seed variable**
E1	9.00	0.32	4.17
E2	6.00	0.21	
E3	8.00	0.29	
E4	5.00	0.18	
	28.00		
Site 2			
E1	5.00	0.17	7.33
E2	8.00	0.28	
E3	9.00	0.31	
E4	7.00	0.24	
	29.00		
Site 3			
E1	8.00	0.25	6.33
E2	9.00	0.28	
E3	5.00	0.16	
E4	10.00	0.31	
	32.00		
Site 4			
E1	7.00	0.33	5.00
E2	6.00	0.29	
E3	8.00	0.38	
E4	21.00		
Site 5			
E1	5.00	0.20	4.67
E2	4.00	0.16	
E3	7.00	0.28	
E4	9.00	0.36	
	25.00		
Site 6			
E1	7.00	0.18	10.67
E2	12.00	0.31	
E3	14.00	0.36	

E4	6.00	0.15	
	39.00		
Site 7	11.00	0.24	10.33
E1	9.00	0.20	
E2	13.00	0.29	
E3	12.00	0.27	
E4	45.00		

Appendix 3-5: Experts' weighted aggregates

Table: Site 1

	Pump 1	**Pump 2**	**Pump 3**
U	0.26	0.18	0.80
M	0.20	0.09	0.70
L	0.21	0.07	0.52
Value	0.22	0.11	0.68

Table: Site 2

	Pump 1	**Pump 2**	**Pump 3**
U	0.26	0.18	0.80
M	0.20	0.09	0.70
L	0.21	0.07	0.52
Value	0.22	0.11	0.68

Table: Site 3

	Pump 1	**Pump 2**	**Pump 3**
U	0.26	0.18	0.80
M	0.20	0.09	0.70
L	0.21	0.07	0.52
Value	0.22	0.11	0.68

Table: Site 4

	Pump 1	**Pump 2**	**Pump 3**
U	0.26	0.18	0.80
M	0.20	0.09	0.70
L	0.21	0.07	0.52
Value	0.22	0.11	0.68

Table: Site 5

	Pump 1	Pump 2	Pump 3
U	0.26	0.18	0.80
M	0.20	0.09	0.70
L	0.21	0.07	0.52
Value	0.22	0.11	0.68

Table: Site 6

	Pump 1	Pump 2	Pump 3
U	0.26	0.18	0.80
M	0.20	0.09	0.70
L	0.21	0.07	0.52
Value	0.22	0.11	0.68

Table: Site 7

	Pump 1	Pump 2	Pump 3
U	0.26	0.18	0.80
M	0.20	0.09	0.70
L	0.21	0.07	0.52
Value	0.22	0.11	0.68

Appendix 3-6: Old and new approaches' results of condition assessment

Table: site 1

	Pump 1	**Pump 2**	**Pump 3**
Old CG	1	1	1
New CG value	1.22	1.11	1.68

Table: site 2

	Pump 1	**Pump 2**	**Pump 3**
Old CG	1	2	2
New CG value	1.22	2.11	2.68

Table: site 3

	Pump 1	**Pump 2**	**Pump 3**
Old CG	1	3	2
New CG value	1.22	3.11	2.68

Table: site 4

	Pump 1	Pump 2	Pump 3
Old CG	3	2	1
New CG value	3.22	2.11	1.68

Table: site 5

	Pump 1	Pump 2	Pump 3
Old CG	2	4	2
New CG value	2.22	4.11	2.68

Table: site 6

	Pump 1	Pump 2	Pump 3
Old CG	1	2	1
New CG value	1.22	2.11	1.68

Table: site 7

	Pump 1	Pump 2	Pump 3
Old CG	2	2	2
New CG value	2.22	2.11	2.68

Appendix 3-7: Asset condition assessments after performance evidence for weighted aggregates

Table: Site 1

	Pump 1	Pump 2	Pump 3
Group condition	1	1	1
Before CM	0.34	0.22	0.86
After CM	0.09	0.21	0.15
Condition before	1.34	1.22	1.86
Condition after	1.09	1.21	1.15
Change	-25	-1	-71

Table: Site 2

	Pump 1	Pump 2	Pump 3
Group condition	1	2	2
Before CM	0.34	0.22	0.86
After CM	0.22	0.11	0.68
Condition before	1.34	2.22	2.86
Condition after	1.22	2.11	2.68
Change	-12	-11	-18

Table: Site 3

	Pump 1	Pump 2	Pump 3
Group condition	1	3	2
Before CM	0.21	0.16	0.38
After CM	0.09	0.14	0.05
Condition before	1.21	2.16	2.38
Condition after	1.09	1.14	2.05
Change	- 12	-0.02	-33

Table: Site 4

	Pump 1	Pump 2	Pump 3
Group condition	3	2	1
Before CM	0.08	0.16	0.44
After CM	0.06	0.08	0.10
Condition before	3.08	2.16	1.44
Condition after	3.22	2.08	1.10
Change	+14	-8	-34

Table: Site 5

	Pump 1	Pump 2	Pump 3
Group condition	2	4	2
Before CM	0.17	0.20	0.26
After CM	0.06	0.60	0.12
Condition before	2.34	4.22	2.26
Condition after	2.22	4.11	2.12
Change	-12	-11	-14

Table: Site 6

	Pump 1	Pump 2	Pump 3
Group condition	1	2	1
Before CM	0.44	0.58	0.09
After CM	0.41	0.68	0.15
Condition before	1.44	2.58	1.09
Condition after	1.41	2.68	1.15
Change	-3	+10	+6

Table: Site 7

	Pump 1	Pump 2	Pump 3
Group condition	2	2	2
Before CM	0.29	0.04	0.33
After CM	0.53	0.04	0.66
Condition before	2.29	2.04	2.33
Condition after	2.53	2.04	2.66
Change	+24	-	+33

Appendix 3:8 Experts unit changes after corrective maintenance evidence

Table: Site 1

Pump	Unit change
1	-25
2	-1
3	-71

Table: Site 2

Pump	Unit change
1	-12
2	-11
3	-18

Table: Site 3

Pump	Unit change
1	- 12
2	-0.02
3	-33

Table: Site 4

Pump	Unit change
1	+14
2	-8
3	-34

Table: Site 5

Pump	Unit change
1	-12
2	-11
3	-14

Table: Site 6

Pump	Unit change
1	-3
2	+10
3	+6

Table: Site 7

Pump	Unit change
1	+24
2	-
3	+33

Appendix 3-9: Evidence data source, site 1

Site 1: Maintenance history: 2002 to 2010

Order	Order Type	Service product	Bas. start date	Description
5187880	WMS2	E1000001009	30/04/2003	BOWERI UTILITY (CANCEL) on 29.04.2004
6006523	WMS2	E1000001009	28/04/2004	PLUMBK UTILITY (CANCEL) on 05.05.2010
5187881	WMS2	E1000001009	30/04/2003	BOWERI UTILITY (CANCEL) on 29.04.2004
6006524	WMS2	E1000001009	28/04/2004	PLUMBK UTILITY (CANCEL) on 05.05.2010
6810680	WMS2	E1000001009	27/04/2005	HV TRIPPING SET - 1Y
4402589	WMS3	9125	25/04/2002	9125-Respond to RTS Grid Alarm
4403115	WMS3	9129	25/04/2002	9129-Process Operation (Non-Advantex
4621725	WMS3	9125	26/07/2002	9125-Respond to RTS Grid Alarm
4621736	WMS3	9125	26/07/2002	9125-Respond to RTS Grid Alarm
4634513	WMS3	9128	31/07/2002	9128-Attend Site: Non-Advantex
4656266	WMS3	9125	07/08/2002	9125-Respond to RTS Grid Alarm
4656334	WMS3	9125	07/08/2002	9125-Respond to RTS Grid Alarm
4669350	WMS3	9125	13/08/2002	9125-Respond to RTS Grid Alarm
4710898	WMS3	9125	01/09/2002	BOWERI UTILITY (CANCEL) on 23.04.2004
4977848	WMS3	I1SB	30/12/2002	SITE NO.2 WPS - PLC FAULT
4995721	WMS3	9125	09/01/2003	BOWERI UTILITY (CANCEL) on 26.04.2004
5304740	WMS3	EMEA	27/05/2003	Site No2 pumping station PLEASE PRICE
5304905	WMS3	I1SI	27/05/2003	Site No2 ps Pump control Please price
5324135	WMS3	9125	03/06/2003	BOWERI UTILITY (CANCEL) on 29.04.2004
5341571	WMS3	I1TB	03/06/2003	SITE WPS - COMMS FAIL SWILLINGTON
5375523	WMS3	I1TB	28/06/2003	CHAMBRST$ UTILITY (TECO) on 19.08.2003
5386431	WMS3	9125	02/07/2003	BOWERI UTILITY (CANCEL) on 29.04.2004
5618294	WMS2	CW110000097	20/10/2003	BOWERI UTILITY (CANCEL) on 10.05.2004
5618295	WMS2	CW110000097	03/11/2003	BOWERI UTILITY (CANCEL) on 10.05.2004
5645753	WMS2	CW110000097	17/11/2003	BOWERI UTILITY (CANCEL) on 10.05.2004
5677351	WMS2	CW110000097	01/12/2003	BOWERI UTILITY (CANCEL) on 11.05.2004
5708603	WMS2	CW110000097	15/12/2003	BOWERI UTILITY (CANCEL) on 11.05.2004
5736651	WMS2	CW110000097	29/12/2003	BOWERI UTILITY (CANCEL) on 11.05.2004
5748378	WMS3	9125	06/12/2003	BOWERI UTILITY (CANCEL) on 11.05.2004
5767724	WMS2	CW110000097	12/01/2004	CHECK OPERATION OF PUMPING STATION
5793035	WMS2	CW110000097	26/01/2004	CHECK OPERATION OF PUMPING STATION
5822143	WMS2	CW110000097	09/02/2004	CHECK OPERATION OF PUMPING STATION
5852702	WMS2	CW110000097	23/02/2004	CHECK OPERATION OF PUMPING STATION
5887532	WMS2	CW110000097	08/03/2004	CHECK OPERATION OF PUMPING STATION
5916698	WMS2	CW110000097	22/03/2004	CHECK OPERATION OF PUMPING STATION
5950864	WMS2	CW110000097	05/04/2004	CHECK OPERATION OF PUMPING STATION
5983594	WMS2	CW110000097	19/04/2004	CHECK OPERATION OF PUMPING STATION
6019191	WMS2	CW110000097	03/05/2004	CHECK OPERATION OF PUMPING STATION
6047038	WMS2	CW110000097	17/05/2004	CHECK OPERATION OF PUMPING STATION
6081948	WMS2	CW110000097	31/05/2004	CHECK OPERATION OF PUMPING STATION
6113088	WMS2	CW110000097	14/06/2004	CHECK OPERATION OF PUMPING STATION
6145507	WMS2	CW110000097	28/06/2004	CHECK OPERATION OF PUMPING STATION
6176069	WMS2	CW110000097	12/07/2004	CHECK OPERATION OF PUMPING STATION
6199066	WMS2	CW110000097	26/07/2004	CHECK OPERATION OF PUMPING STATION

6242279	WMS2	CW110000097	09/08/2004	CHECK OPERATION OF PUMPING STATION
6274088	WMS2	CW110000097	23/08/2004	CHECK OPERATION OF PUMPING STATION
6306839	WMS2	CW110000097	06/09/2004	CHECK OPERATION OF PUMPING STATION
6341872	WMS2	CW110000097	20/09/2004	CHECK OPERATION OF PUMPING STATION
6372909	WMS2	CW110000097	04/10/2004	CHECK OPERATION OF PUMPING STATION
6404308	WMS2	CW110000097	18/10/2004	CHECK OPERATION OF PUMPING STATION
6434232	WMS2	CW110000097	01/11/2004	CHECK OPERATION OF PUMPING STATION
6464486	WMS2	CW110000097	15/11/2004	CHECK OPERATION OF PUMPING STATION
6497108	WMS2	CW110000097	29/11/2004	CHECK OPERATION OF PUMPING STATION
6525438	WMS2	CW110000097	13/12/2004	CHECK OPERATION OF PUMPING STATION
6550620	WMS2	CW110000097	27/12/2004	CHECK OPERATION OF PUMPING STATION
6579838	WMS2	CW110000097	10/01/2005	CHECK OPERATION OF PUMPING STATION
6605694	WMS2	CW110000097	24/01/2005	CHECK OPERATION OF PUMPING STATION
6631355	WMS2	CW110000097	07/02/2005	CHECK OPERATION OF PUMPING STATION
6659584	WMS2	CW110000097	21/02/2005	CHECK OPERATION OF PUMPING STATION
6691208	WMS3	I1IB	02/02/2005	Site res south no2 level (02.02.2005
6692997	WMS3	I1IB	07/02/2005	revisit to fit txmtr ptr
6698547	WMS2	CW110000097	07/03/2005	CHECK OPERATION OF PUMPING STATION
6728207	WMS2	CW110000097	21/03/2005	CHECK OPERATION OF PUMPING STATION
6760569	WMS2	CW110000097	04/04/2005	CHECK OPERATION OF PUMPING STATION
6792925	WMS2	CW110000097	18/04/2005	CHECK OPERATION OF PUMPING STATION
6824786	WMS2	CW110000097	02/05/2005	CHECK OPERATION OF PUMPING STATION
6856364	WMS2	CW110000097	16/05/2005	CHECK OPERATION OF PUMPING STATION
6889262	WMS2	CW110000097	30/05/2005	CHECK OPERATION OF PUMPING STATION
6918531	WMS2	CW110000097	13/06/2005	CHECK OPERATION OF PUMPING STATION
6948659	WMS2	CW110000097	27/06/2005	CHECK OPERATION OF PUMPING STATION
6978141	WMS2	CW110000097	11/07/2005	CHECK OPERATION OF PUMPING STATION
7009238	WMS2	CW110000097	25/07/2005	CHECK OPERATION OF PUMPING STATION
7042715	WMS2	CW110000097	08/08/2005	CHECK OPERATION OF PUMPING STATION
7074209	WMS2	CW110000097	22/08/2005	CHECK OPERATION OF PUMPING STATION
7108163	WMS2	CW110000097	05/09/2005	CHECK OPERATION OF PUMPING STATION
7137726	WMS2	CW110000097	19/09/2005	CHECK OPERATION OF PUMPING STATION
7168043	WMS2	CW110000097	03/10/2005	CHECK OPERATION OF PUMPING STATION
7197783	WMS3	9126	17/09/2005	9126-Respond to RTS ICA Alarm
7199720	WMS2	CW110000097	17/10/2005	CHECK OPERATION OF PUMPING STATION
7232352	WMS2	CW110000097	31/10/2005	CHECK OPERATION OF PUMPING STATION
7264065	WMS2	CW110000097	14/11/2005	CHECK OPERATION OF PUMPING STATION
7267755	WMS3	I1SB	17/10/2005	I1SB-ICA Breakdown (SCADA/PLC)
7295354	WMS2	CW110000097	28/11/2005	CHECK OPERATION OF PUMPING STATION
7326546	WMS2	CW110000097	12/12/2005	CHECK OPERATION OF PUMPING STATION
7356644	WMS2	CW110000097	26/12/2005	CHECK OPERATION OF PUMPING STATION
7389112	WMS2	CW110000097	09/01/2006	CHECK OPERATION OF PUMPING STATION
7417578	WMS2	CW110000097	23/01/2006	CHECK OPERATION OF PUMPING STATION
7445075	WMS2	CW110000097	06/02/2006	CHECK OPERATION OF PUMPING STATION
7476090	WMS2	CW110000097	20/02/2006	CHECK OPERATION OF PUMPING STATION
7510499	WMS2	CW110000097	06/03/2006	CHECK OPERATION OF PUMPING STATION
7543393	WMS2	CW110000097	20/03/2006	CHECK OPERATION OF PUMPING STATION
7580161	WMS2	CW110000097	03/04/2006	CHECK OPERATION OF PUMPING STATION
7617586	WMS2	CW110000097	17/04/2006	CHECK OPERATION OF PUMPING STATION
7652124	WMS2	CW110000097	01/05/2006	CHECK OPERATION OF PUMPING STATION

7684389	WMS2	CW110000097	15/05/2006	CHECK OPERATION OF PUMPING STATION
7713353	WMS2	CW110000097	29/05/2006	CHECK OPERATION OF PUMPING STATION
7747815	WMS2	CW110000097	12/06/2006	CHECK OPERATION OF PUMPING STATION
7780120	WMS2	CW110000097	26/06/2006	CHECK OPERATION OF PUMPING STATION
7811378	WMS2	CW110000097	10/07/2006	CHECK OPERATION OF PUMPING STATION
7843310	WMS2	CW110000097	24/07/2006	CHECK OPERATION OF PUMPING STATION
7877289	WMS2	CW110000097	07/08/2006	CHECK OPERATION OF PUMPING STATION
7909248	WMS2	CW110000097	21/08/2006	CHECK OPERATION OF PUMPING STATION
7944590	WMS2	CW110000097	04/09/2006	CHECK OPERATION OF PUMPING STATION
7977820	WMS2	CW110000097	18/09/2006	CHECK OPERATION OF PUMPING STATION
8009891	WMS2	CW110000097	02/10/2006	CHECK OPERATION OF PUMPING STATION
8037490	WMS3	I1SB	14/09/2006	I1SB-ICA Breakdown (SCADA/PLC)
8041889	WMS2	CW110000097	16/10/2006	CHECK OPERATION OF PUMPING STATION
8073391	WMS2	CW110000097	30/10/2006	CHECK OPERATION OF PUMPING STATION
8104393	WMS2	CW110000097	13/11/2006	CHECK OPERATION OF PUMPING STATION
8133957	WMS2	CW110000097	27/11/2006	CHECK OPERATION OF PUMPING STATION
8165272	WMS2	CW110000097	11/12/2006	CHECK OPERATION OF PUMPING STATION
8194833	WMS2	CW110000097	25/12/2006	CHECK OPERATION OF PUMPING STATION
8206068	WMS3	9126	30/11/2006	Please call S Webster Tel 07790 616269
8226069	WMS2	CW110000097	08/01/2007	CHECK OPERATION OF PUMPING STATION
8255175	WMS2	CW110000097	22/01/2007	CHECK OPERATION OF PUMPING STATION
8282322	WMS2	CW110000097	05/02/2007	CHECK OPERATION OF PUMPING STATION
8315054	WMS2	CW110000097	19/02/2007	CHECK OPERATION OF PUMPING STATION
8351234	WMS2	CW110000097	05/03/2007	CHECK OPERATION OF PUMPING STATION
8385362	WMS2	CW110000097	19/03/2007	CHECK OPERATION OF PUMPING STATION
8420479	WMS2	CW110000097	02/04/2007	CHECK OPERATION OF PUMPING STATION
8457093	WMS2	CW110000097	16/04/2007	CHECK OPERATION OF PUMPING STATION
8485222	WMS3	9126	27/03/2007	9126-Respond to RTS ICA Alarm
8498455	WMS2	CW110000097	30/04/2007	CHECK OPERATION OF PUMPING STATION
8532507	WMS2	CW110000097	14/05/2007	CHECK OPERATION OF PUMPING STATION
8578022	WMS2	CW110000097	28/05/2007	CHECK OPERATION OF PUMPING STATION
8612830	WMS2	CW110000097	11/06/2007	CHECK OPERATION OF PUMPING STATION
8646952	WMS2	CW110000097	25/06/2007	CHECK OPERATION OF PUMPING STATION
8691441	WMS2	CW110000097	09/07/2007	CHECK OPERATION OF PUMPING STATION
8699826	WMS3	EMMR	12/06/2007	EMMR-Mechanical Repair
8728794	WMS2	CW110000097	23/07/2007	CHECK OPERATION OF PUMPING STATION
8766543	WMS2	CW110000097	06/08/2007	CHECK OPERATION OF PUMPING STATION
8801727	WMS2	CW110000097	20/08/2007	CHECK OPERATION OF PUMPING STATION
8837500	WMS2	CW110000097	03/09/2007	CHECK OPERATION OF PUMPING STATION
8848395	WMS3	I1NF	08/08/2007	SP - PLEASE PROCESS PLC REQUEST FOR BRAY
8872724	WMS2	CW110000097	17/09/2007	CHECK OPERATION OF PUMPING STATION
8908154	WMS2	CW110000097	01/10/2007	CHECK OPERATION OF PUMPING STATION
8945080	WMS2	CW110000097	15/10/2007	CHECK OPERATION OF PUMPING STATION
8981256	WMS2	CW110000097	29/10/2007	CHECK OPERATION OF PUMPING STATION
9017849	WMS2	CW110000097	12/11/2007	CHECK OPERATION OF PUMPING STATION
9053159	WMS2	CW110000097	26/11/2007	CHECK OPERATION OF PUMPING STATION
9086659	WMS3	9126	09/11/2007	9122-Respond to Service Delivery Alarm
9090653	WMS2	CW110000097	10/12/2007	CHECK OPERATION OF PUMPING STATION
9126279	WMS2	CW110000097	24/12/2007	CHECK OPERATION OF PUMPING STATION
9163779	WMS2	CW110000097	07/01/2008	CHECK OPERATION OF PUMPING STATION

9200979	WMS2	CW110000097	21/01/2008	CHECK OPERATION OF PUMPING STATION
9230948	WMS2	CW110000097	04/02/2008	CHECK OPERATION OF PUMPING STATION
9264830	WMS3	9126	18/01/2008	9126-Respond to RTS ICA Alarm
9267499	WMS2	CW110000097	18/02/2008	CHECK OPERATION OF PUMPING STATION
9308510	WMS2	CW110000097	03/03/2008	CHECK OPERATION OF PUMPING STATION
9342346	WMS2	CW110000097	17/03/2008	CHECK OPERATION OF PUMPING STATION
9382854	WMS2	CW110000097	31/03/2008	CHECK OPERATION OF PUMPING STATION
9420851	WMS2	CW110000097	14/04/2008	CHECK OPERATION OF PUMPING STATION
9453888	WMS2	CW110000097	28/04/2008	CHECK OPERATION OF PUMPING STATION
9497833	WMS2	CW110000097	12/05/2008	CHECK OPERATION OF PUMPING STATION
9534821	WMS2	CW110000097	26/05/2008	CHECK OPERATION OF PUMPING STATION
9570193	WMS2	CW110000097	09/06/2008	CHECK OPERATION OF PUMPING STATION
9604833	WMS2	CW110000097	23/06/2008	CHECK OPERATION OF PUMPING STATION
9638247	WMS2	CW110000097	07/07/2008	CHECK OPERATION OF PUMPING STATION
9670118	WMS2	CW110000097	21/07/2008	CHECK OPERATION OF PUMPING STATION
9706876	WMS2	CW110000097	04/08/2008	CHECK OPERATION OF PUMPING STATION
9739741	WMS2	CW110000097	18/08/2008	CHECK OPERATION OF PUMPING STATION
9775216	WMS2	CW110000097	01/09/2008	CHECK OPERATION OF PUMPING STATION
9812889	WMS2	CW110000097	15/09/2008	CHECK OPERATION OF PUMPING STATION
9849084	WMS2	CW110000097	29/09/2008	CHECK OPERATION OF PUMPING STATION
9891702	WMS2	CW110000097	13/10/2008	CHECK OPERATION OF PUMPING STATION
9923395	WMS2	CW110000097	27/10/2008	CHECK OPERATION OF PUMPING STATION
9961217	WMS2	CW110000097	10/11/2008	CHECK OPERATION OF PUMPING STATION
10024421	WMS2	CW110000097	24/11/2008	CHECK OPERATION OF PUMPING STATION
10052324	WMS2	CW110000097	08/12/2008	CHECK OPERATION OF PUMPING STATION
10090393	WMS2	CW110000097	22/12/2008	CHECK OPERATION OF PUMPING STATION
10128100	WMS2	CW110000097	05/01/2009	CHECK OPERATION OF PUMPING STATION
10144934	WMS3	I1QX	12/12/2008	Site visit required to establish if PW i
10144935	WMS3	I1QX	12/12/2008	Site visit required to establish if PW i
10165354	WMS2	CW110000097	19/01/2009	CHECK OPERATION OF PUMPING STATION
10197305	WMS2	CW110000097	02/02/2009	CHECK OPERATION OF PUMPING STATION
10237187	WMS2	CW110000097	16/02/2009	CHECK OPERATION OF PUMPING STATION
10249377	WMS3	I1QX	30/06/2009	Site visit required to establish if PW i
10276645	WMS2	CW110000097	02/03/2009	CHECK OPERATION OF PUMPING STATION
10310104	WMS3	EME4	12/02/2009	Site No2 WPS - Flow control valve sti
10313789	WMS2	CW110000097	16/03/2009	CHECK OPERATION OF PUMPING STATION
10355155	WMS2	CW110000097	30/03/2009	CHECK OPERATION OF PUMPING STATION
10397322	WMS2	CW110000097	13/04/2009	CHECK OPERATION OF PUMPING STATION
10441302	WMS2	CW110000097	27/04/2009	CHECK OPERATION OF PUMPING STATION
10482007	WMS2	CW110000097	11/05/2009	CHECK OPERATION OF PUMPING STATION
10522117	WMS2	CW110000097	25/05/2009	CHECK OPERATION OF PUMPING STATION
10562979	WMS2	CW110000097	08/06/2009	CHECK OPERATION OF PUMPING STATION
10603655	WMS2	CW110000097	22/06/2009	CHECK OPERATION OF PUMPING STATION
10644132	WMS2	CW110000097	06/07/2009	CHECK OPERATION OF PUMPING STATION
10685884	WMS2	CW110000097	20/07/2009	CHECK OPERATION OF PUMPING STATION
10728917	WMS2	CW110000097	03/08/2009	CHECK OPERATION OF PUMPING STATION
10772919	WMS2	CW110000097	17/08/2009	CHECK OPERATION OF PUMPING STATION
10815051	WMS2	CW110000097	31/08/2009	CHECK OPERATION OF PUMPING STATION
10857718	WMS2	CW110000097	14/09/2009	CHECK OPERATION OF PUMPING STATION
10897133	WMS2	CW110000097	28/09/2009	CHECK OPERATION OF PUMPING STATION

10938170	WMS2	CW110000097	12/10/2009	CHECK OPERATION OF PUMPING STATION
10974142	WMS2	CW110000097	26/10/2009	CHECK OPERATION OF PUMPING STATION
11014980	WMS2	CW110000097	09/11/2009	CHECK OPERATION OF PUMPING STATION
11054302	WMS2	CW110000097	23/11/2009	CHECK OPERATION OF PUMPING STATION
11092636	WMS2	CW110000097	07/12/2009	CHECK OPERATION OF PUMPING STATION
11131045	WMS2	CW110000097	21/12/2009	CHECK OPERATION OF PUMPING STATION
11170042	WMS2	CW110000097	04/01/2010	CHECK OPERATION OF PUMPING STATION
11207172	WMS2	CW110000097	18/01/2010	CHECK OPERATION OF PUMPING STATION
11243225	WMS2	CW110000097	01/02/2010	CHECK OPERATION OF PUMPING STATION
11284154	WMS2	CW110000097	15/02/2010	CHECK OPERATION OF PUMPING STATION
11330695	WMS2	CW110000097	01/03/2010	CHECK OPERATION OF PUMPING STATION
11371541	WMS2	CW110000097	15/03/2010	CHECK OPERATION OF PUMPING STATION
11408701	WMS2	CW110000097	29/03/2010	CHECK OPERATION OF PUMPING STATION
11444952	WMS2	CW110000097	12/04/2010	CHECK OPERATION OF PUMPING STATION
11484347	WMS2	CW110000097	26/04/2010	CHECK OPERATION OF PUMPING STATION
11531360	WMS2	CW110000097	10/05/2010	CHECK OPERATION OF PUMPING STATION
11575289	WMS2	CW110000097	24/05/2010	CHECK OPERATION OF PUMPING STATION
11617266	WMS2	CW110000097	07/06/2010	CHECK OPERATION OF PUMPING STATION
11658778	WMS2	CW110000097	21/06/2010	CHECK OPERATION OF PUMPING STATION
11700486	WMS2	CW110000097	05/07/2010	CHECK OPERATION OF PUMPING STATION
11743586	WMS2	CW110000097	19/07/2010	CHECK OPERATION OF PUMPING STATION
11788057	WMS2	CW110000097	02/08/2010	CHECK OPERATION OF PUMPING STATION
11833378	WMS2	CW110000097	16/08/2010	CHECK OPERATION OF PUMPING STATION
11878869	WMS2	CW110000097	30/08/2010	CHECK OPERATION OF PUMPING STATION
5694745	WMS3	I1TB	10/11/2003	Site no2 WPS Please remove inhbit to
5714562	WMS3	I1SX	19/11/2003	BOWERI UTILITY (CANCEL) on 10.05.2004
5882614	WMS2	I1TE0000201	01/02/2004	MCVEYD UTILITY (COMPLETE) on 11.02.2004
6166613	WMS3	I1TB	08/06/2004	Pump control pumps will only operate on
6167916	WMS3	IRES	09/06/2004	ICA - RESTOCK
6237787	WMS3	IRES	08/07/2004	IRDN for repair E3383
6685549	WMS3	I1IB	01/02/2005	SITE WPS - PID LOOP CONTROLLER FAULT.
6690842	WMS3	I1IB	02/02/2005	SITE WPS - PID LOOP CONTROLLER FAULT.
6692836	WMS3	I1TB	03/02/2005	Site No2 WPS Auto Control Problems
7410438	WMS3	I1IB	21/12/2005	I1IB-Breakdown (Instrumentation)
7423678	WMS3	I1IB	28/12/2005	I1IB-Breakdown (Instrumentation)
5451079	WMS2	E1000000245	28/08/2003	DISTRUBUTION BOARD SERVICE
9749922	WMS2	E1000000245	21/08/2008	DISTRIBUTION BOARD SERVICE-5Y
7487896	WMS2	E1000000293	24/02/2006	EMERGENCY LIGHTING SERVICE
8079633	WMS2	E1000000293	01/11/2006	EMERGENCY LIGHTING SERVICE
8505649	WMS2	E1000000293	02/05/2007	EMERGENCY LIGHTING SERVICE
8989234	WMS2	E1000000293	31/10/2007	EMERGENCY LIGHTING SERVICE
9461475	WMS2	E1000000293	30/04/2008	EMERGENCY LIGHTING SERVICE
9930786	WMS2	E1000000293	29/10/2008	EMERGENCY LIGHTING SERVICE
10483116	WMS2	E1000000293	11/05/2009	EMERGENCY LIGHTING SERVICE
10844329	WMS2	E1000000293	08/09/2009	EMERGENCY LIGHTING SERVICE
11357684	WMS2	E1000000293	09/03/2010	EMERGENCY LIGHTING SERVICE
4643383	WMS2	E1000000228	02/09/2002	FIRE ALARM SERVICE
5462476	WMS2	E1000000228	01/09/2003	FIRE ALARM SERVICE
6290433	WMS2	E1000000228	30/08/2004	PLUMBK UTILITY (CANCEL) on 05.05.2010
7089102	WMS2	E1000000228	29/08/2005	FIRE ALARM SERVICE

7929071	WMS2	E1000000228	28/08/2006	FIRE ALARM SERVICE
6171531	WMS3	I1IB	10/06/2004	BARKERJ UTILITY (COMPLETE) on 30.07.2004
7407135	WMS3	I1TB	19/12/2005	I1TB-ICA Breakdown (Telemetry)
7595052	WMS3	I1IB	10/03/2006	I1IB-Breakdown (Instrumentation)
9159463	WMS3	I1IB	06/12/2007	I1IB-Breakdown (Instrumentation)
4553449	WMS3	EMER	27/06/2002	Site No2 variable speed pump
4631554	WMS3	EMER	30/07/2002	Site No2 wps VSP No1 fault
4638328	WMS2	E1000000931	30/08/2002	INVERTER SERVICE
4656614	WMS3	EMER	08/08/2002	Site no2 Wps No1 vsp
5753669	WMS3	EMER	08/12/2003	Site N02 wps Inverter drive Fault Ple
5826019	WMS3	EMER	12/01/2004	EMER-Electrical Repair Please repair two
6281424	WMS2	E1000000931	27/08/2004	INVERTER SERVICE Rescheduled for Aug 05
7089106	WMS2	E1000000931	29/08/2005	NO 1 PUMP INVERTER SERVICE
8076402	WMS2	E1000000931	01/11/2006	INVERTER SERVICE
9928551	WMS2	E1000000931	29/10/2008	VARIABLE FREQ STARTER SERVICE-2Y
11361498	WMS2	E1000000931	11/03/2010	VARIABLE FREQ STARTER SERVICE-2Y
11693653	WMS2	E1000002298	02/06/2010	VARIABLE FREQ STARTER SERVICE-2Y
4340369	WMS2		02/05/2002	26W STATUTORY INSPECTION
4780583	WMS2		31/10/2002	26W STATUTORY INSPECTION
5179888	WMS2	L1000000524	01/05/2003	26W STATUTORY INSPECTION
5602438	WMS2	L1000000524	30/10/2003	26W STATUTORY INSPECTION
6004942	WMS2	L1000000524	29/04/2004	26W STATUTORY INSPECTION
6424268	WMS2	L1000000524	28/10/2004	26W STATUTORY INSPECTION
6813818	WMS2	L1000000524	28/04/2005	26W STATUTORY INSPECTION
7222744	WMS2	L1000000524	27/10/2005	26W STATUTORY INSPECTION
7727145	WMS2	L1000000524	27/04/2006	26W STATUTORY INSPECTION
8062434	WMS2	L1000000524	26/10/2006	26W STATUTORY INSPECTION
8490942	WMS2	L1000000524	26/04/2007	26W STATUTORY INSPECTION
8970487	WMS2	L1000000524	25/10/2007	26W STATUTORY INSPECTION
9443473	WMS2		24/04/2008	26W STATUTORY INSPECTION
9912984	WMS2	L1000000524	23/10/2008	26W STATUTORY INSPECTION
10428776	WMS2	L1000000524	23/04/2009	26W STATUTORY INSPECTION
10962927	WMS2	L1000000524	22/10/2009	26W STATUTORY INSPECTION
11471978	WMS2	L1000000524	22/04/2010	26W STATUTORY INSPECTION
4340368	WMS2		02/05/2002	26W STATUTORY INSPECTION
4780582	WMS2		31/10/2002	26W STATUTORY INSPECTION
5179887	WMS2	L1000000390	01/05/2003	26W STATUTORY INSPECTION
5602437	WMS2	L1000000390	30/10/2003	26W STATUTORY INSPECTION
6004941	WMS2	L1000000390	29/04/2004	26W STATUTORY INSPECTION
6424267	WMS2	L1000000390	28/10/2004	26W STATUTORY INSPECTION
6813817	WMS2	L1000000390	28/04/2005	26W STATUTORY INSPECTION
7222743	WMS2	L1000000390	27/10/2005	26W STATUTORY INSPECTION
7727144	WMS2	L1000000390	27/04/2006	26W STATUTORY INSPECTION
8062433	WMS2	L1000000390	26/10/2006	26W STATUTORY INSPECTION
8490941	WMS2	L1000000390	26/04/2007	26W STATUTORY INSPECTION
8970486	WMS2	L1000000390	25/10/2007	26W STATUTORY INSPECTION
9443472	WMS2		24/04/2008	26W STATUTORY INSPECTION
9912983	WMS2	L1000000390	23/10/2008	26W STATUTORY INSPECTION
10428775	WMS2	L1000000390	23/04/2009	26W STATUTORY INSPECTION
10962926	WMS2	L1000000390	22/10/2009	26W STATUTORY INSPECTION

11471977	WMS2	L1000000390	22/04/2010	26W STATUTORY INSPECTION
4340372	WMS2		02/05/2002	STATUTORY INSPECTION
4780586	WMS2		31/10/2002	STATUTORY INSPECTION
5179891	WMS2	L1000000712	01/05/2003	STATUTORY INSPECTION
5602441	WMS2	L1000000712	30/10/2003	STATUTORY INSPECTION
6004945	WMS2	L1000000712	29/04/2004	STATUTORY INSPECTION
6424271	WMS2	L1000000712	28/10/2004	STATUTORY INSPECTION
6813821	WMS2	L1000000712	28/04/2005	STATUTORY INSPECTION
7222747	WMS2	L1000000712	27/10/2005	STATUTORY INSPECTION
7727148	WMS2	L1000000712	27/04/2006	STATUTORY INSPECTION
8062437	WMS2	L1000000712	26/10/2006	STATUTORY INSPECTION
8490945	WMS2	L1000000712	26/04/2007	STATUTORY INSPECTION
8970490	WMS2	L1000000712	25/10/2007	STATUTORY INSPECTION
9443476	WMS2		24/04/2008	STATUTORY INSPECTION
9912987	WMS2	L1000000712	23/10/2008	STATUTORY INSPECTION
10428779	WMS2	L1000000712	23/04/2009	STATUTORY INSPECTION
10962930	WMS2	L1000000712	22/10/2009	STATUTORY INSPECTION
11471981	WMS2	L1000000712	22/04/2010	STATUTORY INSPECTION
6811550	WMS2	L1000000755	28/04/2005	STATUTORY INSPECTION
7220744	WMS2	L1000000755	27/10/2005	STATUTORY INSPECTION
7726091	WMS2	L1000000755	27/04/2006	STATUTORY INSPECTION
8062204	WMS2	L1000000755	26/10/2006	STATUTORY INSPECTION
8483238	WMS2	L1000000755	26/04/2007	STATUTORY INSPECTION
8970194	WMS2	L1000000755	25/10/2007	STATUTORY INSPECTION
9443246	WMS2	L1000000755	24/04/2008	STATUTORY INSPECTION
9912769	WMS2	L1000000755	23/10/2008	STATUTORY INSPECTION
10428527	WMS2	L1000000755	23/04/2009	STATUTORY INSPECTION
10962710	WMS2	L1000000755	22/10/2009	STATUTORY INSPECTION
11471859	WMS2	L1000000755	22/04/2010	STATUTORY INSPECTION
5252813	WMS3	EMER	30/04/2003	EMER-Electrical Repair Please attend sit
7144167	WMS3	EMER	23/08/2005	EMER-Electrical Repair
7505368	WMS3	EMER	02/02/2006	Site No2 Power fail
4638322	WMS2	E1000000610	30/08/2002	MOTOR & STARTER SERVICE
4687746	WMS3	EMMR	21/08/2002	Please repair oil thrower on VSP1
6281418	WMS2	E1000000610	27/08/2004	MOTOR & STARTER SERVICE Rescheduled for
7089104	WMS2	E1000000610	29/08/2005	NO 1 PUMP
8076396	WMS2	E1000000610	01/11/2006	MOTOR & STARTER SERVICE
9928545	WMS2	E1000000610	29/10/2008	MOTOR & STARTER SERVICE
11361493	WMS2	E1000000610	11/03/2010	MOTOR & STARTER SERVICE
11693650	WMS2	E1000002241	02/06/2010	MOTOR & STARTER SERVICE
4638320	WMS2	E1000000610	30/08/2002	MOTOR & STARTER SERVICE
4638321	WMS2	E1000000610	30/08/2002	MOTOR & STARTER SERVICE
4638323	WMS2	E1000000610	30/08/2002	MOTOR & STARTER SERVICE
4638324	WMS2	E1000000610	30/08/2002	MOTOR & STARTER SERVICE
4638325	WMS2	E1000000610	30/08/2002	MOTOR & STARTER SERVICE
4917946	WMS3	EMER	02/12/2002	EMER-Electrical Repair PLEASE REPAIR NOI
6281416	WMS2	E1000000610	27/08/2004	MOTOR & STARTER SERVICE
6281417	WMS2	E1000000610	27/08/2004	MOTOR & STARTER SERVICE
6281419	WMS2	E1000000610	27/08/2004	MOTOR & STARTER SERVICE Rescheduled for
6281420	WMS2	E1000000610	27/08/2004	MOTOR & STARTER SERVICE

6281421	WMS2	E1000000610	27/08/2004	MOTOR & STARTER SERVICE
6460978	WMS3	I1TI	15/10/2004	Please commission K to B Backfeed at Bra
7089105	WMS2	E1000000610	29/08/2005	NO 2 PUMP
7999493	WMS3	EMER	29/08/2006	PLEASE INVESTIGATE FAULT ON No.3 PUMP ST
8076394	WMS2	E1000000610	01/11/2006	MOTOR & STARTER SERVICE
8076395	WMS2	E1000000610	01/11/2006	MOTOR & STARTER SERVICE
8076397	WMS2	E1000000610	01/11/2006	MOTOR & STARTER SERVICE
8076398	WMS2	E1000000610	01/11/2006	MOTOR & STARTER SERVICE
8076399	WMS2	E1000000610	01/11/2006	MOTOR & STARTER SERVICE
9928543	WMS2	E1000000610	29/10/2008	MOTOR & STARTER SERVICE
9928544	WMS2	E1000000610	29/10/2008	MOTOR & STARTER SERVICE
9928546	WMS2	E1000000610	29/10/2008	MOTOR & STARTER SERVICE
9928547	WMS2	E1000000610	29/10/2008	MOTOR & STARTER SERVICE
9928548	WMS2	E1000000610	29/10/2008	MOTOR & STARTER SERVICE
11361491	WMS2	E1000000610	11/03/2010	MOTOR & STARTER SERVICE
11361492	WMS2	E1000000610	11/03/2010	MOTOR & STARTER SERVICE
11361494	WMS2	E1000000610	11/03/2010	MOTOR & STARTER SERVICE
11361495	WMS2	E1000000610	11/03/2010	MOTOR & STARTER SERVICE
11693651	WMS2	E1000002241	02/06/2010	MOTOR & STARTER SERVICE
11693652	WMS2	E1000002241	02/06/2010	MOTOR & STARTER SERVICE
4643393	WMS2	M1000000811	02/09/2002	COMPRESSOR SERVICE
5462486	WMS2	M1000000811	01/09/2003	COMPRESSOR SERVICE
6290443	WMS2	M1000000811	30/08/2004	COMPRESSOR SERVICE - CANC Requires shutd
7089115	WMS2	M1000000811	29/08/2005	COMPRESSOR SERVICE
8076411	WMS2	M1000000811	01/11/2006	COMPRESSOR SERVICE
8428358	WMS3	EMER	06/03/2007	EMER-Electrical Repair
8986444	WMS2	M1000000811	31/10/2007	COMPRESSOR SERVICE
9928560	WMS2	M1000000811	29/10/2008	COMPRESSOR SERVICE-1Y
11356996	WMS2	M1000000811	09/03/2010	COMPRESSOR SERVICE-1Y
4638318	WMS2	E1000000331	30/08/2002	MOTOR & STARTER SERVICE
6281414	WMS2	E1000000331	27/08/2004	MOTOR & STARTER SERVICE
8076392	WMS2	E1000000331	01/11/2006	MOTOR & STARTER SERVICE
9928541	WMS2	E1000000331	29/10/2008	MOTOR & STARTER SERVICE
11361489	WMS2	E1000000331	11/03/2010	MOTOR & STARTER SERVICE
4643385	WMS2	M1000000338	02/09/2002	PUMP SERVICE
4643386	WMS2	M1000000337	02/09/2002	PRESSURE GAUGE SERVICE
5462478	WMS2	M1000000338	01/09/2003	PUMP SERVICE
5462479	WMS2	M1000000337	01/09/2003	PRESSURE GAUGE SERVICE
5639355	WMS3	EMMR	16/10/2003	Site no2 WPS
6212401	WMS3	EMMR	24/06/2004	Site No2 WPS Repack No1 HLP
6290435	WMS2	M1000000338	30/08/2004	PUMP SERVICE - CANC Requires shutdown TB
6290436	WMS2	M1000000337	30/08/2004	PRESSURE GAUGE SERVICE -CANC Requires sh
7089107	WMS2	M1000000338	29/08/2005	PUMP SERVICE
7089108	WMS2	M1000000337	29/08/2005	PRESSURE GAUGE SERVICE
8076403	WMS2	M1000000338	01/11/2006	PUMP SERVICE
8076404	WMS2	M1000000337	01/11/2006	PRESSURE GAUGE SERVICE
8699822	WMS3	EMMR	12/06/2007	EMMR-Mechanical Repair
8983239	WMS2	M1000001416	29/10/2007	PUMP BEARING OIL SAMPLE-2Q
8986436	WMS2	M1000000338	31/10/2007	PUMP SERVICE
8986437	WMS2	M1000000337	31/10/2007	PRESSURE GAUGE SERVICE

9928552	WMS2	M1000000338	29/10/2008	PUMP SERVICE
9928553	WMS2	M1000000337	29/10/2008	PRESSURE GAUGE SERVICE-1Y
11356990	WMS2	M1000000338	09/03/2010	PUMP SERVICE
11356991	WMS2	M1000000337	09/03/2010	PRESSURE GAUGE SERVICE-1Y
4643394	WMS2	M1000000811	02/09/2002	COMPRESSOR SERVICE
5462487	WMS2	M1000000811	01/09/2003	COMPRESSOR SERVICE
6290444	WMS2	M1000000811	30/08/2004	COMPRESSOR SERVICE - CANC Requires shutd
7089116	WMS2	M1000000811	29/08/2005	COMPRESSOR SERVICE
8076412	WMS2	M1000000811	01/11/2006	COMPRESSOR SERVICE
8428360	WMS3	EMER	06/03/2007	EMER-Electrical Repair
8680871	WMS3	EME3	05/06/2007	Site No 2 WPS No 2 compressor
8986445	WMS2	M1000000811	31/10/2007	COMPRESSOR SERVICE
9928561	WMS2	M1000000811	29/10/2008	COMPRESSOR SERVICE-1Y
11356997	WMS2	M1000000811	09/03/2010	COMPRESSOR SERVICE-1Y
4638319	WMS2	E1000000331	30/08/2002	MOTOR & STARTER SERVICE
6281415	WMS2	E1000000331	27/08/2004	MOTOR & STARTER SERVICE
8076393	WMS2	E1000000331	01/11/2006	MOTOR & STARTER SERVICE
9928542	WMS2	E1000000331	29/10/2008	MOTOR & STARTER SERVICE
11361490	WMS2	E1000000331	11/03/2010	MOTOR & STARTER SERVICE
4643387	WMS2	M1000000338	02/09/2002	PUMP SERVICE
4643388	WMS2	M1000000337	02/09/2002	PRESSURE GAUGE SERVICE
5462480	WMS2	M1000000338	01/09/2003	PUMP SERVICE
5462481	WMS2	M1000000337	01/09/2003	PRESSURE GAUGE SERVICE
6290437	WMS2	M1000000338	30/08/2004	PUMP SERVICE - CANC Requires shutdown TB
6290438	WMS2	M1000000337	30/08/2004	PRESSURE GAUGE SERVICE - CANC Requires s
7089109	WMS2	M1000000338	29/08/2005	PUMP SERVICE
7089110	WMS2	M1000000337	29/08/2005	PRESSURE GAUGE SERVICE
7533584	WMS3	EMER	14/02/2006	No2 pump motor power management unit
8076405	WMS2	M1000000338	01/11/2006	PUMP SERVICE
8076406	WMS2	M1000000337	01/11/2006	PRESSURE GAUGE SERVICE
8986438	WMS2	M1000000338	31/10/2007	PUMP SERVICE
8986439	WMS2	M1000000337	31/10/2007	PRESSURE GAUGE SERVICE
9928554	WMS2	M1000000338	29/10/2008	PUMP SERVICE
9928555	WMS2	M1000000337	29/10/2008	PRESSURE GAUGE SERVICE-1Y
4643389	WMS2	M1000000338	02/09/2002	PUMP SERVICE
4643390	WMS2	M1000000337	02/09/2002	PRESSURE GAUGE SERVICE
5462482	WMS2	M1000000338	01/09/2003	PUMP SERVICE
5462483	WMS2	M1000000337	01/09/2003	PRESSURE GAUGE SERVICE
6290439	WMS2	M1000000338	30/08/2004	PUMP SERVICE - CANC Requires shutdown TB
6290440	WMS2	M1000000337	30/08/2004	PRESSURE GAUGE SERVICE - CANC Requires s
6504282	WMS3	EMER	05/11/2004	EMER-Electrical Repair
6538750	WMS3	EMER	22/11/2004	EMER-Electrical Repair
6680563	WMS3	EMER	30/01/2005	EMER-Electrical Repair
7089111	WMS2	M1000000338	29/08/2005	PUMP SERVICE
7089112	WMS2	M1000000337	29/08/2005	PRESSURE GAUGE SERVICE
7423802	WMS3	EMER	28/12/2005	investigate fault on No.3 pump, stop but
8076407	WMS2	M1000000338	01/11/2006	PUMP SERVICE
8076408	WMS2	M1000000337	01/11/2006	PRESSURE GAUGE SERVICE
8983240	WMS2	M1000001416	29/10/2007	PUMP BEARING OIL SAMPLE-2Q
8986440	WMS2	M1000000338	31/10/2007	PUMP SERVICE

8986441	WMS2	M1000000337	31/10/2007	PRESSURE GAUGE SERVICE
9928556	WMS2	M1000000338	29/10/2008	PUMP SERVICE
9928557	WMS2	M1000000337	29/10/2008	PRESSURE GAUGE SERVICE-1Y
11356992	WMS2	M1000000338	09/03/2010	PUMP SERVICE
11356993	WMS2	M1000000337	09/03/2010	PRESSURE GAUGE SERVICE-1Y
4643391	WMS2	M1000000338	02/09/2002	PUMP SERVICE
4643392	WMS2	M1000000337	02/09/2002	PRESSURE GAUGE SERVICE
5462484	WMS2	M1000000338	01/09/2003	PUMP SERVICE
5462485	WMS2	M1000000337	01/09/2003	PRESSURE GAUGE SERVICE
5639359	WMS3	EMMR	16/10/2003	Bryton no2 No4 Pump
6290441	WMS2	M1000000338	30/08/2004	PUMP SERVICE - CANC Requires shutdown TB
6290442	WMS2	M1000000337	30/08/2004	PRESSURE GAUGE SERVICE -CANC Requires sh
7089113	WMS2	M1000000338	29/08/2005	PUMP SERVICE
7089114	WMS2	M1000000337	29/08/2005	PRESSURE GAUGE SERVICE
8076409	WMS2	M1000000338	01/11/2006	PUMP SERVICE
8076410	WMS2	M1000000337	01/11/2006	PRESSURE GAUGE SERVICE
8699827	WMS3	EMMR	12/06/2007	EMMR-Mechanical Repair
8983241	WMS2	M1000001416	29/10/2007	PUMP BEARING OIL SAMPLE-2Q
8986442	WMS2	M1000000338	31/10/2007	PUMP SERVICE
8986443	WMS2	M1000000337	31/10/2007	PRESSURE GAUGE SERVICE
9928558	WMS2	M1000000338	29/10/2008	PUMP SERVICE
9928559	WMS2	M1000000337	29/10/2008	PRESSURE GAUGE SERVICE-1Y
10517229	WMS3	EME2	23/04/2009	Site No2 PS - No4 pump flow sensor fa
11356994	WMS2	M1000000338	09/03/2010	PUMP SERVICE
11356995	WMS2	M1000000337	09/03/2010	PRESSURE GAUGE SERVICE-1Y
8942782	WMS2	I1IN0000660	01/11/2007	OUTSTATION BATTERY RE7-12 MAINT (6Y)
4638326	WMS2	E1000000610	30/08/2002	MOTOR & STARTER SERVICE
6281422	WMS2	E1000000610	27/08/2004	MOTOR & STARTER SERVICE
8076400	WMS2	E1000000610	01/11/2006	MOTOR & STARTER SERVICE
9928549	WMS2	E1000000610	29/10/2008	MOTOR & STARTER SERVICE
11361496	WMS2	E1000000610	11/03/2010	MOTOR & STARTER SERVICE
4638327	WMS2	E1000000610	30/08/2002	MOTOR & STARTER SERVICE
6281423	WMS2	E1000000610	27/08/2004	MOTOR & STARTER SERVICE
8076401	WMS2	E1000000610	01/11/2006	MOTOR & STARTER SERVICE
9928550	WMS2	E1000000610	29/10/2008	MOTOR & STARTER SERVICE
11361497	WMS2	E1000000610	11/03/2010	MOTOR & STARTER SERVICE
10490401	WMS2	I1IN0000460	01/05/2009	SUPPLY TO SWILLINGTON FLOW MAIN(12M)DIM)
4643384	WMS2	E1000000316	02/09/2002	TRACE HEATER SERVICE
5462477	WMS2	E1000000316	01/09/2003	TRACE HEATER SERVICE
6290434	WMS2	E1000000316	30/08/2004	TRACE HEATER SERVICE
7089103	WMS2	E1000000316	29/08/2005	TRACE HEATER SERVICE
8076391	WMS2	E1000000316	01/11/2006	TRACE HEATER SERVICE
8986435	WMS2	E1000000316	31/10/2007	TRACE HEATER SERVICE
9928540	WMS2	E1000000316	29/10/2008	TRACE HEATER SERVICE
11356989	WMS2	E1000000316	09/03/2010	TRACE HEATER SERVICE
4923451	WMS3	I1IB	04/12/2002	Coms Fault.Confirm Phil Rushby
4965096	WMS3	I1TB	24/12/2002	Site No2 water pumping station .Pleas
4981861	WMS3		30/12/2002	B-K PUMP CONTROL
5252822	WMS3	I1SB	30/04/2003	Site No2 PLC Pumps not conrolling fro
5304611	WMS3	I1SB	23/05/2003	PLC/Radio link No2 Please repair

5623112	WMS2		07/11/2003	BOWERI UTILITY (CANCEL) on 11.05.2004
6171332	WMS3	I1TB	10/06/2004	Low level res alarm
6381452	WMS2	I1TE0000223	01/10/2004	TELEMETRY LOOP MAINT(12m)
6499549	WMS3	ILIB	02/11/2004	Site No2 WPS Auto Control Problems Pl
6503671	WMS3	I1IB	04/11/2004	Site No2 WPS Auto Control Problems Pl
7173091	WMS2	I1TE0000223	03/10/2005	TELEMETRY LOOP MAINT(12m)
7270214	WMS3	I1TB	18/10/2005	I1TB-ICA Breakdown (Telemetry)
7505375	WMS3	I1SB	02/02/2006	Site no2 PLC Problems
8015710	WMS2	I1TE0000223	02/10/2006	TELEMETRY LOOP MAINT(12m)
8915193	WMS2	I1TE0000223	01/11/2007	TELEMETRY LOOP MAINT(12m)
9614100	WMS3	I1TB	28/05/2008	Site no2 wps Telemetry fault Unable t
9871116	WMS2	I1TE0000223	01/10/2008	TELEMETRY LOOP MAINT(12m)
10272682	WMS2	I1TE0000223	02/02/2009	TELEMETRY LOOP MAINT(12m)THIS WAS DONE O
11273851	WMS2	I1TE0000223	01/02/2010	TELEMETRY LOOP MAINT(12m)
7423834	WMS3	EMER	28/12/2005	EMER-Electrical Repair
11090618	WMS3	EMM4	06/11/2009	Site WPS 2 - Kirkhamgate to Site c
11369701	WMS3	EMM3	12/02/2010	Site replace water damaged actuators
11494455	WMS3	M1FT	12/02/2010	DUMVILLE UTILITY (CANCEL) on 31.03.2010
11501673	WMS3	M1FT	12/02/2010	M1FT-WBU Mech fault 11369701 12.02.2010
11838940	WMS3	M1FT	19/07/2010	Site to Kirkhamgate WPS - please ove
4580553	WMS3		08/07/2002	DAVE JOHNSON GRID TEAM
4583228	WMS3	EMMR	09/07/2002	ANDREW ROBINSON PV INSPECTION
4586232	WMS3	9114	10/07/2002	BOWERI UTILITY (CANCEL) on 22.04.2004
5795578	WMS2	L1000000909	28/01/2004	2Y STATUTORY EXAMINATION
5795580	WMS2	M1000001275	28/01/2004	PREPARE P.V. FOR EXAMINATION
7420650	WMS2	L1000000909	25/01/2006	2Y STATUTORY EXAMINATION
7420652	WMS2	M1000001275	25/01/2006	PREPARE P.V. FOR EXAMINATION
9205898	WMS2	L1000000909	23/01/2008	2Y STATUTORY EXAMINATION
9205900	WMS2	M1000001275	23/01/2008	PREPARE P.V. FOR EXAMINATION
9802311	WMS3	EME1	12/08/2008	EME1 - Electrical Repair upto £100. Plea
11212246	WMS2	L1000000909	20/01/2010	2Y STATUTORY EXAMINATION
11212248	WMS2	M1000001275	20/01/2010	PREPARE P.V. FOR EXAMINATION
4583441	WMS3	EMMR	09/07/2002	ANDREW ROBINSON PV INSPECTIONS
5795579	WMS2	L1000000909	28/01/2004	2Y STATUTORY EXAMINATION
5795581	WMS2	M1000001275	28/01/2004	PREPARE P.V. FOR EXAMINATION
7420651	WMS2	L1000000909	25/01/2006	2Y STATUTORY EXAMINATION
7420653	WMS2	M1000001275	25/01/2006	PREPARE P.V. FOR EXAMINATION
9205899	WMS2	L1000000909	23/01/2008	2Y STATUTORY EXAMINATION
9205901	WMS2	M1000001275	23/01/2008	PREPARE P.V. FOR EXAMINATION
11212247	WMS2	L1000000909	20/01/2010	2Y STATUTORY EXAMINATION
11212249	WMS2	M1000001275	20/01/2010	PREPARE P.V. FOR EXAMINATION
4336846	WMS2		30/04/2002	52W STATUTORY INSPECTION
5173707	WMS2	L1000000408	29/04/2003	52W STATUTORY INSPECTION
5999025	WMS2	L1000000408	27/04/2004	52W STATUTORY INSPECTION
6809359	WMS2	L1000000408	26/04/2005	52W STATUTORY INSPECTION
7727143	WMS2	L1000000408	25/04/2006	52W STATUTORY INSPECTION
8490940	WMS2	L1000000408	24/04/2007	52W STATUTORY INSPECTION
9440274	WMS2	L1000000408	22/04/2008	52W STATUTORY INSPECTION
10422873	WMS2	L1000000408	21/04/2009	52W STATUTORY INSPECTION
10726545	WMS3	BTHM3	30/06/2009	Site Barf WPS_CAT C_Lifting Equipment

11466703	WMS2	L1000000408	20/04/2010	52W STATUTORY INSPECTION
4340377	WMS2		02/05/2002	STATUTORY INSPECTION
4780591	WMS2		31/10/2002	STATUTORY INSPECTION
5179896	WMS2	L1000000782	01/05/2003	STATUTORY INSPECTION
5602446	WMS2	L1000000782	30/10/2003	STATUTORY INSPECTION
6004950	WMS2	L1000000782	29/04/2004	STATUTORY INSPECTION
6424276	WMS2	L1000000782	28/10/2004	STATUTORY INSPECTION
6813826	WMS2	L1000000782	28/04/2005	STATUTORY INSPECTION
7222752	WMS2	L1000000782	27/10/2005	STATUTORY INSPECTION
7727153	WMS2	L1000000782	27/04/2006	STATUTORY INSPECTION
8062442	WMS2	L1000000782	26/10/2006	STATUTORY INSPECTION
8490950	WMS2	L1000000782	26/04/2007	STATUTORY INSPECTION
8970495	WMS2	L1000000782	25/10/2007	STATUTORY INSPECTION
9443481	WMS2		24/04/2008	STATUTORY INSPECTION
9912992	WMS2	L1000000782	23/10/2008	STATUTORY INSPECTION
10428784	WMS2	L1000000782	23/04/2009	STATUTORY INSPECTION
10726544	WMS3	BTHM2	29/06/2009	Site Barff WPS - Cat A - Lifting Equi
10962935	WMS2	L1000000782	22/10/2009	STATUTORY INSPECTION
11471986	WMS2	L1000000782	22/04/2010	STATUTORY INSPECTION
4340376	WMS2		02/05/2002	STATUTORY INSPECTION
4780590	WMS2		31/10/2002	STATUTORY INSPECTION
5179895	WMS2	L1000000782	01/05/2003	STATUTORY INSPECTION
5602445	WMS2	L1000000782	30/10/2003	STATUTORY INSPECTION
6004949	WMS2	L1000000782	29/04/2004	STATUTORY INSPECTION
6424275	WMS2	L1000000782	28/10/2004	STATUTORY INSPECTION
6813825	WMS2	L1000000782	28/04/2005	STATUTORY INSPECTION
7222751	WMS2	L1000000782	27/10/2005	STATUTORY INSPECTION
7727152	WMS2	L1000000782	27/04/2006	STATUTORY INSPECTION
8062441	WMS2	L1000000782	26/10/2006	STATUTORY INSPECTION
8490949	WMS2	L1000000782	26/04/2007	STATUTORY INSPECTION
8970494	WMS2	L1000000782	25/10/2007	STATUTORY INSPECTION
9443480	WMS2		24/04/2008	STATUTORY INSPECTION
9912991	WMS2	L1000000782	23/10/2008	STATUTORY INSPECTION
10428783	WMS2	L1000000782	23/04/2009	STATUTORY INSPECTION
10962934	WMS2	L1000000782	22/10/2009	STATUTORY INSPECTION
11471985	WMS2	L1000000782	22/04/2010	STATUTORY INSPECTION
4340375	WMS2		02/05/2002	STATUTORY INSPECTION
4780589	WMS2		31/10/2002	STATUTORY INSPECTION
5179894	WMS2	L1000000782	01/05/2003	STATUTORY INSPECTION
5602444	WMS2	L1000000782	30/10/2003	STATUTORY INSPECTION
6004948	WMS2	L1000000782	29/04/2004	STATUTORY INSPECTION
6424274	WMS2	L1000000782	28/10/2004	STATUTORY INSPECTION
6813824	WMS2	L1000000782	28/04/2005	STATUTORY INSPECTION
7222750	WMS2	L1000000782	27/10/2005	STATUTORY INSPECTION
7727151	WMS2	L1000000782	27/04/2006	STATUTORY INSPECTION
8062440	WMS2	L1000000782	26/10/2006	STATUTORY INSPECTION
8490948	WMS2	L1000000782	26/04/2007	STATUTORY INSPECTION
8970493	WMS2	L1000000782	25/10/2007	STATUTORY INSPECTION
9443479	WMS2		24/04/2008	STATUTORY INSPECTION
9912990	WMS2	L1000000782	23/10/2008	STATUTORY INSPECTION

10428782	WMS2	L1000000782	23/04/2009	STATUTORY INSPECTION
10962933	WMS2	L1000000782	22/10/2009	STATUTORY INSPECTION
11471984	WMS2	L1000000782	22/04/2010	STATUTORY INSPECTION
4336845	WMS2		30/04/2002	STATUTORY INSPECTION
5173706	WMS2	L1000000349	29/04/2003	STATUTORY INSPECTION
5999024	WMS2	L1000000349	27/04/2004	STATUTORY INSPECTION
6809358	WMS2	L1000000349	26/04/2005	STATUTORY INSPECTION
7727142	WMS2	L1000000349	25/04/2006	STATUTORY INSPECTION
8490939	WMS2	L1000000349	24/04/2007	STATUTORY INSPECTION
9440273	WMS2	L1000000349	22/04/2008	STATUTORY INSPECTION
10422872	WMS2	L1000000349	21/04/2009	STATUTORY INSPECTION
11466702	WMS2	L1000000349	20/04/2010	STATUTORY INSPECTION
4340373	WMS2		02/05/2002	STATUTORY INSPECTION
4780587	WMS2		31/10/2002	STATUTORY INSPECTION
5179892	WMS2	L1000000755	01/05/2003	STATUTORY INSPECTION
5602442	WMS2	L1000000755	30/10/2003	STATUTORY INSPECTION
6004946	WMS2	L1000000755	29/04/2004	STATUTORY INSPECTION
6424272	WMS2	L1000000755	28/10/2004	STATUTORY INSPECTION
6813822	WMS2	L1000000755	28/04/2005	STATUTORY INSPECTION
7222748	WMS2	L1000000755	27/10/2005	STATUTORY INSPECTION
7727149	WMS2	L1000000755	27/04/2006	STATUTORY INSPECTION
8062438	WMS2	L1000000755	26/10/2006	STATUTORY INSPECTION
8490946	WMS2	L1000000755	26/04/2007	STATUTORY INSPECTION
8970491	WMS2	L1000000755	25/10/2007	STATUTORY INSPECTION
9443477	WMS2		24/04/2008	STATUTORY INSPECTION
9912988	WMS2	L1000000755	23/10/2008	STATUTORY INSPECTION
10428780	WMS2	L1000000755	23/04/2009	STATUTORY INSPECTION
10962931	WMS2	L1000000755	22/10/2009	STATUTORY INSPECTION
11471982	WMS2	L1000000755	22/04/2010	STATUTORY INSPECTION
4340374	WMS2		02/05/2002	STATUTORY INSPECTION
4780588	WMS2		31/10/2002	STATUTORY INSPECTION
5179893	WMS2	L1000000755	01/05/2003	STATUTORY INSPECTION
5602443	WMS2	L1000000755	30/10/2003	STATUTORY INSPECTION
6004947	WMS2	L1000000755	29/04/2004	STATUTORY INSPECTION
6424273	WMS2	L1000000755	28/10/2004	STATUTORY INSPECTION
6813823	WMS2	L1000000755	28/04/2005	STATUTORY INSPECTION
7222749	WMS2	L1000000755	27/10/2005	STATUTORY INSPECTION
7727150	WMS2	L1000000755	27/04/2006	STATUTORY INSPECTION
8062439	WMS2	L1000000755	26/10/2006	STATUTORY INSPECTION
8490947	WMS2	L1000000755	26/04/2007	STATUTORY INSPECTION
8970492	WMS2	L1000000755	25/10/2007	STATUTORY INSPECTION
9443478	WMS2		24/04/2008	STATUTORY INSPECTION
9912989	WMS2	L1000000755	23/10/2008	STATUTORY INSPECTION
10428781	WMS2	L1000000755	23/04/2009	STATUTORY INSPECTION
10962932	WMS2	L1000000755	22/10/2009	STATUTORY INSPECTION
11471983	WMS2	L1000000755	22/04/2010	STATUTORY INSPECTION
4340370	WMS2		02/05/2002	STATUTORY INSPECTION
4780584	WMS2		31/10/2002	STATUTORY INSPECTION
5179889	WMS2	L1000000616	01/05/2003	STATUTORY INSPECTION
5602439	WMS2	L1000000616	30/10/2003	STATUTORY INSPECTION

6004943	WMS2	L1000000616	29/04/2004	STATUTORY INSPECTION
6424269	WMS2	L1000000616	28/10/2004	STATUTORY INSPECTION
6813819	WMS2	L1000000616	28/04/2005	STATUTORY INSPECTION
7222745	WMS2	L1000000616	27/10/2005	STATUTORY INSPECTION
7727146	WMS2	L1000000616	27/04/2006	STATUTORY INSPECTION
8062435	WMS2	L1000000616	26/10/2006	STATUTORY INSPECTION
8490943	WMS2	L1000000616	26/04/2007	STATUTORY INSPECTION
8970488	WMS2	L1000000616	25/10/2007	STATUTORY INSPECTION
9443474	WMS2		24/04/2008	STATUTORY INSPECTION
9912985	WMS2	L1000000616	23/10/2008	STATUTORY INSPECTION
10428777	WMS2	L1000000616	23/04/2009	STATUTORY INSPECTION
10962928	WMS2	L1000000616	22/10/2009	STATUTORY INSPECTION
11471979	WMS2	L1000000616	22/04/2010	STATUTORY INSPECTION
4340371	WMS2		02/05/2002	STATUTORY INSPECTION
4780585	WMS2		31/10/2002	STATUTORY INSPECTION
5179890	WMS2	L1000000616	01/05/2003	STATUTORY INSPECTION
5602440	WMS2	L1000000616	30/10/2003	STATUTORY INSPECTION
6004944	WMS2	L1000000616	29/04/2004	STATUTORY INSPECTION
6424270	WMS2	L1000000616	28/10/2004	STATUTORY INSPECTION
6813820	WMS2	L1000000616	28/04/2005	STATUTORY INSPECTION
7222746	WMS2	L1000000616	27/10/2005	STATUTORY INSPECTION
7727147	WMS2	L1000000616	27/04/2006	STATUTORY INSPECTION
8062436	WMS2	L1000000616	26/10/2006	STATUTORY INSPECTION
8490944	WMS2	L1000000616	26/04/2007	STATUTORY INSPECTION
8970489	WMS2	L1000000616	25/10/2007	STATUTORY INSPECTION
9443475	WMS2		24/04/2008	STATUTORY INSPECTION
9912986	WMS2	L1000000616	23/10/2008	STATUTORY INSPECTION
10428778	WMS2	L1000000616	23/04/2009	STATUTORY INSPECTION
10962929	WMS2	L1000000616	22/10/2009	STATUTORY INSPECTION
11471980	WMS2	L1000000616	22/04/2010	STATUTORY INSPECTION
7723617	WMS2	L1000000564	30/04/2006	52 WEEK STATURY INSPECTION
8494254	WMS2	L1000000564	29/04/2007	52 WEEK STATURY INSPECTION
9451082	WMS2	L1000000564	27/04/2008	52 WEEK STATURY INSPECTION
10438218	WMS2	L1000000564	26/04/2009	52 WEEK STATURY INSPECTION
11481324	WMS2	L1000000564	25/04/2010	52 WEEK STATURY INSPECTION

Where : WMS2 = Planned maintenance

WMS3 = Corrective maintenance

Appendix 3-10: Responses to bias assessment

Table: Site 1

Question	Response	Heuristic	Experts
1. Subjective motivation to assessments.	- What I think assessor wants. - To attract priority management attention.	- Bias. - Personal gain.	75% - 75%
2. Group influence.	- Yes. Group conformity	- Group think.	75%
3. Other influences.	- Previous responses. - Work experience	- Anchoring - Availability	- 75% - 100%

Table: Site 2

Question	Response	Heuristic	Experts
1. Subjective motivation to assessments.	- What I think assessor wants. - To attract priority management attention.	- Bias. - Personal gain.	50% - 100%
2. Group influence.	- Yes. Group conformity	- Group think.	50%
3. Other influences.	- Previous responses. - Work experience	- Anchoring - Availability	- 75% - 100%

Table: Site 3

Question	Response	Heuristic	Experts
1. Subjective motivation to assessments.	- What I think assessor wants. - To attract priority management attention.	- Bias. - Personal gain.	50% - 100%
2. Group influence.	- Yes. Group conformity	- Group think.	50%
3. Other influences.	- Previous responses. - Work experience	- Anchoring - Availability	- 75% - 100%

Table: Site 4

Question	Response	Heuristic	Experts
1. Subjective motivation to assessments.	- What I think assessor wants. - To attract priority management attention.	- Bias. - Personal gain.	-75% - 75%
2. Group influence.	- Yes. Group conformity	- Group think.	50%
3. Other influences.	- Previous responses. - Work experience	- Anchoring - Availability	- 50% - 100%

Table: Site 5

Question	Response	Heuristic	Experts
1. Subjective motivation to assessments.	- What I think assessor wants. - To attract priority management attention.	- Bias. - Personal gain.	100% - 50%
2. Group influence.	- Yes. Group conformity	- Group think.	50%
3. Other influences.	- Previous responses. - Work experience	- Anchoring - Availability	- 75% - 100%

Table: Site 6

Question	Response	Heuristic	Experts
1. Subjective motivation to assessments.	- What I think assessor wants. - To attract priority management attention.	- Bias. - Personal gain.	100% - 75%
2. Group influence.	- Yes. Group conformity	- Group think.	75%
3. Other influences.	- Previous responses. - Work experience	- Anchoring - Availability	- 75% - 100%

Table: Site 7

Question	Response	Heuristic	Experts
1. Subjective motivation to assessments.	- What I think assessor wants. - To attract priority management attention.	- Bias. - Personal gain.	50% - 100%
2. Group influence.	- Yes. Group conformity	- Group think.	75%
3. Other influences.	- Previous responses. - Work experience	- Anchoring - Availability	- 100% - 100%

Appendix 3-11: Experts work experience

Table: Site 1

Expert	Expert's work experience (years)
E1	15
E2	11
E3	18
E4	13

Table: Site 2

Expert	Expert's work experience (years)
E1	25
E2	10
E3	1
E4	12

Table: Site 3

Expert	Expert's work experience (years)
E1	7
E2	16
E3	17
E4	10

Table: Site 4

Expert	Expert's work experience (years)
E1	14
E2	8
E3	19
E4	13

Table: Site 5

Expert	Expert's work experience (years)
E1	9
E2	11
E3	16
E4	21

Table: Site 6

Expert	Expert's work experience (years)
E1	15
E2	12
E3	7
E4	11

Table: Site 7

Expert	Expert's work experience (years)
E1	18
E2	12
E3	15
E4	6

Appendix 3-12: Experts' weights against seed variable

Table: Site 1

Experts	Performance	Weights	True value
E1	5.00	0.17	7.33
E2	8.00	0.28	
E3	9.00	0.31	
E4	7.00	0.24	
Total	29.00		

Table: Site 2

Experts	Performance	Weights	True value
E1	5.00	0.17	7.33
E2	8.00	0.28	
E3	9.00	0.31	
E4	7.00	0.24	
Total	29.00		

Table: Site 3

Experts	Performance	Weights	True value
E1	5.00	0.17	7.33
E2	8.00	0.28	
E3	9.00	0.31	
E4	7.00	0.24	
Total	29.00		

Table: Site 4

Experts	Performance	Weights	True value
E1	5.00	0.17	7.33
E2	8.00	0.28	
E3	9.00	0.31	
E4	7.00	0.24	
Total	29.00		

Table: Site 5

Experts	Performance	Weights	True value
E1	5.00	0.17	7.33
E2	8.00	0.28	
E3	9.00	0.31	
E4	7.00	0.24	
Total	29.00		

Table: Site 6

Experts	Performance	Weights	True value
E1	5.00	0.17	7.33
E2	8.00	0.28	
E3	9.00	0.31	
E4	7.00	0.24	
Total	29.00		

Table: Site 7

Experts	Performance	Weights	True value
E1	5.00	0.17	7.33
E2	8.00	0.28	
E3	9.00	0.31	
E4	7.00	0.24	
Total	29.00		

Appendix 3-13: Experts confidence in their asset condition assessments

Table: site 1

Experts	Confidence
E1	70%
E2	85%
E3	75%
E4	70%

Table: site 2

Experts	Confidence
E1	95%
E2	95%
E3	85%
E4	70%

Table: site 3

Experts	Confidence
E1	75%
E2	70%
E3	85%
E4	95%

Table: site 4

Experts	Confidence
E1	90%
E2	90%
E3	95%
E4	85%

Table: site 5

Experts	Confidence
E1	85%
E2	75%
E3	85%
E4	80%

Table: site 6

Experts	Confidence
E1	75%
E2	95%
E3	75%
E4	90%

Table: site 7

Experts	Confidence
E1	95%
E2	90%
E3	80%
E4	70%

APPNDIX 4: MAINTENANCE EFFECTIVENESS

Appendix 4.1: Performance weights for CA and ME assessments.

Table 4-1: Experts' performance weights

Experts Site 1	EO	Weights
E1	9.00	0.32
E2	6.00	0.21
E3	8.00	0.29
E4	5.00	0.18
	28.00	
Site 2		
E1	5.00	0.17
E2	8.00	0.28
E3	9.00	0.31
E4	7.00	0.24
	29.00	
Site 3		
E1	8.00	0.25
E2	9.00	0.28
E3	5.00	0.16
E4	10.00	0.31
	32.00	
Site 4		
E1	7.00	0.33
E2	6.00	0.29
E3	8.00	0.38
E4	21.00	
Site 5		
E1	5.00	0.20
E2	4.00	0.16
E3	7.00	0.28
E4	9.00	0.36
	25.00	
Site 6		

E1	7.00	0.13
E2	12.00	0.23
E3	14.00	0.27
E4	6.00	0.12
	13.00	0.25
	52.00	
Site 7	11.00	0.24
E1	9.00	0.20
E2	13.00	0.29
E3	12.00	0.27
E4	45.00	

Appendix 4-2: Experts' coherence test results

Table: Site 1

Expert	**Probability pump 1 in CG 1**	**Probability pump 1 in CG 1**	**Total**
E1	0.95	0.05	1.00
E2	0.90	0.10	1.00
E3	0.70	0.30	1.00
E4	0.75	0.25	1.00

Table: Site 2

Expert	Probability pump 1 in CG 1	Probability pump 1 in CG 1	Total
E1	0.90	0.10	1.00
E2	0.99	0.01	1.00
E3	0.70	0.15	0.85
E4	0.80	0.20	1.00

Table: Site 3

Expert	Probability pump 1 in CG 1	Probability pump 1 in CG 1	Total
E1	0.90	0.10	1.00
E2	0.80	0.20	1.00
E3	0.80	0.20	1.00
E4	0.70	0.30	1.00

Table: Site 4

Expert	Probability pump 1 in CG 1	Probability pump 1 in CG 1	Total
E1	0.85	0.15	1.00
E2	0.75	0.25	1.00
E3	0.70	0.30	1.00
E4	0.90	0.10	1.00

Table: Site 5

Expert	Probability pump 1 in CG 1	Probability pump 1 in CG 1	Total
E1	0.85	0.15	1.00
E2	0.80	0.20	1.00
E3	0.75	0.25	1.00
E4	0.80	0.20	1.00

Table: Site 6

Expert	Probability pump 1 in CG 1	Probability pump 1 in CG 1	Total
E1	0.70	0.30	1.00
E2	0.90	0.10	1.00
E3	0.70	0.30	1.00
E4	0.80	0.20	1.00

Table: Site 7

Expert	Probability pump 1 in CG 1	Probability pump 1 in CG 1	Total
E1	0.90	0.10	1.00
E2	0.95	0.05	1.00
E3	0.90	0.10	1.00
E4	0.70	0.30	1.00

Appendix 4-3: Experts confidence in their ME assessments, site 1- 7

Table: Site 1

Experts	**Confidence**
E1	90%
E2	75%
E3	90%
E4	85%

Table: Site 2

Experts	**Confidence**
E1	90%
E2	95%
E3	60%
E4	85%

Table: Site 3

Experts	Confidence
E1	90%
E2	75%
E3	80%
E4	75%

Table: Site 4

Experts	Confidence
E1	70%
E2	75%
E3	90%
E4	95%

Table: Site 5

Experts	Confidence
E1	90%
E2	95%
E3	95%
E4	95%

Table: Site 6

Experts	Confidence
E1	80%
E2	95%
E3	90%
E4	80%

Table: Site 7

Experts	Confidence
E1	80%
E2	90%
E3	70%
E4	85%

APPENDIX 5: MAINTENANCE REGIME SELECTION AHP CRITERIA AND ALTERNATIVE MATRICES

APPENDIX 5.1: AHP formulas

Consistency Ratio (CR) = CI / RI

Consistency index (CI) = $(\lambda_{max} - n)/(n-1)$

Where λ_{max} = largest eigenvalue

n = number of columns in the matrix

Random Consistency Index (RI).

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Consistency Ratio smaller or equal to 10% means that the inconsistency is acceptable.

APPENDIX 5.2: CRITERIA AND ALTERNATIVE MATRICES

Site 1

	C1	C2	C3	C4	C5
C1	1.00	0.50	2.00	0.50	2.00
C2	2.00	1.00	1.00	0.50	2.00
C3	0.50	1.00	1.00	3.00	2.00
C4	2.00	2.00	0.33	1.00	0.50
C5	0.50	0.50	2.00	2.00	1.00

Site 2

	C1	C2	C3	C4	C5
C1	1.00	0.25	2.00	0.50	0.17
C2	4.00	1.00	1.00	0.20	0.14
C3	0.33	1.00	1.00	0.11	0.17
C4	2.00	4.00	8.00	1.00	2.00
C5	5.00	0.50	5.00	0.50	1.00

Site 3

	C1	C2	C3	C4	C5
C1	1.00	0.25	4.00	0.50	0.17
C2	4.00	1.00	1.00	0.20	0.14
C3	0.33	1.00	1.00	0.11	0.17
C4	0.50	2.00	0.33	1.00	2.00
C5	3.00	0.50	1.00	0.50	1.00

Site 4

	C1	C2	C3	C4	C5
C1	1.00	0.25	3.00	0.50	0.17
C2	4.00	1.00	1.00	0.20	0.14
C3	0.33	1.00	1.00	0.11	0.17
C4	2.00	0.10	0.33	1.00	2.00
C5	3.00	0.50	0.50	0.50	1.00

Site 5

	C1	C2	C3	C4	C5
C1	1.00	0.25	3.00	0.50	0.17
C2	2.00	1.00	1.00	0.20	0.14
C3	0.33	1.00	1.00	0.11	0.17
C4	2.00	0.33	3.00	1.00	2.00
C5	0.50	0.50	2.00	0.50	1.00

Site 6

	C1	C2	C3	C4	C5
C1	1.00	0.25	3.00	0.50	0.17
C2	4.00	1.00	1.00	0.20	0.14
C3	0.33	1.00	1.00	0.11	0.17
C4	2.00	0.50	2.00	1.00	2.00
C5	1.00	0.50	1.00	0.50	1.00

Site 7

	C1	C2	C3	C4	C5
C1	1.00	0.25	3.00	0.50	0.17
C2	4.00	1.00	1.00	0.20	0.14
C3	0.33	1.00	1.00	0.11	0.17
C4	2.00	0.50	2.00	1.00	2.00
C5	0.33	0.50	1.00	0.50	1.00

Maintenance regime matrices:

Site 1

	PM	RM	CBM
PM	1.00	0.33	5.00
RM	3.00	1.00	7.00
CBM	0.20	0.14	1.00

Site 2

	PM	CM	CBM
PM	1.00	0.50	4.00
CM	2.00	1.00	6.00
CBM	0.25	0.17	1.00

Site 3

	PM	CM	CBM
PM	1.00	0.20	2.00
CM	5.00	1.00	7.00
CBM	0.50	0.14	1.00

Site 4

	PM	CM	CBM
PM	1.00	0.33	4.00
CM	3.00	1.00	8.00
CBM	0.25	0.13	1.00

Site 5

	PM	CM	CBM
PM	1.00	0.25	3.00
CM	4.00	1.00	6.00
CBM	0.33	0.17	1.00

Site 6

	PM	CM	CBM
PM	1.00	0.25	3.00
CM	4.00	1.00	6.00
CBM	0.33	0.17	1.00

Site 7

	PM	CM	CBM
PM	1.00	0.25	3.00
CM	4.00	1.00	6.00
CBM	0.33	0.17	1.00

APPENDIX 5.3 Maintenance regime selection AHP hierarchies and preferences tables

Site 1

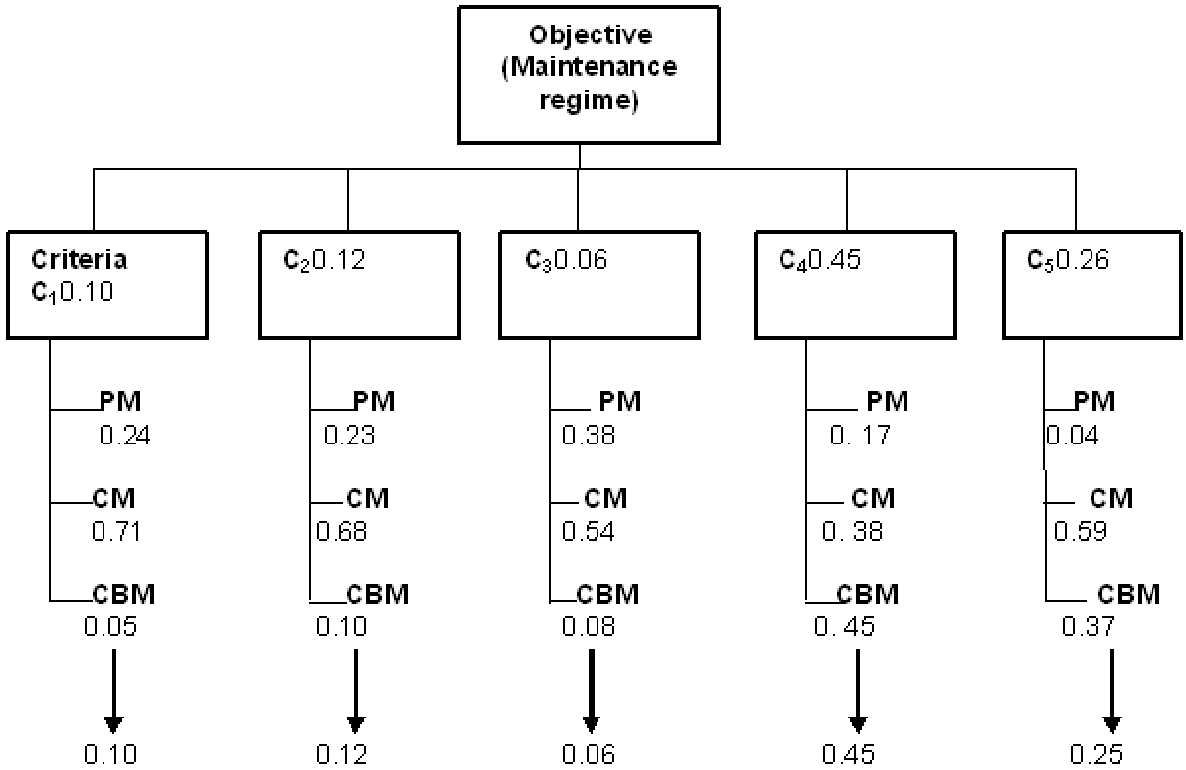

Figure 5-1: Site 1 overall results AHP hierarchy.

Table 5-1: Overall hierarchy results, site 1.

	C1	**C2**	**C3**	**C4**	**C5**
Criteria	0.10	0.12	0.06	0.45	0.26
PM	0.24	0.23	0.38	0.17	0.04
CM	**0.71**	**0.68**	**0.54**	0.38	**0.59**
CBM	0.05	0.1	0.08	**0.45**	0.37
Total	0.103	0.121	0.06	**0.452**	0.259

Site 2

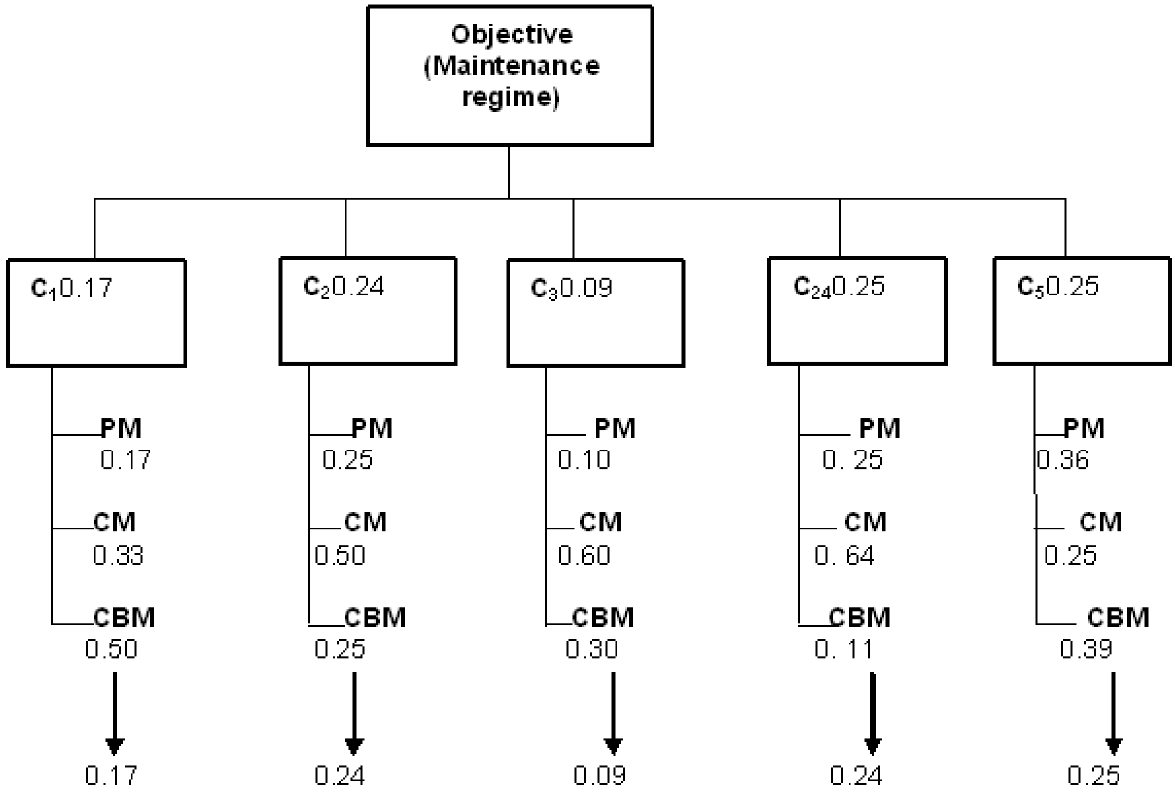

Figure 5-2: Site 2 overall results hierarchy.

Table 5-2: Overall hierarchy results, site 2.

	C1	**C2**	**C3**	**C4**	**C5**
Criteria	0.17	0.24	0.09	0.25	0.25
PM	0.17	0.25	0.10	0.25	0.36
CM	0.33	**0.50**	**0.60**	**0.64**	0.25
CBM	**0.50**	0.25	0.30	0.11	**0.39**
Total	0.173	0.244	0.091	0.248	**0.252**

Site 3

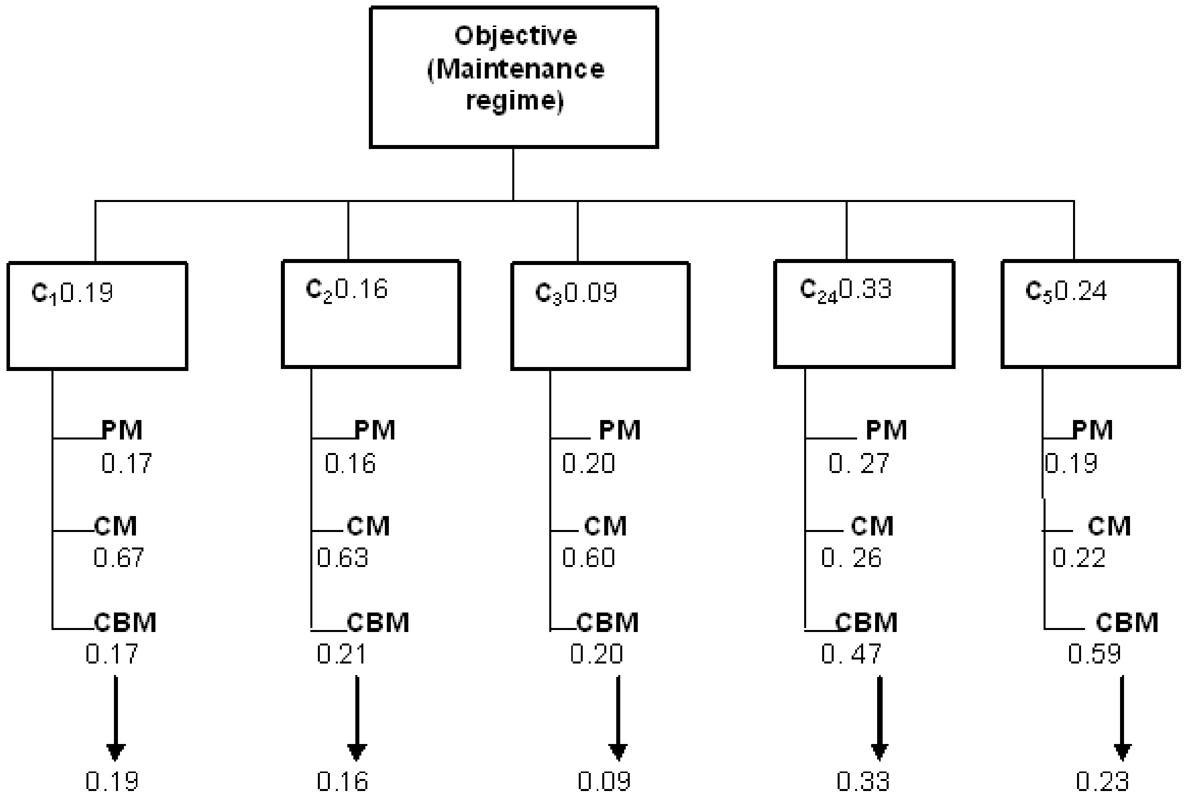

Figure 5-3: Site 3 overall results hierarchy.

Table 5-3: Overall hierarchy results, site 3.

	C1	C2	C3	C4	C5
Criteria	0.19	0.16	0.09	0.33	0.24
PM	0.17	0.16	0.20	0.27	0.19
CM	**0.67**	**0.63**	**0.60**	0.26	0.22
CBM	0.17	0.21	0.20	**0.47**	**0.59**
Total	0.190	0.162	0.091	**0.332**	0.238

Site 4

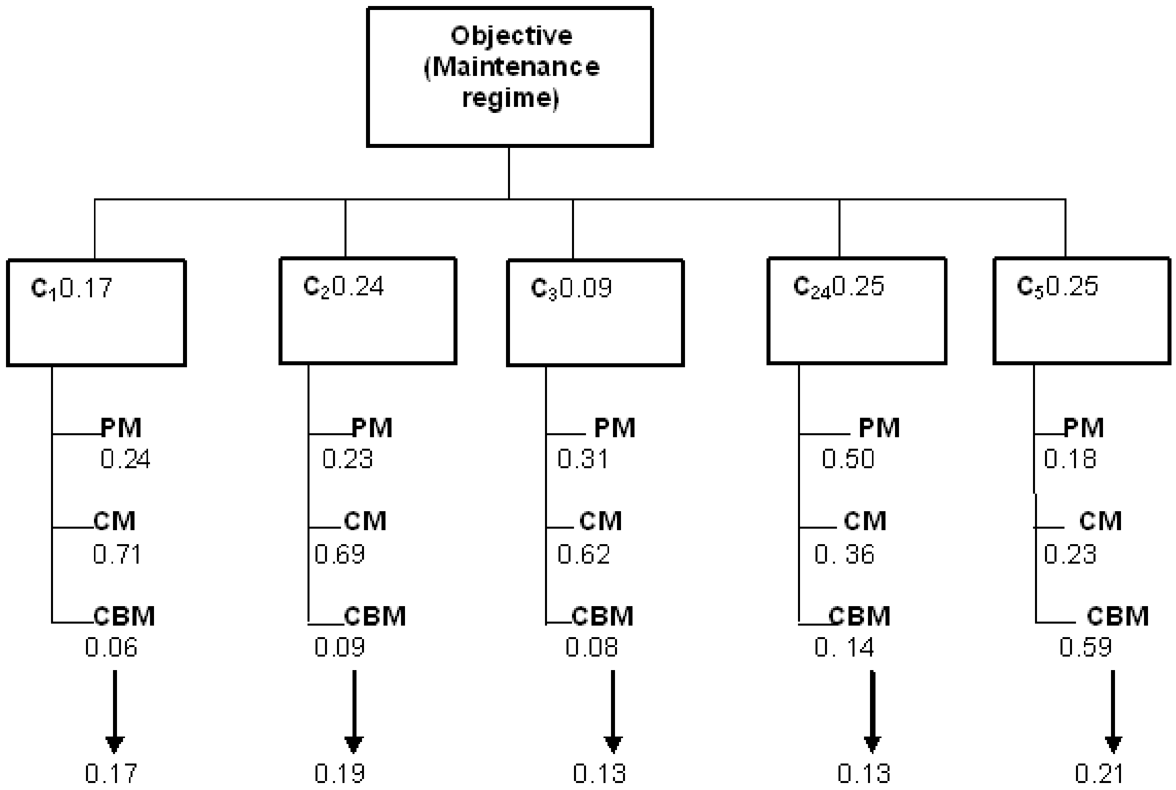

Figure 5-4: Site 4 overall results hierarchy.

Table 5-4: Overall hierarchy results, site 4.

	C1	**C2**	**C3**	**C4**	**C5**
Criteria	0.17	0.19	0.13	0.31	0.20
PM	0.24	0.23	0.31	**0.50**	0.18
CM	**0.71**	**0.69**	**0.62**	0.36	0.23
CBM	0.06	0.09	0.08	0.14	**0.59**
Total	0.170	0.193	0.132	0.137	**0.210**

Site 5

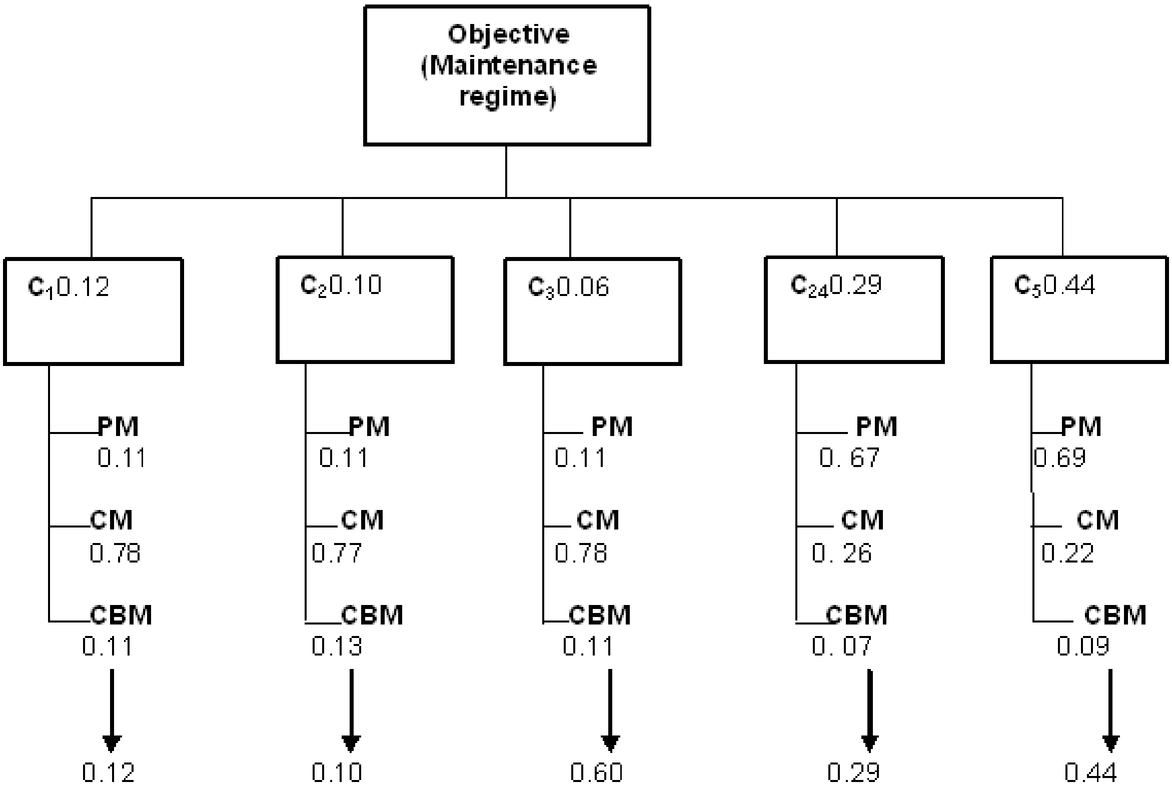

Figure 5-5: Site 5 overall results hierarchy.

Figure 5-5: Overall hierarchy results, site 5.

	C1	**C2**	**C3**	**C4**	**C5**
Criteria	0.12	0.10	0.06	0.29	0.44
PM	0.11	0.11	0.11	**0.67**	**0.69**
CM	**0.78**	**0.77**	**0.78**	0.26	0.22
CBM	0.11	0.13	0.11	0.07	0.09
Total	0.121	0.101	0.060	0.292	**0.441**

Site 6

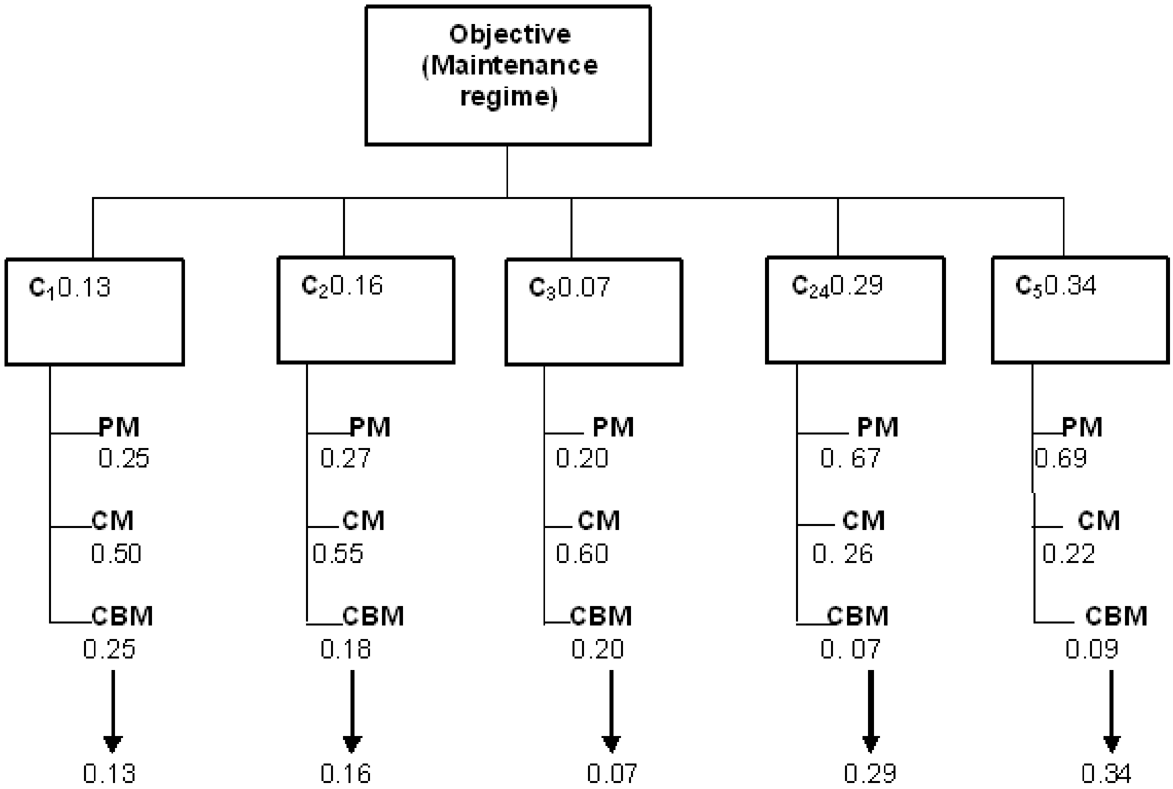

Figure 5-6: Site 6 overall results hierarchy.

Table 5-6: Overall hierarchy results, site 6.

	C1	**C2**	**C3**	**C4**	**C5**
Criteria	0.13	0.16	0.07	0.29	0.34
PM	0.25	0.27	0.20	**0.67**	**0.69**
CM	**0.50**	**0.55**	**0.60**	0.26	0.22
CBM	0.25	0.18	0.20	0.07	0.09
Total	0.131	0.162	0.071	0.290	**0.341**

Site 7

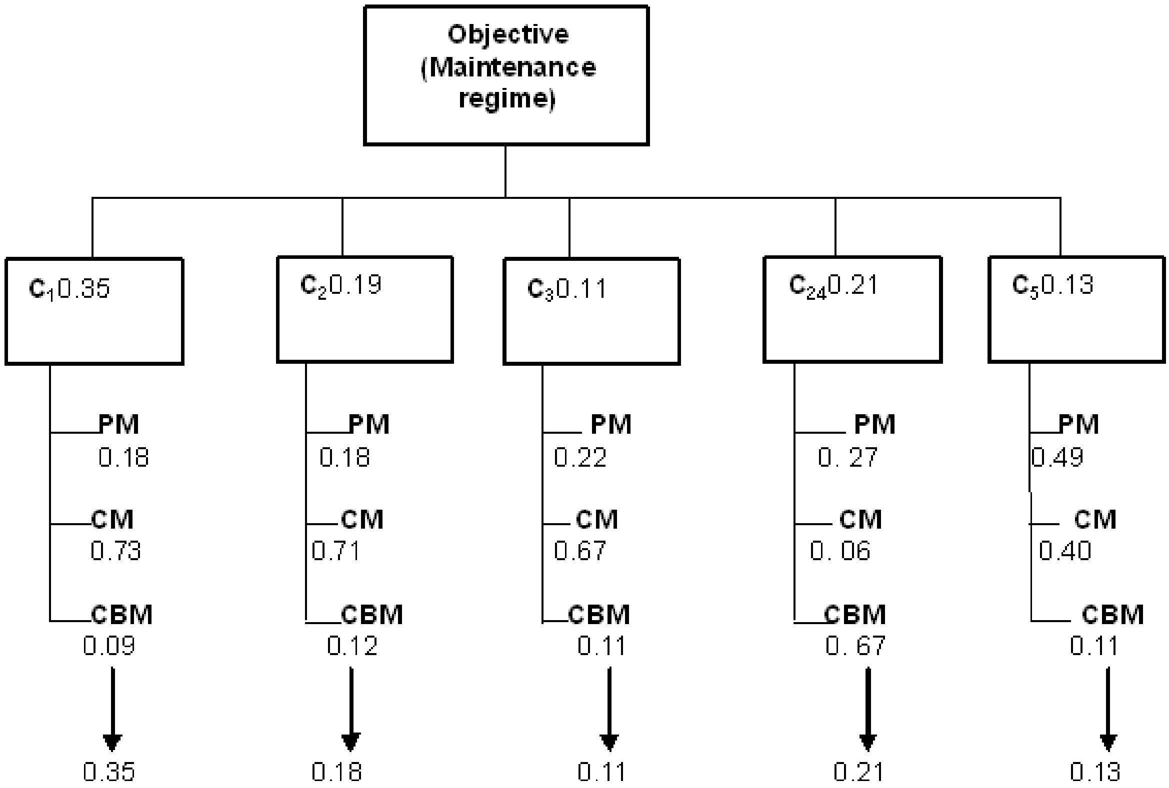

Figure 5-7: Site 7 overall results hierarchy.

Table 5-7: Overall hierarchy results, site 7.

	C1	C2	C3	C4	C5
Criteria	0.35	0.19	0.11	0.21	0.13
PM	0.18	0.18	0.22	0.27	**0.49**
CM	**0.73**	**0.71**	**0.67**	0.06	0.40
CBM	0.09	0.12	0.11	**0.67**	0.11
Total	0.352	0.189	0.110	**0.208**	0.133

Combined sites

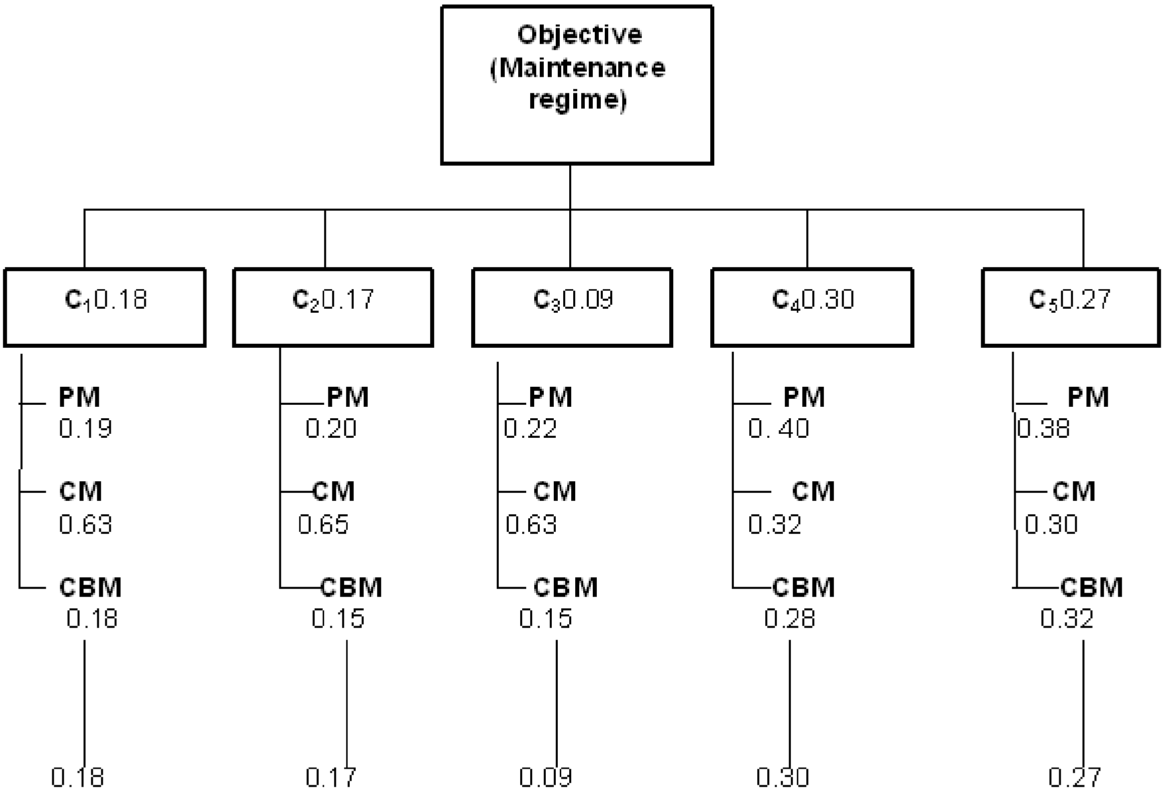

Figure 5-8: Sites 1 - 7 overall combined results.

APPENDIX 5-4: Eigen values for maintenance regime selection

Table 5-8: Eigen values, site 1

Criteria	Eigenvalues	Normalised preference scores	Criteria preference
C1	0.10	0.45	C4
C2	0.12	0.26	C5
C3	0.07	0.12	C2
C4	0.45	0.10	C1
C5	0.26	0.07	C3

Table 5-9: Eigen values, site 2

Criteria	Eigenvalues	Normalised preference scores	Criteria preference
C1	0.17	0.26	C5
C2	0.24	0.25	C4
C3	0.09	0.24	C2
C4	0.25	0.17	C1
C5	0.25	0.09	C3

Table 5-10: Eigen values, site 3

Criteria	Eigenvalues	Normalised preference scores	Criteria preference
C1	0.19	0.33	C5
C2	0.16	0.24	C5
C3	0.09	0.19	C1
C4	0.33	0.16	C2
C5	0.24	0.09	C3

Table 5-11: Eigen values, site 4

Criteria	Eigenvalues	Normalised preference scores	Criteria preference
C1	0.17	0.31	C4
C2	0.19	0.20	C5
C3	0.13	0.19	C2
C4	0.31	0.17	C1
C5	0.20	0.13	C3

Table 5-12: Eigen values, site 5

Criteria	Eigenvalues	Normalised preference scores	Criteria preference
C1	0.10	0.44	C5
C2	0.12	0.29	C4
C3	0.06	0.12	C2
C4	0.29	0.10	C1
C5	0.44	0.06	C3

Table 5-13: Eigen values, site 6

Criteria	Eigenvalues	Normalised preference scores	Criteria preference
C1	0.13	0.34	C5
C2	0.16	0.29	C4
C3	0.07	0.16	C2
C4	0.29	0.13	C1
C5	0.34	0.07	C3

Table 5-14: Eigen values, site 7

Criteria	Eigenvalues	Normalised preference scores	Criteria preference
C1	0.35	0.35	C1
C2	0.19	0.21	C4
C3	0.11	0.19	C2
C4	0.21	0.13	C5
C5	0.13	0.11	C3