CRANFIELD UNIVERSITY

CRANFIELD HEALTH

Final Project – Individual Thesis

Academic Year 2008-2009

James Ingham

An examination of Knowledge Acquisition (KA) requirements and practices within the gas turbine energy industry – does effective KA impact reliability and availability?

Supervisor: K Sehdev

September 2009

This thesis is submitted in partial fulfillment of the requirements for the degree of
Master of Science.

Abstract

In order to manage a modern day gas turbine plant, an operator must collect and disseminate a wide range of knowledge, for decision making and for reporting to high level management. Often, an operator must also justify its decisions to a parent company. A key element of power plant management is the use of maintenance strategy, in order to maintain its equipment in an adequate condition so as to reliably produce power when required. This thesis seeks to explore and define the links between effective knowledge management and effective power plant management, which are explored to produce a replicable best practice methodology for a human capital and technology driven KM system in order to enhance operator profitability.

Acknowledgements

I would like to thank my project supervisor Kamal Sehdev and director of education Dr Charles Wainwright for their academic support. I would also like to thank Clare Humphries for her assistance in obtaining literature. Finally I would like to thank the participating power plants for their input and support.

List of Abbreviations

CCGT – Combined Cycle Gas Turbine
DCS – Distributed Control System
EOC – Equivalent Operating Cycles
EOH – Equivalent Operating Hours
FAA – Federal Aviation Authority
KA – Knowledge Acquisition
KBS – Knowledge Based Systems
MSG – Maintenance Steering Group
MTBF – Mean Time Between Failures
MTTR – Mean Time To Repair
PM – Preventive Maintenance
PdM – Predictive Maintenance
RCM – Reliability Centred Maintenance
RR – Running Reliability
SLA – Service Level Agreement
SR – Starting Reliability

List of Contents

List of Figures

Chapter 1: Introduction

I) Background

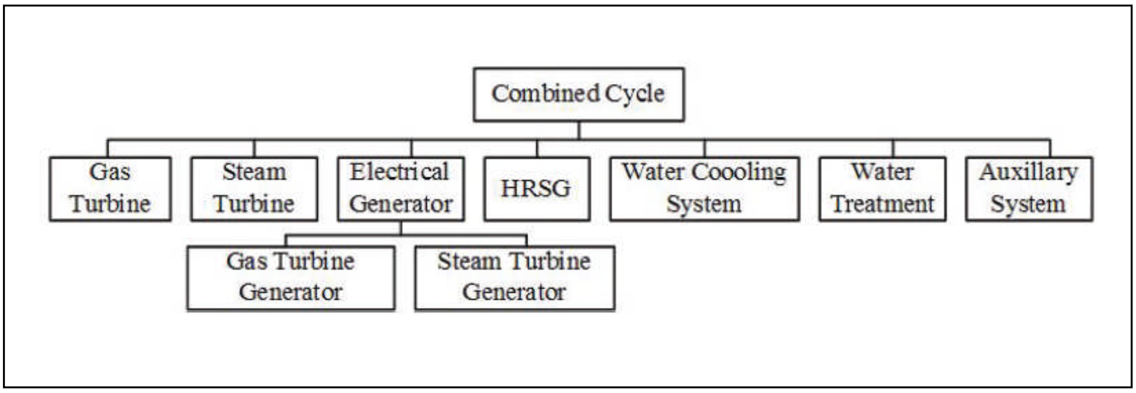
“The gas turbine… converts heat into work by a cycle using a gas as the working medium, the processes being compression, addition of heat and expansion and requiring continuous flow of the gas during these changes of state” (Shepherd, 1948). The complexity of single or combined cycle gas turbine power plants is such that there is an extensive set of processes required for effective maintenance and management. This complexity has now become so great that the overall management system could be considered as Knowledge Based Systems (herein KBS), which can also utilise extensive data modelling to support decision making. Knowledge Management “…is the process of capturing, and making use of a firm’s collective expertise anywhere in the business – on paper, in documents, in databases (called explicit knowledge), or in people’s heads (called *tacit* knowledge).” (Awad and Ghaziri, 2004). Given the requirements for effective use of the knowledge that is captured and utilised, the need arises for detailed examination of plant operator practices by knowledge engineers, who can apply recognised KM theories into the practical context considered.

“For knowledge to be managed it must first of all be captured or acquired in some useful form, e.g. stored in an ontology.” (Brewster et al, 2001). The levels of data captured on a regular basis can thus be treated as a form of Knowledge Acquisition (herein KA). If KBS can be used to drive decision making, then its output (decision making) is only as strong as the inputs, exacerbating the need for effective KA. The research seeks to address whether the application of conventional KA techniques into power plant management would facilitate better turbine performance. This would be achieved through their impact on decision making in terms of maintenance policy deployment. “The maintenance strategy, *if it is to make its maximum contribution to profitability*, must take account of more than just the technical characteristics of the hardware, of the plant itself.” (Kelly, 1997)

Gas turbine power plants provide power to the grid in one of two ways. Base Load plants provide power on a continuous basis, while Peaking or Two-Shifting plants provide power as requested by the dispatch authority, and are paid a premium for doing so. For both of these types of plant, the availability and reliability of the turbine is key to commercial profitability.

In order to maintain reliability and availability, an operator must understand the life cycle of its critical components, as well as the maintenance requirements in order to minimise business interruption.

Figure 1: Example of a CCGT Functional Tree (Carazas and de Sousa, 2009)



There are three types of data that an operator will collect as a matter of course. Operational data will record the running time, plant reserves and shutdowns. Event data will record system trips and forced shutdowns. System trips have a high impact on critical component life, while forced shutdowns have less impact. Counter readings from the various components are also recorded on a regular basis.

“A significant factor that negatively impacts a plant’s operation and maintenance costs, productivity or availability, and possibly operational safety is unexpected failures – especially those which cause a full or partial plant outage” (Smith, 1992)

II) Aims and Objectives

The overall aim is to examine the extent to which best practice KA can influence maintenance strategies with the aim of increasing reliability and availability.

The secondary aims of the thesis are as follows:

- To examine the KA requirements of gas turbine power plants.

- To examine the different KA practices among operators in the collection of operational, event and counter data.
- To understand the concepts of reliability and availability.
- To examine the effectiveness of differing maintenance programmes in increasing reliability and availability.
- To examine the potential for KA in influencing the type of maintenance programme deployed.

The objectives of the thesis are as follows:

- To examine the currently deployed KA practices.
- To present a replicable best practice methodology for future knowledge acquisition.
- To utilise the KA and associated analysis to identify the most effective plant maintenance programmes.
- To identify tangible or intangible benefits of a best practice methodology in light of plant reliability and availability.

III) Chapter Structure

In chapter two, justifications for the selected research methodology are presented, drawing on research methods literature to present a framework for the study. This includes detailed breakdowns of the inductive and deductive research elements.

In chapter three, a review of literature relevant to knowledge management and associated fields such as KA is presented. This includes an examination of the differences between knowledge management systems and expert systems in light of requirements in power plant operation.

In chapter four, a review of availability and reliability as well of its operational implications for plant operators is discussed. The links between these concepts and deployed maintenance strategies are also explored, drawing on subject literature from engineering.

In chapter five, the primary evidence from the case study will be presented. This will include the review and analysis of the qualitative and quantitative primary data. Statistical inference will be drawn upon and applied to concepts identified within literature from previous chapters. A replicable, best practice methodology will be devised with the aim of improving reliability and availability through effective maintenance strategy deployment.

The final chapter will draw upon both primary and secondary evidence to provide a full set of conclusions and recommendations. Suggestions will be made as to further studies in line with the research findings.

Chapter 2: Research Methodology

I) Research Setting

The research will be undertaken through two different perspectives. First, a deductive investigation will be conducted, employing a review of secondary academic and market literature. This will facilitate understanding of the research area and identify previously undertaken work. The literature content will be combined with the author's own thoughts to offer an in-depth analysis of the issues pertinent to the research.

Secondly, an inductive investigation will be undertaken, using primary research to consider the application and understanding of the relevant issues within industrial context. This will take the form of systematic interviews with a range of power plants using an assisted questionnaire to capture the processes currently deployed and offer analysis as to the best and worst practice within the industry. The deductive and inductive investigation will lead to the formulation of a replicable best practice methodology for the industry in order to enhance data capture and utilization and improve associated knowledge management processes – in particular the design and deployment of maintenance strategy.

The research will be undertaken over a period of 18 weeks, with completion initially scheduled for 7th September 2009. The research will incur minimal budget costs, and is performed under the supervision of Kamal Sehdev, Course Director MSc Organisational Knowledge, Cranfield School of Health.

II) Ethical Considerations

In undertaking primary research, it is important to adhere to ethical principles in order to maintain the integrity of the study. Bryman and Bell (2007) propose a set of guidelines in order to address the various ethical issues that could potentially arise while performing primary research.

- The dignity of research participants should be respected at all times. This is especially important when undertaking research involving human subjects.

- Where sensitive data is used, the outputs should be anonymised in order to protect the privacy of the participants.
- The express consent of the selected participants should also be obtained, subject to them being fully informed as to the means and proposed use of the research data. This means honesty and transparency are key during research communications, without any false reporting of the data in analysis and dissemination.
- The confidentiality of the research data must be ensured, complying with relevant internal and external legislation.

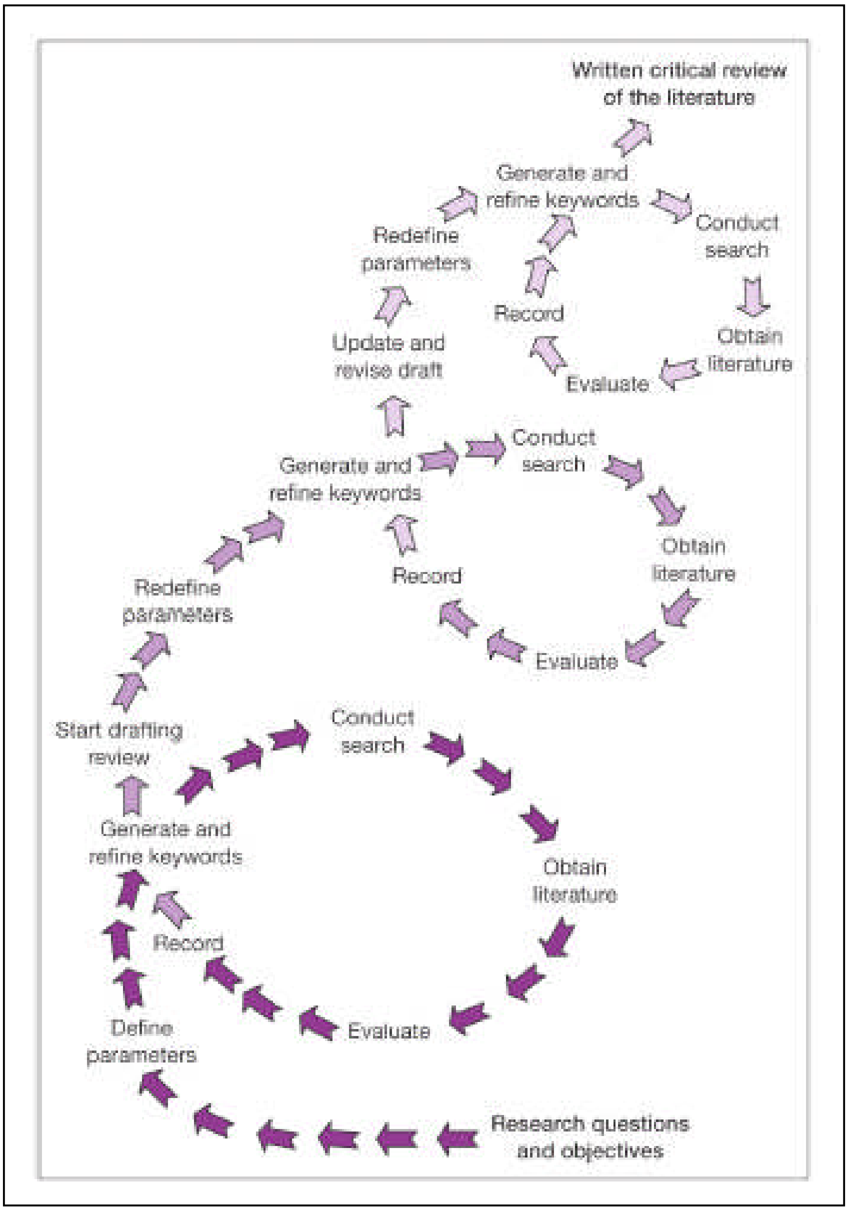
The research process must also adhere to the health and safety and site regulations of any interviewed operators. In studying power plants as part of inductive investigation, the anonymity of operator findings must be protected in order to protect commercial confidence.

III) Literature Review

The ability to critically review literature is essential in writing academically sound research. The review of literature allows the author to understand the scope and breadth of previously undertaken research and identify the precise study boundaries. “There is little point in reinventing the wheel… the work that you do is not done in a vacuum, but builds on the ideas of other people who have studied the field before you.” (Jankowicz, 2005)

Saunders et al (2007) proposes a framework that involves the generation and refinement of key words and phrases within the subject field (Figure 2). The constant regeneration of these defining parameters results in the author reviewing the widest scope of literature available. Up to a point, the more literature reviewed, the stronger the academic robustness of the literature review. The regeneration of parameters is performed through the reading of literature aligned to the authors own deductions, theories and thoughts as the review is conducted.

Figure 2: The Literature Review Process (Saunders et al, 2007)



As a starting point for the critical review, the framework of Easterby-Smith and Thorpe (2008) was adopted. Their framework proposes the initial generation of research strands according to the following questions:

- What research has already been undertaken in the subject area?
- What established peer reviewed theories and concepts exist in the subject area?
- How has research previously been conducted?

- Are there any areas of debate or controversy within the subject area?
- Are the elements of inconsistency in previous research findings?
- Are there unaddressed research strands within the subject area?

Through initial review conducted through the project proposal the following research strands have been identified for critical literature review:

- Maintenance Typologies
- Inspection Scheduling
- Gas Turbine Reliability and Availability
- Failure Mode Effect Analysis (FMEA)
- KA in Engineering

These were then refined as per the recommendations of Saunders et al (2007).

The output of the literature review will be incorporated into chapters three and four, which will dovetail the literature review with the author’s own thoughts and deductions in the subject areas of Knowledge Management, and Plant Reliability, Availability and Maintenance respectively.

IV) Primary Investigation: Participant Selection and Characteristics

When undertaking qualitative research, participant selection should be undertaken on qualitative assessment based on the advice of industry stakeholders and academic advice. However, when undertaking quantitative research, participant selection is more effective when based on random selection or cross referencing. On this basis, selection for the research proposal was done on the advice of academic contacts and advice from the industry sponsor. Those power plants that had worked with academia and/or the research sponsor were contacted by telephoning the relevant personnel. Those that had not were contacted by mail, utilising an operator engagement letter.

The defining factor in the research was not to obtain a broad spectrum of operators, but to instead obtain interviews with those operators that expressed an interest in the research. This is because:

- Those that express an interest in KM within the industry are those that are utilizing KM in one way or another through the deployment of the ERP, DSC and Data Management Systems.
- Those firms are also aware of the complexity of KM within a large scale industrial application and are willing to participate in the study as they have seen at first hand the effect of poor KM on organisational operations.
- Those that do not respond will have little or no interest in KM either because they do not understand it, or the operations are efficient enough based on IS principles. Either type of participant may be less forthcoming or open to KM during the interview process.

In total, ten potential participants were contacted.

V) Primary Investigative Procedure

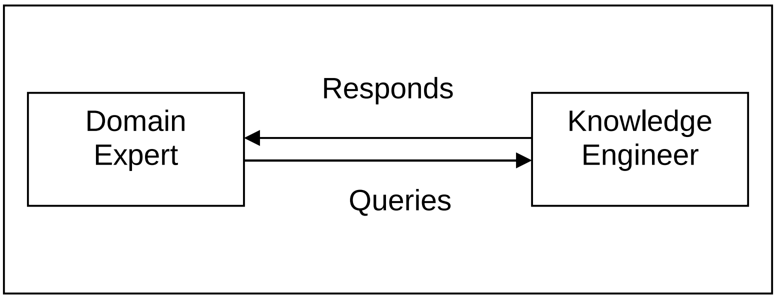
The research will utilise an assisted questionnaire which will be completed onsite with production support. The results of the questionnaires will be analysed in order to identify the best and worst practice amongst operators, although the names of the operators interviewed will be anonymised. The output from the primary research will be used to develop the replicable methodology. Finally, the thesis will draw on the literature review and primary research in order to address the research question.

VI) Interview Structure

It must be noted that the use of the term “knowledge acquisition” in literature refers to interview typologies and is different to KA for KBS, as discussed in the introduction and subsequent chapters.

“The key to the knowledge acquisition process is the interaction between the knowledge engineer and the expert.” (Pigford and Baur, 1990). The use of semi-structured interviewing is based around a series of queries and responses between the knowledge engineer and the selected domain expert. The knowledge engineer in this instance is the research author. The domain expert consists of the production support at the participating power plant. In some instances, there may be a further domain expert present in interview where crossover exists between the designated individual roles within the organization.

Figure 3: The Knowledge Acquisition Process (Adapted from Pigford and Baur, 1990)



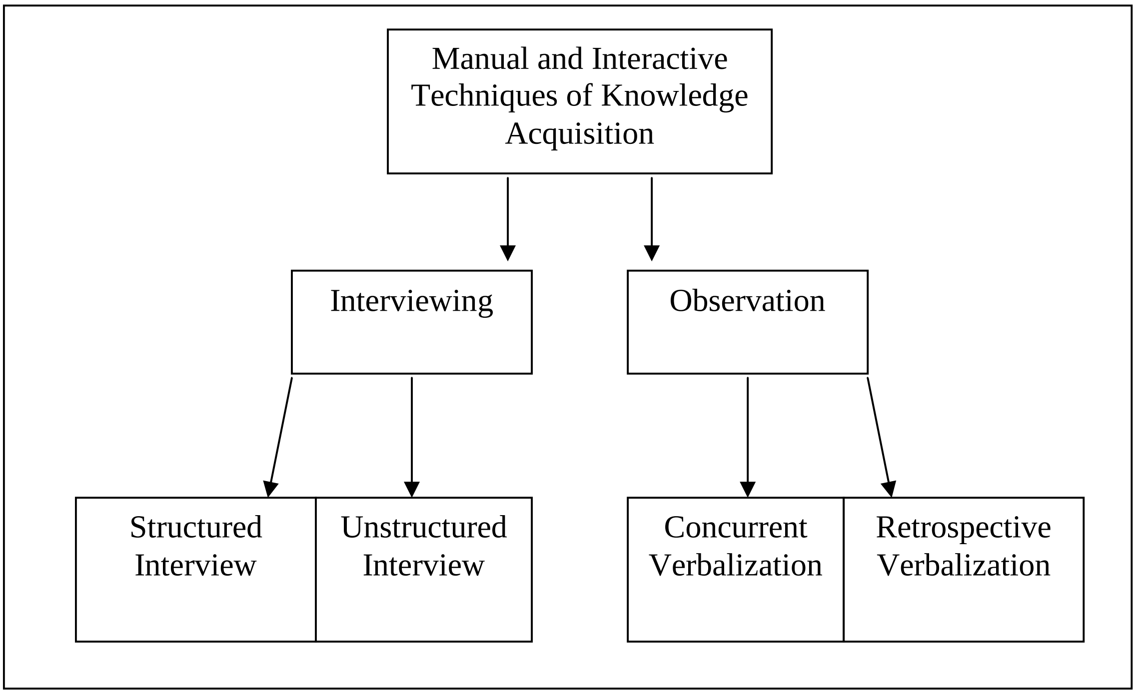
Academic literature provides a set of guidelines as to the preparation for the interview by the knowledge engineer: "Prior to the initial session with the expert, the knowledge engineer must gain a basic understanding of the expert's area of domain and an understanding of the problem(s) to be solved. It is often difficult for an expert to express thoughts pertinent to subject domain. Because an expert has deep knowledge about the subject, as he or she talks assumptions are made about the qualifications of the listener (knowledge engineer). If the listener is unprepared for the subject, what the expert says is likely to be meaningless, causing frustration during the communication process and possibly resulting in a waste of time as each tries to understand the other." (Pigford and Baur, 1990).

The preparation by the knowledge engineer prior to the research is critical if substantial qualitative observations are to be obtained. "In a typical interviewing session, the knowledge engineer spends most of the time preparing for the session, then analyzing the session, and the least time actually conducting the session" (Grzymala-Busse, 1991).

Creating the structure for the interview requires substantial preparation through:

- The author’s familiarization with the subject area and related market and academic literature. This includes discussions with contacts within industry as to the type of data that is collected as standard across generating units.
- The examination of different interview structures and questionnaire design.

Figure 4: Techniques of Knowledge Acquisition (Adapted from Grzymala-Busse, 1991)



The chosen interview structure combines elements of structured and unstructured interview techniques. This utilises a questionnaire to provide the general script of the interview. While the completion of the questionnaire is essential to complete information capture it also provides the groundwork to facilitate discussion around some of the relationships between the KA at plant level and the deployed maintenance strategy.

In conducting either a structured or unstructured interview, there are four main types of questions that the knowledge engineer may use to query the domain expert. These are:

- Direct – questions that are used to obtain specific information pertinent to the issue being discussed.

- Indirect – questions that are used to capture general information on the concepts discussed or the processes involved in organisational function.
- Probe – questions that are used to “drill down” into a topic area and understand the crux of the problem or issue under discussion.
- Prompts – questions that are used to direct the interview or change the focus from one topic area to another.

When undertaking interviews as part of a primary investigation it is essential to obtain the highest quality data possible. Without high quality data, the findings and recommendations based on the analysis of the undertaken interview data may lack the robustness required for peer review. There are a number of imperfections that can exist during the capture process. These are:

- Incomplete information exists when one or more of the data fields have missing values. This may mean that gaps exist in the following analysis, meaning that the conclusions may lack robustness.
- Superficial information exists where a data field is populated with very high level (low detail) information. Without a certain level of depth, the usefulness of qualitative information is dramatically reduced.
- Imprecise information exists where data is collected in the wrong format, or using the wrong parameters, which may cause problems in analysis.
- Inconsistent information exists where data fields are populated with a number of different formats, or at a number of different levels of detail.
- Incorrect information exists when a response during data collection is recorded incorrectly. Alternatively the record may be correct but the participant may have intentionally or unintentionally have given an incorrect response.
- Unstructured information exists when responses are collected without any parameter being assigned, which can cause problems in analysis of quantitative data.

Information imperfections can be avoided by comprehensive checking and validation. Checking can be performed on a qualitative or quantitative basis, depending on the nature of the research investigation. Within the investigation, checking and validation is performed as part of the interview process. The approach used means that the researcher is in a position to assess the accuracy of responses during interview, and can perform validation through probing questions. The relationships developed with the participants also allows for further contact post interview in order to assess the accuracy of the plant description. The further contact is also essential in order to pre-submit the plant description document to the participant to check that the participant finds the level of anonymisation acceptable.

VII) Data Capture and Analysis: A Combined Quantitative and Qualitative Approach

“We distinguish four main ways of gathering quantitative data: interviews, questionnaires, tests/measures and observation. Information can also be gathered from archives and data banks…” (Easterby-Smith et al, 2008). The devised primary investigative procedure uses two of the quantitative data capture methods defined; interview and questionnaire. This is due to the combined nature of the investigative procedure in that the questionnaire is completed during interview. This should in theory increase quality and reliability captured because; a) the researcher can contextualize the answers given and b) because any required validation can be obtained in a timely and effective fashion and without the need for a traditional questionnaire follow-up validation. This means the quantitative data captured can be relied upon and that any statistical anomalies will exist due only to sample size, eliminating the need for calculation of error margin to take into account inaccurate questionnaire responses. The quantitative data captured is in the form of multiple choice responses, either to yes/no queries or through the coding of a number of standard responses in a particular parameter.

The primary investigative technique employed mainly provides opportunities for qualitative information capture. This is performed through a) the scripting of the questionnaire and b) the further discussions that may take place based on a particular query response. In this example the level of detail required for the qualitative data is high, and as such the following principles were applied when discussing counter readings, operational data and forced outage data;

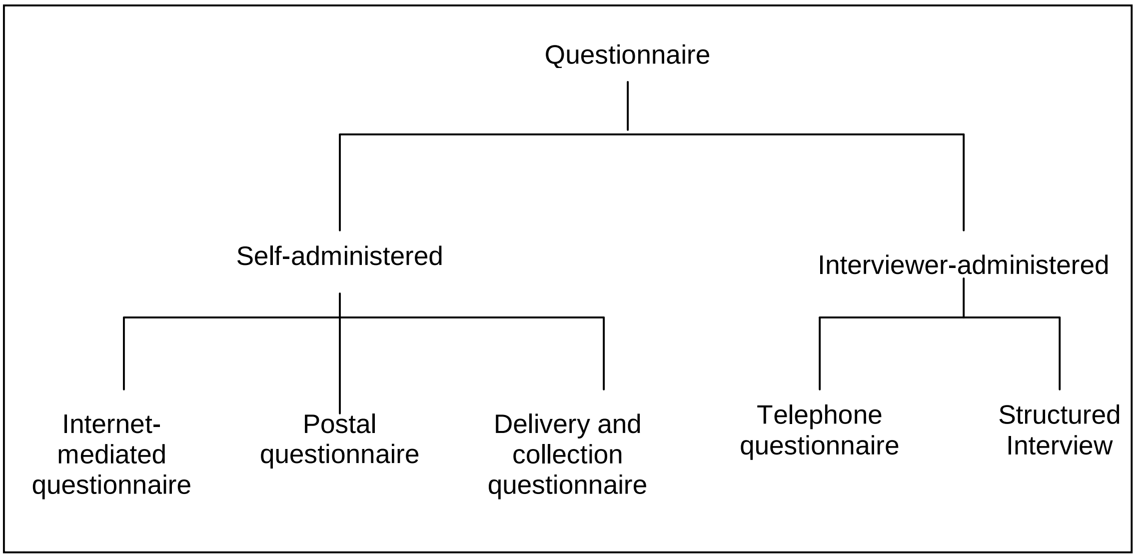
- WHAT is collected?
- HOW is the data collected?
- WHY is it collected?
- WHO collects the data?
- WHERE is it reported to?

By following these guidelines, it is possible to ascertain the different data and/or knowledge flows that exist within the organization, the origins of the different data/knowledge, the number of handoffs in reporting and the way in which reporting mechanisms function. The aim of this is to be able to base the replicable methodology on the final destination for the source data, via reporting, to its eventual use in different decision making functions.

There are differing views within academia as to the definition of a questionnaire. Some refer the term to activities where questions are answered and recorded in a preset order. Others define a questionnaire as any situation where an interview is administered in a structured fashion. For the purpose of the research, the following definition is utilised:

Saunders et al (2007) state six factors that must be considered in questionnaire design:
- The characteristics of the selected participants.
- The importance of obtaining responses from a specific member of the organisation.
- The importance of data quality and minimising respondent bias.
- The required sample size and predictions as the percentage of respondents.
- The range of questions required to obtain useful responses.
- The number of questions required to obtain useful responses.

Figure 5: Types of questionnaire (Adapted from Saunders et al, 2007)



Saunders et al (2007) are of the opinion that a questionnaire per se is predominantly used as represented in Figure 5 (above). The devised questionnaire can be found in Appendix 1, and draws on many of the factors discussed. The questionnaire features seven different sections:

1. The first section is for collecting general plant information, offering multiple choice boxes to aid in the timely collection of data such as the plant configuration, operating mode further contextual information.
2. The second section is to collect information as to the type of maintenance strategy deployed, focussing on the influencing factors and supporting data/knowledge requirements.
3. The third section focuses on the collection of event data, and aims to assess how event data is captured, analysed and reported. Also collected is whether a plant performs engineering ratio calculations.
4. The fourth section focuses on the collection of counter readings, and aims to assess if reliability and availability calculations are important and included in the collection and reporting mechanisms.

5. The fifth section focuses on the collection of operational data, assessing how it is captured and reported (alongside counter readings), and how regulatory and legislative reporting is performed.
6. The penultimate section focuses on the use of benchmarking, and aims to capture how a power plant performs benchmarking and its thoughts as to the advantages and disadvantages.
7. The final section of the questionnaire is included to identify any further data collection that could be performed to facilitate better decision making in any of the above areas discussed.

VIII) Limitations of the Research Enquiry

When proposing a primary investigative technique, it is pertinent to identify and minimize the limitations of the research enquiry. Bryman and Bell (2007) identify the impact of Ethnography, which occurs during primary research settings and leads the researcher to become immersed in the research group. While this benefits the understanding of the interview data (by assigning significance levels and context to responses) it also leads to limitations. When engaged with domain expert(s), the knowledge engineer can become emotionally involved with the issues discussed – leading to interviewer bias based on the details of the particular case study. This risk was minimized through prior research into the domain, leading to a fundamental understanding of the basic functioning of power plants. This meant that the researcher’s observations were not based solely on the plight of the particular domain expert, but were linked to many of the generic issues that exist within the research setting.

The number of participating power plants and the low sample size is the main limitation of the research enquiry. When undertaking primary research, the key aim is the sampling of as many participants as is feasible to be able to produce quantifiable recommendations. However, this research enquiry seeks not to address the relationship between two measurables, but to explore the relationship between two intangibles (data flows and maintenance strategies) and ascertain the use of one intangible to enhance the application of another. While there would be a benefit to the research enquiry by engaging with more power plants, the case by case study of four power plants allows for detailed comparison. This comparison is essential when attempting to apply the two intangibles into a further intangible – of a replicable best practice methodology.

IX) Risk Assessment

The risk assessment for the study and proposed methodology can be found in Appendix 2 and represents the nature and impact of associated risks. The overall risk for the study is deemed to be Low-Medium.

Chapter 3: Knowledge Management

I) Background

“In recent years, organizations have increasingly realized that one of their most valuable assets is the knowledge that is developed internally and possessed by individuals within the organization” (McCall et al, 2008). “Knowledge management (KM) is a newly emerging, interdisciplinary business model that has knowledge within the framework of an organization as its focus.” (Awad and Ghaziri, 2004). Its purpose is to develop organisational capability from across all areas of strategic operations and the value chain. It is the process of making appropriate information available to the right people at the right time and processed in the right way so as add value to organisational decision making. This is a discipline that often uses technology as an enabler in order to distribute and process the data, often using a set of algorithms to provide the quantifiable result that can be then be compared to organisational targets.

“The transformation from the old economy to a new, knowledge-based economy is driven largely by the recognition that knowledge rather than financial capital, land or labour is the major source of continued economic growth, value and improved standards of living.” (Handzic, 2004) Understanding the nature and purpose of the organisation’s own valuable knowledge is crucial. In order to successfully manage the knowledge, its nature must be understood – for example the formatting, source, origins etc – so that the management system put in place is the most effective for each unique organisation.

Skyrme (1991) highlights a case in point where U.S telecommunications giant AT&T paid upwards of $80,000 for technical information that was (unknown to them) available for just $13 from commercial partner Bell Research Corporation. Here, the value of understanding where knowledge exists within organisational operations is paramount, particularly in the modern business world where commercial partnering and takeovers are commonplace. Likewise there must be a purpose for knowledge. Simply capturing knowledge without a specified end purpose results in knowledge overload in an organisation, and results in knowledge simply stored in databases or filing systems and never used.

Implemented knowledge management strategies can be either complex, large scale programmes or relatively simple and straightforward. For example, a large Multi National Corporation may choose to implement a knowledge strategy across the organisation to serve as the hub of decision making support systems. This would take a large period of time to implement or realise benefits. In contrast, a manufacturing plant utilising foreign workers may implement a programme to teach the native language, thereby removing communication barriers. This is relatively straightforward to implement and realise benefits in a short time frame. Any KM strategy must be enterprise wide in order to realise the intended benefits. If the strategy is deployed in a select few organisational functions then this serves only to segment the knowledge base further.

The successful deployment of a KM strategy is dependant on the organisational culture. If there is already a culture that is susceptible to change, learning and sharing then the deployment of a KM strategy has a higher chance of success (note that each organisation’s definition of “success” will be different). The cultural resistance from organisational human resources is one of the biggest challenges for commercial KM practitioners and consultants. Often, reward mechanisms are deployed in tandem with change management in order to overcome these issues.

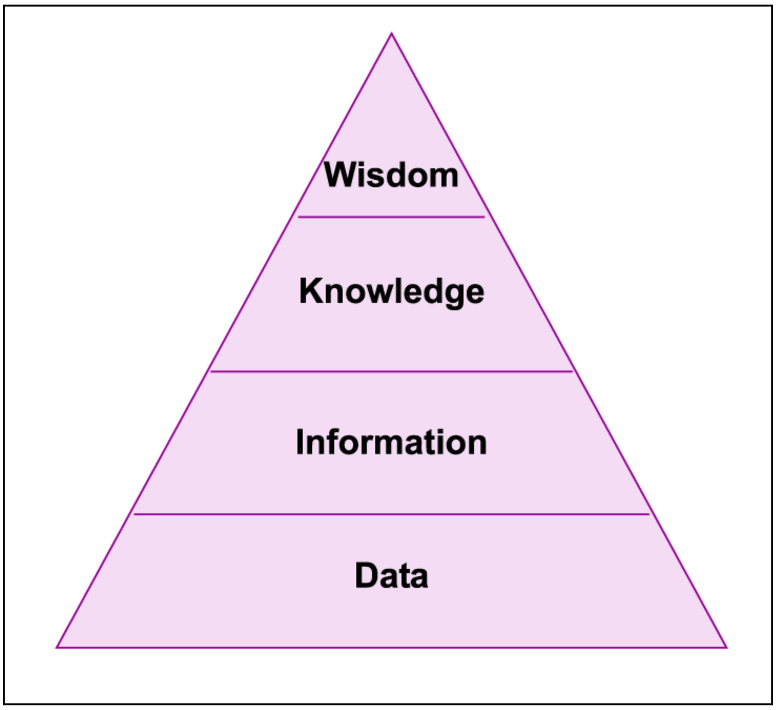
The work of de Grosbois (Date Unknown) examines KM in the context of nuclear power plants; using KM benchmarking to establish the links between best practice within the nuclear industry and the KM usage within those operators. This represents the closest comparative study to the thesis proposal.

The knowledge pyramid (Figure 6), shows the relevant stages of the codification of knowledge from raw data through to wisdom. This is performed by:

1. Obtaining the relevant data set.
2. Adding context and definition to the data to create information.
3. Refining the information and applying it organisational activities to become knowledge.

4. Internalising the knowledge into decision making or day to day decision making utilising the expert tacit knowledge. This creates wisdom.

Figure 6: The Knowledge Pyramid (Faucher et al. 2008)



II) Knowledge Based Systems vs. Expert Systems

There are two key types of systems related to KM. The first is a KBS, which seeks to collate data and perform the relevant formatting and distributing of the knowledge (often using algorithms or data configuration coding) to the necessary expert. This seeks to provide the expert with the relevant knowledge in order to make the best possible decision based on the knowledge available. An expert system will take this one step further by using rules and distributions to actually present an end decision, which will be based on the knowledge provided and the configuration of the rules based on historical activity and existing tacit knowledge.

The advantage of the KBS is that it combines both the technological and human elements of KM in driving decision making. The fact that the final decision rests with the expert, who may have considerable operational experience in the particular domain means it is well suited to power plant application. The disadvantage of this is that the final decision is still exposed to human error, and the presentation of knowledge from a KBS may only offer a small leverage over existing IS systems.

The use of expert or rule based systems carries weight when applied to situations that require a definitive answer, for example an insurance pricing tool. “Although rule-based systems look neat, their application is rather restricted. They work well only when the following five conditions are simultaneously satisfied.

1. You know the variables in your problem.
2. You can express them quantitatively.
3. The relevant rules apply to most of them.
4. These rules do not overlap.
5. The rules are rigorously validated.” (Tiwana, 2002)

Expert systems are therefore not applicable to power plant maintenance decision making because of the fact that rules for maintenance deployment are not subject validated rules. The rules for maintaining a particular installation will differ from plant to plant, and as such this means that the development of a set of rules poses huge problems.

On this basis, the application of a KBS is more suited to power plants than an expert or rule based system.

III) Knowledge Acquisition

There are two types of KA; the extraction or capture of the knowledge of a specified domain expert, or the capture or extraction of knowledge from operational systems to populate KBS.

The knowledge held by the domain expert is often unique, although often the application of knowledge is the true value adding entity. The extraction of this knowledge can be difficult for a number of reasons:

- The more an expert knows on a particular subject domain, the more difficulty they will have articulating that knowledge to a non-domain expert.
- The objectivity required by the domain expert to communicate the knowledge can be difficult to maintain.
- Many experts will rely on tacit, intuitive knowledge in their day to day operations. Thus, much of the reasoning behind their decision making is based on prior experience and instinct.

The use of KA in populating a KBS is critical if the KBS is to produce the correct knowledge in the correct format to the end user, or the decision maker. This may be performed through using population ontologies derived from IS material.

IV) Knowledge Requirements in Power Stations

Many power stations have been subconsciously performing certain KM elements since the beginning of power generation. In the early days, when manual logging and paper based filing was used, through to the 1960s with punch cards and early computers, to the sophisticated sensor based IS systems of today, the key features of KM can be identified in power plant activities. In modern power plant operational management, functions “such as: equipment reliability programs, systematic approach to training, configuration management of design basis information, documented operational procedures, plant work management systems, outage planning systems, pre-job briefing practices, and document management systems, etc.” (de Groisbois, Date Unknown) all represent practices within power plant management that could be considered to form part of this subconscious KM execution. The functions listed by de Groisbois represent those elements that capture, store and disseminate knowledge (as defined by the knowledge pyramid, Figure 6), as they represent stores of contextualised data as applied to those organisational activities that add value.

In order to manage and perform energy production, a power station has a certain set of minimum data requirements. This is the operational data mainly related to the gas turbine. A power station is normally run through a digital Distributed Control System

(DCS) that is used to send commands to the power plant. This includes the starting mechanism, fuelling systems, turbine(s), boiler/HRSG, circuit breakers, voltage regulators and all necessary auxiliaries to be able to produce electricity. The DCS is normally operated from a remote on site location, as the actual turbine and related equipment housings represent a Health and Safety (H&S) threat which prohibits manual control.

The data fed back to the DCS control panel is critical in establishing that the generating unit is working within normal operational boundaries and allows the operator to also adjust those parameters on the various controllable elements (for example altering the angle on a turbine blade or the injection of chemicals into water cooling systems to ensure the output remains at the correct pH). The standard data set of a DCS forms the basis of the minimum data requirements. This data set is required in order to be able to analyse plant performance and ensure that the required MW are produced to meet contractual demands. The use of the DCS for a power plant is reliant upon the tacit knowledge of the operator team in understanding the data and its meaning in relation to plant management and whether the generating unit can safely be run under full load.

In order to produce the required MW on a consistent basis (and therefore be profitable), a power plant must be maintained appropriately. This requires a set of data regardless of the methodology used. The plant operator must be aware of the lifecycles for critical components, most importantly the gas turbines. The data required to track the lifecycle of the turbine is collected normally in service hours or Equivalent Operating Hours (EOH) which normally have a unique algorithm that must match that employed by the turbine OEM to produce their lifecycle figures. The data from the DCS will normally also incorporate an alarm based system linked to sensors and their associated parameters. The alarm system is crucial in identifying failures in the overall plant system that may need addressing. This provides the basis for engineering examination which will determine if the part is faulty, has exceeded its lifecycle, or been installed and operated incorrectly. This tacit knowledge from the engineering team is crucial in correctly identifying failures.

The essential data set has a number of requirements that must be adhered to if maximum utilisation is to be realised. The IS department must understand the business value of the electronic data set in order to archive and store the information correctly in terms of its usage and application. Likewise, the data itself must be captured in a manner that considers its various applications and ensure the right format is captured for each. The IS itself must distribute the data to the right people at the right time in order maximise business activity. By achieving these characteristics, the IS system forms the backbone of the overall KBS, which will itself often be made up of a number of subsystems. In a power plant this often means that there are reporting mechanisms (often spreadsheets) which form the basis of the subsystems (some formal, others informal) that facilitate the conversion of information into knowledge.

V) Technology Driven Approaches

Many organisations attempting to implement KM do so from an almost exclusively IT based perspective. However, any IT based system still requires human interaction and communications. Thus, the addition of human interaction and the application of logical processes begins to create system effectiveness. Organisations that in the past have invested in purely IT based KBSs saw little to no return on their original investment. Those that combined the implementation of IT systems with the human skill sets within their organisation saw a much stronger ROI.

Many generic software packages and portals are commercially available and have been used across organisations. The problem with these “off-the-shelf” portals is that they succeed in only making knowledge available. They do not work to deploy the knowledge to the correct functional areas and as such do not support decision making. While these packages are capable of making knowledge available, they are not capable of vertically integrating that knowledge into the organisation.

Technology can be used in many ways in support of a KM strategy: “(i) building knowledge repositories, (ii) promoting virtual socialisation and collaboration, (iii) facilitating knowledge search and discovery and (iv) stimulating creativity and complex problem solving. Categories 1 and 3 support ‘codification’ and categories 2 and 4 ‘personalisation’ strategies.” (Handzic, 2004) While the use of categories 1 and 3 carry great weight to power plant application, 2 and 4 do not, as the need for personalisation is greatly reduced within the identified problem. In order for technology to be utilised properly for the required application in decision making, it is key to also consider the human elements.

VI) <u>People Driven Approaches</u>

One perspective of KM is the soft element; that is focusing on people as opposed to technology. Many firms will compete in the commercial arena based around their intangible assets – such as their own unique knowledge. The use of KM helps to protect valuable knowledge and execute that knowledge to provide commercial advantage and to exploit gaps in the chosen market. Some organisations seek to perform this through codification of knowledge into large repositories and databases. However, the nature of knowledge and its main application in decision making support means that it is best performed through human interaction and spreading the valuable knowledge through the human domain of the organisation. When properly integrated, these knowledge assets can become the key driver of value within an organisation.

VII) <u>Benchmarking and RAMs</u>

The use of benchmarking schemes within the industry is of great interest to many power plants. The use of benchmarking allows a certain level of comparison between other plants and thus can provide stimulus as to problem identification in levels of low performance. Schemes operated by 3rd parties are often performed through the use of a series of data input proforma relating to the event data, operational data and counter readings. This is then subject to algorithm based reasoning to provide a score or index for the plant, being then reported back. There are however a number of problems which at present reduce the usefulness of these schemes from the plant perspective.

- The results of other plants is not made available due to confidentiality.
- The scoring of the plants is only as strong as the data captured.

- The different configurations of the various plants within the industry makes direct comparison difficult.
- The reasoning behind a particular score or index may not always be readily identifiable.

For this reason, many plants that operate as part of a fleet may well also participate in fleet benchmarking. Being part of a fleet breaks down some of the confidentiality barriers and enables a plant to facilitate more discussion with its peers. Until the industry becomes more open, direct comparison through third party benchmarking may remain difficult to perform.

VIII) Concluding Remarks

In concluding, it is possible to see the wider benefits that KM and the use of KBS systems can bring in terms of facilitating decision making. Indeed, the continued work within the field identifies the equal importance of both technology and people focused KM strategies, incorporating the use of IS ontologies. Through the use of KM, an organisation can enhance its effectiveness and build on existing KM/IS to provide leverage in the marketplace. For a power plant, this comes through more effective decision making. This however must be performed aligned to engineering principles, which will be discussed in more depth.

Chapter 4: Reliability, Availability and Maintainability

I) Background

The components within a power station are subject to deterioration during their lifecycles. This deterioration of components can, if unchecked, cause failure among the overall unit, resulting in unavailability. The critical components within a plant (e.g. the gas turbine) will have recommendations made by the OEM as to the inspection and maintenance periods. If a particular component was simply run to point of failure, the overall effect on the generating unit would be much greater than the effect of plant shutdown for scheduled inspection or maintenance. Typically, little redundancy exists within critical components, as the cost of holding parts offline from operating cycles is too high to be economically viable. However, redundancy may well exist in supplementary systems such as pumps, generators and control mechanisms.

The literature on systems maintenance is vast and includes many different approaches. To state that one particular strategy is preferential to another involves a high level of generalisation as to the management of a power plant. In order to deploy the most effective strategy, an operator has to examine the way in which a plant works (including the various typologies of single/combined cycle etc) and tailor a particular strategy to that plant’s configuration. No two plants will use exactly the same strategy.

II) Reliability

“Reliability is defined to be the probability that a component or system will perform a required function for a given period of time when used under stated operating conditions” (Ebeling, 1997) Reliability is normally expressed as MTBF, or Mean Time Between Failures, which expresses the average amount of time between forced outages

A power station is typically arranged in a serial arrangement, meaning that all components of the system must function for the overall system to function. On this basis, the overall system is only as reliable as the *least* reliable system component. Understanding the reliability of a system at both high level and component level is therefore critical. Reliability is key to a power plant because any system downtime results in lost revenue. In the case of base load plants, unreliability at any time will result in lost revenue. In a peaking plant, unreliability at time of dispatch request will result in lost revenue (This is exacerbated by the price premium a peaking unit obtains in line with dispatch authority requests). On this basis, the ability of a peaking unit to perform state transition (from offline to online) is critical.

Common Mode Failure occurs when multiple components are reliant on, or influenced by, a common source. For example, multiple components within a generating unit will require power, meaning that if power is lost within the plant then the generating unit will not perform. This means that the criticality of those components that determine the function of others (generators, cooling systems, pipe work etc) is exaggerated according to the number of components they supply.

The work of Ekstrom (1995) is written from the context of warranty management for gas turbines. His work identifies the main issue of warranties in this context, most notably the fact that there are no standardised formulae for the calculation of reliability worldwide. "Despite the IEEE and NERC definitions, the majority of utilities still use their own 'home-grown' traditional measures which tend to combine classical reliability theory with specific system configuration, operating or administrative needs." (Ekstrom, 1995). This lack of formulae can cause problems for power plants in making sure they use the correct algorithm in line with other direct stakeholders to their operations.

"Starting Reliability (SR) is easily understood as the ratio of the number of successful starts to the number of attempted starts" (Ekstrom, 1995). Starting on demand is crucial to those power plants that operate on cycles or engage in switching from base load to two shifting. If they are unable to start on demand, they must still work to *provide* the specified power as per contractual obligations, either to private customers or to the grid. This means that if they are unable to start, power must be sourced. For an IPP this is done on the open market, leaving IPPs financially exposed to price spikes if their SR is low. For those that are part of a fleet and operate under a parent company, the financial exposure is reduced – often replacement power can be obtained from fleet reserves, or at the very least, negotiated through parent company contracts. This financial exposure is another critical factor in a plant's ability to perform state transition.

"One must recognize that no product can be assumed to have 100% reliability at any point in its life cycle – even in the first minutes of its use" (Niebel, 1994) The reliability requirements of the power plant will normally be specified pre-commission. The reliability of the plant, being a key concern for its performance, comes from the inherent reliability of the components that make up the overall system. This means that the configuration and installation of the components contribute towards the overall reliability. With the degree of uniqueness that exists between the majority of generating units, the testing and design of that configuration is essential to realise an operationally reliable power plant.

The Running Reliability (herein RR) can be defined as; "the probability that the equipment, or system, can fulfill its function *for the planned period of need* "(Ekstrom, 1995). RR is also essential to power plants. A plant must be able to run reliably at full load without business interruptions caused by forced outages. The same price spiking that financially exposes non-state transition also exposes those plants that have low RR. The added problem with low RR is that it will also translate to greater degradation of plant components. A forced trip causes higher degradation than an operator controlled shutdown, and so having a low reliability indicates a high number of trips. This is undesirable due to the increased service and repair costs on the generating unit. While most plants will succumb at some point to forced outage, those that have fewer trips are the plants that are inherently reliable in their design and installation.

III) Maintainability

"Maintainability is defined to be the probability that a failed component or system will be restored or repaired to a specified condition within a period of time when maintenance is performed in accordance with prescribed procedures" (Ebeling, 1997). Maintainability is most commonly expressed as MTTR, or Mean Time to Repair, which shows the average length between outages occurring and the facility being repaired.

"The function of *maintenance* is to sustain the integrity of physical assets by repairing, modifying or replacing them as necessary." (Kelly, 1997) Smith and Hinchcliffe (2004) proposed that the focus of maintenance procedures should be based upon the preservation of the core equipment function, as opposed to merely preserving the equipment. Daley (2007) presents an overview of reliability management that begins to address the data collection and mapping of failures in a manner that combines the fields of maintenance with reliability and KA.

“Power station maintenance work can be divided into that which: (i) requires a reduction in the available output of the station before it can be carried out; (ii) can be performed without reducing generating capacity” (Jardine, 1970). The principle of maintainability is to design and install a particular facility in such a way that maintenance can be performed in the most efficient way possible, minimising the outage and reducing business interruption. In a power plant this can be achieved through the consideration of various design principles pre-commission. In particular, the specifying of materials for selected components is one area that undergoes considerable scrutiny. Three examples of this are:

“a. Would nylon (or other plastic) gears, which would not require maintenance, be suitable?
b. Can standard ‘sealed for life’ bearings be utilized with the present economic constraints?
c. Can electrical components that are sealed and of adequate size, such as condensers, resistors, and transformers, be specified so as to assure freedom of failure” (Niebel, 1994)

Clearly, the main consideration in specification and design of a power plant is that it can run a full load, for a period of time in line with the proposed ISO Megawatt rating. While the specification of materials for the various components will be primarily influenced in this manner, consideration must also be given to the concept of maintainability. Failure to do so in this instance could result in unrequited maintenance due to over-specifying of component materials.

There are other principles that must be considered during design and installation. The actual physical design of the components must be in such a way that they can be maintained using standard tools, requiring low user skill level. Any fasteners or screws that must be removed to service a particular component must be accessible to the engineer, making maintenance as easy to perform as possible. On this basis, any components that require regular servicing or replacement should be accessible, being installed close to the outer perimeter of the system to avoid complexity in routine tasks. Using clear, logical design principles can achieve a system that provides optimum accessibility to all components with a higher frequency maintenance requirement. For example, the building of jacking or pulley points into a heavy component can aid maintenance through the use of a jack or hoist respectively.

Fault identification should ideally be built into all systems. In a power plant, this is normally controlled by the Distributed Control System (DCS) as the design requirements facilitate extensive use of sensors and control mechanisms so that the plant can be controlled remotely from the operations room. Linked to this should be positive part identification (in the form or numbering, colour coding etc) that enables faster maintenance. The final consideration during installation of power plant is the documentation of devised maintenance schedules and installation plans so as to aid future maintenance. Primarily this will be based on OEM lifecycles and historical data.

IV) Availability

“Availability is the probability that a facility scheduled for service will be operating at any point in time.” (Niebel, 1994) MTBF and MTTR are the two calculations most commonly used when determining availability. Thus, the availability of a specific facility can be expressed as MTBF/(MTBF + MTTR). This calculation can then be used to determine the number of failures for a specified operating period, and thus, the availability of the system or facility in question. “Like reliability and maintainability, availability is a probability. Therefore the rules of probability theory can be applied to availability when it is being quantified.” (Ebeling, 1997). It is important to consider the rules of probability theory to reduce the risk of misanalysis of availability.

“Plant Availability is improved (i.e. forced outages are reduced) in one of two ways: maintain or increase equipment MTBF and/or reduce its MTTR.” (Smith, 1992) Increasing MTBF can be performed through part replacement or use of maintenance to restore or refurbish existing components of the facility. Design changes may take place to alter the installation of the equipment in a manner which decreases degradation. Reduction of MTTR is achieved through making the system more maintainable or through the procurement of spares and replacement parts. MTTR can also be reduced through training of maintenance staff or the use of outsourcing to third party contractors. On this basis, it is clear that in order to obtain high availability; a system must inherently be both reliable and maintainable.

The availability of a power plant is determined by both the reliability and maintainability of the system. The availability of a gas turbine fired power plant must be considered in the context of its commercial contracts and operations. In context of the research undertaken, availability/unavailability take into account both forced and scheduled outages. Forced outages pose a bigger risk because scheduled outages are planned in advance, and thus the resultant loss of output is predicted and accounted for.

Inherent availability is based upon the distributions of repair time and failure probability, and is therefore considered as a required parameter of the design specifications. The achieved availability considers the operational history of the generating unit up until a specified point in time, and as such is subject to influence from the unit's mortality curve and random failure distributions. If the achieved availability is lower than the inherent availability, then there may be operational influences to consider. For example, a gas turbine plant situated in close proximity to the coast may have lower achieved availability due to the effects of operating in an ambient environment that has high levels of salt. A gas turbine plant that engages in regular two shifting may also have a lower achieved availability due to the reliability issues arising from increased EOH or EOC in a specified time period.

A power plant's primary objective is to produce a specified amount of power to meet contractual obligations and thus, turn a profit. The economic considerations of availability have led to a number of economic models developed for industrial application of equipment that is dependant on availability.

“Our objective is profit maximization. Define profit to be revenue minus costs, and consider only those costs affected by the system reliability and maintainability. Then

Profit = revenue – acquisition cost – repair costs – supply costs” (Ebeling, 1997)

In order to design a gas turbine installation that will realise profit through high availability, the unit must have specified upper and lower limits for MTTR and MTBF. If the parameter limits are not known, then the plant does not have limits to work towards, and so are able to judge profitability on a retrospective basis. If the parameter limits are pre-specified, then the profitability of a turbine can be calculated on a continual basis to allow a power plant to put in place the necessary financial requirements in order to minimise risk.

The calculation of availability can be adapted for different types of systems. “Systems fail because one or more equipment failures have occurred. The events that cause system failure are also events that contribute to equipment unavailability… but the converse is not necessarily true. Equipment can fail… with no loss of production.” (Jones, 1995). The use of Production Time-Based Availability (PTBA) is of more use to two shifting plants that do not need to be available all the time, only at time of dispatch request. While in theory a dispatch request could be performed at any time, in reality the requirements are shaped by general patterns across the whole grid and electricity supply networks. A two shifting plant would therefore find PTBA of more use than a straight availability calculation.

“Throughput Availability is the measure of availability that deals directly with production volume of throughput. Unlike the operations time based version… throughput availability adds a key variable, the time of the failure, to the measurement.” (Jones, 1995) The loss of production due to system failure must be considered because it directly influences the profitability. By considering the lost revenue due to failure, a plant can more accurately track its profitability. Likewise, this calculation has applications for power plants when considering the time taken to perform state transition from offline to full load. This is not performed instantaneously, as the turbine must be started, brought to minimum load, and satisfy a number of operational criteria before being moved to full load. This time period between start-up and the production of power is critical to the plant, which must be able to supply power on full load and the precise time needed for dispatch, so the system is started in advance of the dispatch time. This means the plant must be available for the whole time period from start-up to shutdown, not just that time required for production.

V) Measurement

In order to establish if a particular maintenance strategy has been effective in adding value to an organisation, it is necessary to identify and utilise a series of relevant measurement criteria on which to assess effectiveness. This is normally performed by a set of indices that an organisation can measure against; these may be organisation specific, efficiency based criteria, or predefined indices from literature.

Organisational specific measures will normally be based around a series of desirable properties for the plant or overall system. "Having accepted that some measures of performance would be beneficial it is necessary to decide the properties that such a measure should possess and those properties which should be avoided if possible." (Jardine, 1970). It stands to reason that the exact set of properties will be unique to each plant. In the case of a power plant, the configuration of the plant, as well as the application of its output and the system availability, maintainability and reliability should all be taken into account when defining those properties. "In many ways technology… provides the user with more choices for measurement, more types of measurement devices, more data from which to extract information, more capability for precision, more opportunity to succeed and more opportunity to fail." (Jones, 1995).

There is an alternative view, of a set of eleven criteria should be used in assessing those performance parameters for measurement. These are; "organization, control systems, estimating and measurement of maintenance work, inventory control and the use of maintenance materials, planning and scheduling, predictive and preventive maintenance, diagnostic techniques, application of the digital computer, training of maintenance employees, compensation of maintenance employees, and reports to management." (Niebel, 1994). It should be noted that some of these criteria may hold greater weight to an organisation than others, most notably the measurement of maintenance work. This is not to say that the other criteria should be ignored, indeed the systemic nature of measurement means that the use of a wide range of criteria is essential to effective measurement. It is up to the specific power plant to select its criteria according to its objectives. “All measures of performance should satisfy requirement… and all should endeavour to satisfy requirement” (Jardine, 1970).

Efficiency and effectiveness are normally expressed as a percentage, and as such defining the desirable, achievable ratios is the first point of action before calculation. It is difficult however, to tailor these measures exclusively to maintenance effectiveness measurement. This is because the efficiency/effectiveness of the plant prior to maintenance must be calculated and understood, with the factors influencing those calculations understood. For example a power plant that has low efficiency may be caused by dirty compressors, the need to dredge water cooling channels and so on. If these factors are not known or understood, than the reasoning behind a particular efficiency ratio pre-maintenance lacks context, meaning that measurement post-maintenance reveals nothing about the effectiveness of the maintenance in question. It is therefore also necessary for a plant to define the relationship between different factors and the ability of maintenance to impact the variables.

Predefined indices can be drawn from a variety of engineering literature – it is not necessary to examine the indices in high detail for this study – and thus each index is tailored towards different applications. Jardine (1970) presents three different indices:

- Corder’s index – Corder examines maintenance efficiency as an examination of costs time and waste, and calculates these incorporating constants. If the maintenance planner has identified costs, time and waste as three variables that are important to the organisation, then the indice can be measured to measure efficiency year on year (or other fixed time periods).
- Priel’s indices – Priel considers a number of interrelated indices in measuring effectiveness. By considering the relationships between the different indices, a number of ratios can be defined. However, the indices are data hungry and can appear overly complicated to a non-expert.

- Luck’s method – Luck uses variables from both Corder and Luck but predefines the relationship between the indices to provide a single measure of effectiveness. Although this is still data hungry, the use of a finite single measure is of greater use to a non-expert.

The use of measurement can be problematic. Measuring the wrong variables or misinterpreting the output of a defined set of measurement criteria can lead to a negative impact on decision making. On this basis, the training of maintenance planners to utilise measurement techniques appropriately is just as important as the selection of the technique itself.

VI) Concluding Remarks

The uses of engineering ratios and probabilities are mature and have been widely documented across standard engineering literature. It is the *application* of these concepts where power plants can gain leverage by using the outputted figures to analyse and contextualise plant performance. Through more enhanced understanding of these concepts the decision making within a plant can be quantified through the above discussed concepts.

Chapter 5: Maintenance Strategy

I) Background

Any piece of industrial equipments will be subject to degradation through use and be subject to failure at some point. The use of maintenance to keep a particular unit running and functioning within certain design parameters can be performed in many different ways. It is therefore necessary to assess the advantages and disadvantages of relevant maintenance strategies in light of their deployment to a gas turbine power plant.

II) Preventive Maintenance

“Preventive maintenance refers to those repairs and rebuilds that are scheduled based upon the mean time between failures (MTBF) and mean forced outage time (MFOT). Preventive maintenance also includes those inspections and regular maintenance activities… that are planned in order to prevent sudden failure of equipment and to help assure equipment is operating in a satisfactory manner.” (Niebel, 1994). PM is therefore a maintenance typology which focuses on the use of routine inspection linked to failure detection to drive parts replacement and servicing.

“A good preventive maintenance (PM) program is the heart of effective maintenance” (Patton, 1983). The objectives of PM are based around three concepts: “1. to prevent or retard equipment deterioration and failure, 2. to detect incipient failure, and 3. to discover hidden failures in off-line (or masked) equipment before a demand occurs.” (Smith, 1992). The use of these concepts are applied primarily on cost benefit. While inspection routines cost money in terms of a short, planned outage, the benefit from identifying hitherto unknown issues with production is realised by avoidance of unplanned outage or significant business interruption. Often the inspection routines and service intervals for equipment comes predominantly from OEM recommendations. These recommendations are based on historical data across the OEM fleet which is subject to long term trend analyses and statistics.

Patton (1983) presents two elements of PM:

1. On-Condition – this is maintenance that is carried out as and when the equipment requires, with inspection being carried out post-failure.
2. Scheduled – the use of fixed period inspections can be performed in order to detect failures before they occur, while fixed period replacement is performed whether or not the equipment necessarily requires part replacement.

In order to improve the life plan for a specified unit, three specific tasks must be performed: “(i) identifying the maintenance-causing assemblies, sub-assemblies and components that make up a unit; (ii) determining the best maintenance procedure for each of the above; (iii) assembling the life plan as an amalgam of the selected procedures.” (Kelly, 1997). Historically, PM was performed simply based on scheduled replacement – the concept of inspection routines and other maintenance functions was not widely used due to the highly specialised knowledge required. Repair makes up just one function of any maintenance strategy – in the form of Corrective Maintenance. Many other functions are now widely used in PM. These include testing, different levels of inspection and calculation of equipment life cycles. The use of historical data linked to algorithms provides backup to human expertise to reduce the risk of human error.

Niebel (1994) presents six objectives of PM:

1. To reduce critical component breakdowns to a minimum.
2. To minimize the impact of failures on production output.
3. To increase the life cycle of critical equipment.
4. To capture and utilize relevant performance and engineering data to make informed maintenance decisions.
5. To provide a basis for more effective maintenance planning.
6. To reduce health and safety risks to human capital.

PM includes not only planned overhauls and major component replacement, but also includes activities such as lubrication, calibration, and cleaning of equipment. Small scale maintenance activities such as these are essential in performing the second objective of PM as stated above. This is crucial if the life span of the machine is to be extended. In a power plant, the opportunities for performing in service maintenance are limited by the H&S risk to staff of entering turbine housings, meaning that defined scheduling of PM to reduce the overall downtime is a cost benefit to the operator.

Niebel (1994) presents five characteristics of systems which would benefit from PM deployment:

1. Those that are subject to high levels of unscheduled loss of production output.
2. Those systems where the operators experience high idle periods due to downtime.
3. High level of sub-standard or rejected output.
4. Those experiencing increasing repair costs due to deteriorating equipment condition.
5. Those facing an adverse effect on equipment life cycles because of poor maintenance.

The characteristics listed above could be applied to a number of different industries, with the exception of point three, which applies mainly to manufacturing. While these are fairly high level characteristics, they are all inter-related and so may provide a basis for multiple cause analysis for loss revenue due to ineffective maintenance. Achieving the reverse of the above points would indicate that the currently deployed maintenance strategy is performing effectively enough that the adoption of PM would offer few advantages.

Where PM *is* deployed, there are many advantages that an adopter will find. Patton (1983) discusses a number of generic advantages of PM adoption. These include the ability to perform proactive management, the reduction of required operation overtime, workload balancing, increased equipment uptime, increased production (and therefore, revenue), standardisation of formalisation of maintenance procedures, reduction of parts inventories, increased safety, reduced pollution, increased quality (for secondary industries), and attractive levels of cost benefit. It must be noted that the ability to draw on the advantages of PM are based to a certain extent on the availability of historical data on which to draw inspection schedules. If there is little or no data available, then it will take time to realise the full benefits as the scheduling and inspection content is refined over time.

Patton (1983) also presents a number of disadvantages. These include the potential for damage through inspection, the infant mortality rate of replacement parts, the use of inappropriate replacement policies that do not utilise the full parts life cycle, the initial implementation costs, and the ability to access equipment to perform inspection. There are other potential disadvantages. "If it is performed too frequently, preventive maintenance can have a negative impact on the achieved availability even though it may increase MBTF" (Ebeling, 1997). In particular, the main disadvantage to PM is that problems can be exacerbated through inappropriate deployment. This means that, although a drawback, the initial costs are critical to implementing PM successfully. Attempting to reduce initial costs will result in a fragmented PM programme that ill fits the design specifications. This could incur further costs through inappropriate part replacement strategies that replace parts before they need replacing. This increases costs, negating the original cost cutting.

III) Predictive Maintenance

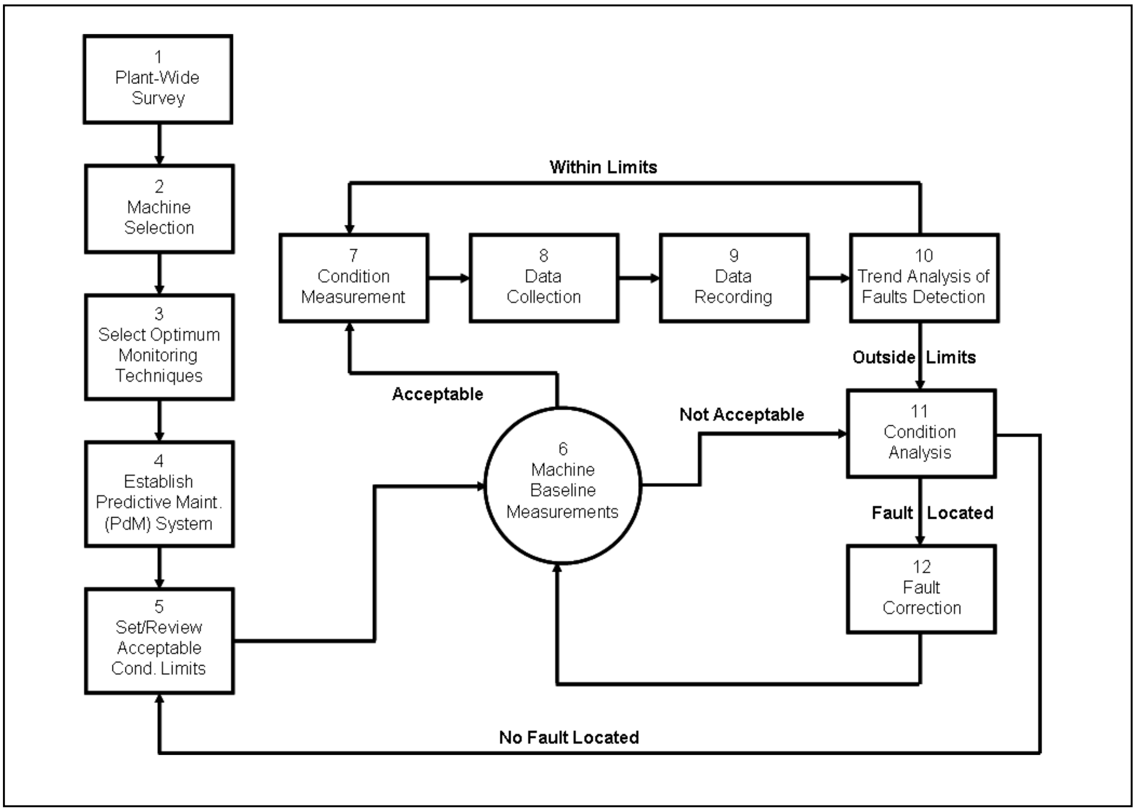
"Predictive maintenance is that maintenance that takes place in advance of the time a failure would occur if the maintenance were not performed" (Niebel, 1994). Predictive Maintenance (herein PdM) is a methodology which aims to evaluate the condition of system components through condition monitoring. This can either be performed whiles the system is online or offline. For a power plant, the ability to perform condition monitoring is dependant on the installation of sensors, due to the high percentage of time spent online. Through the use of condition monitoring, linked to historical system data and current efficiency and performance calculation, the optimum point of maintenance scheduling can be ascertained. Often, the various data will be subject to Statistical Process Control (herein SPC) to provide statistical robustness to the calculations.

“Under this strategy, the condition of the asset is monitored regularly until it begins to give evidence of deteriorating performance or incipient failure. Maintenance is then performed “just-in-time” to prevent asset failure” (Stargardt, 2008).

PdM is used to reduce capital expenditure on unscheduled maintenance, through predicting failure periods based on the equipment condition. “There are five nondestructive techniques typically used to do this monitoring. These are

1. Vibration Monitoring
2. Process parameter monitoring
3. Thermography
4. Tribology
5. Visual inspection” (Niebel, 1994).

Figure 7: Twelve Essential Steps in Building a Predictive Maintenance Program (Shreve, 2007)



In reality, PdM is rarely used in isolation. Often it will sit as part of an overall maintenance strategy, as it does not allow for scheduled maintenance or inspection that may be required as part of OEM recommendations for specified components. It is often also used in conjunction with PM in order to both prevent failure and predict failure. “Typically, predictive maintenance is implemented for one of the following reasons:

- As a maintenance management tool
- As a plant optimization tool
- As a reliability improvement tool” (Mobley, 2002)

“Preventive maintenance action performed too frequently may actually decrease availability. An alternative proactive maintenance concept is predictive, or diagnostic, maintenance.” (Ebeling, 1997). However, it stands to reason that exclusive use of PdM, while it may work to prevent failure, may not take into account the most efficient operational parameters for a particular piece of equipment. In this way, efficiency may be reduced towards the point of replacement if that point is purely defined by PdM. In addition, complex systems such as gas turbines offer little opportunities for PdM because engineers cannot enter the turbine housing while the plant is online. For this reason, PdM is better suited to simple systems, or auxiliary subsystems.

PdM has the potential to offer cost savings against PM, because maintenance tasks are performed based on need, as opposed to time. This prevents unnecessary (and costly) maintenance. “Condition-based maintenance can help reduce overall maintenance costs while maintaining asset reliability and it is an attractive and feasible strategy for certain types of equipment... New wireless technologies are now enabling broader use of condition-based maintenance by lowering the overall costs of these solutions.” (Stargardt, 2008)

The Federal Energy Management Program (2007) presents a number of further advantages of PdM:

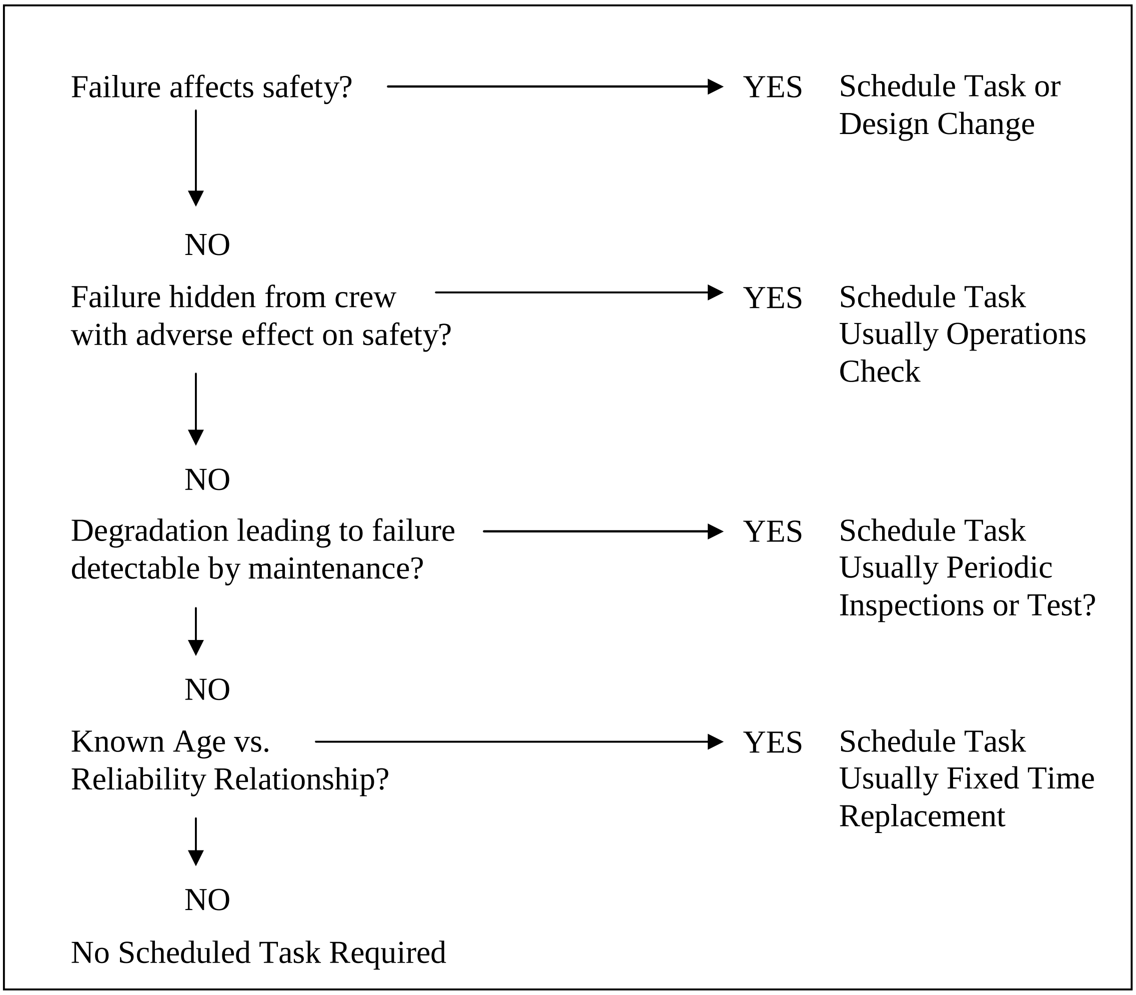
- The component life cycles are increased or extended
- System downtime is decreased
- Product quality is maintained at a constant level between upper and lower parameters

The FEMP (2007) also recognises the drawbacks of using PdM. The key disadvantage stated is the initial setup costs, which are incurred through the implementation of condition monitoring equipment, as well as the training of the staff to correctly use the condition monitoring output to enforce appropriate decision making. Expenditure is also required to ensure human capital commitment to the project, which may represent a vastly different approach to currently deployed maintenance strategies.

IV) Reliability Centred Maintenance

Reliability Centred Maintenance (Herein RCM) is a concept “created to provide guidelines on which equipment should be addressed by which maintenance tasks and at what frequencies.” (Jones 1995). The concept of RCM originates from the aviation industry. In the 1950’s bigger and more complex aircraft were being deployed in civil aviation. The airlines, who up until this point had carried out fixed period replacement of hardware, found the complexity of the new aircraft was leading to unmanageable maintenance requirements. The Federal Aviation Authority (herein FAA) setup the Maintenance Steering Group (herein MSG) to investigate the problem. The output was three handbooks; “MSG-1 (1968), MSG-2 (1970) and MSG-3 (1980)” (Kelly, 1997). The output of the studies found that the application of logical algorithms and decision making tools could be used to greater effect. This was first applied to deployment of the maintenance programme for the Boeing 747.

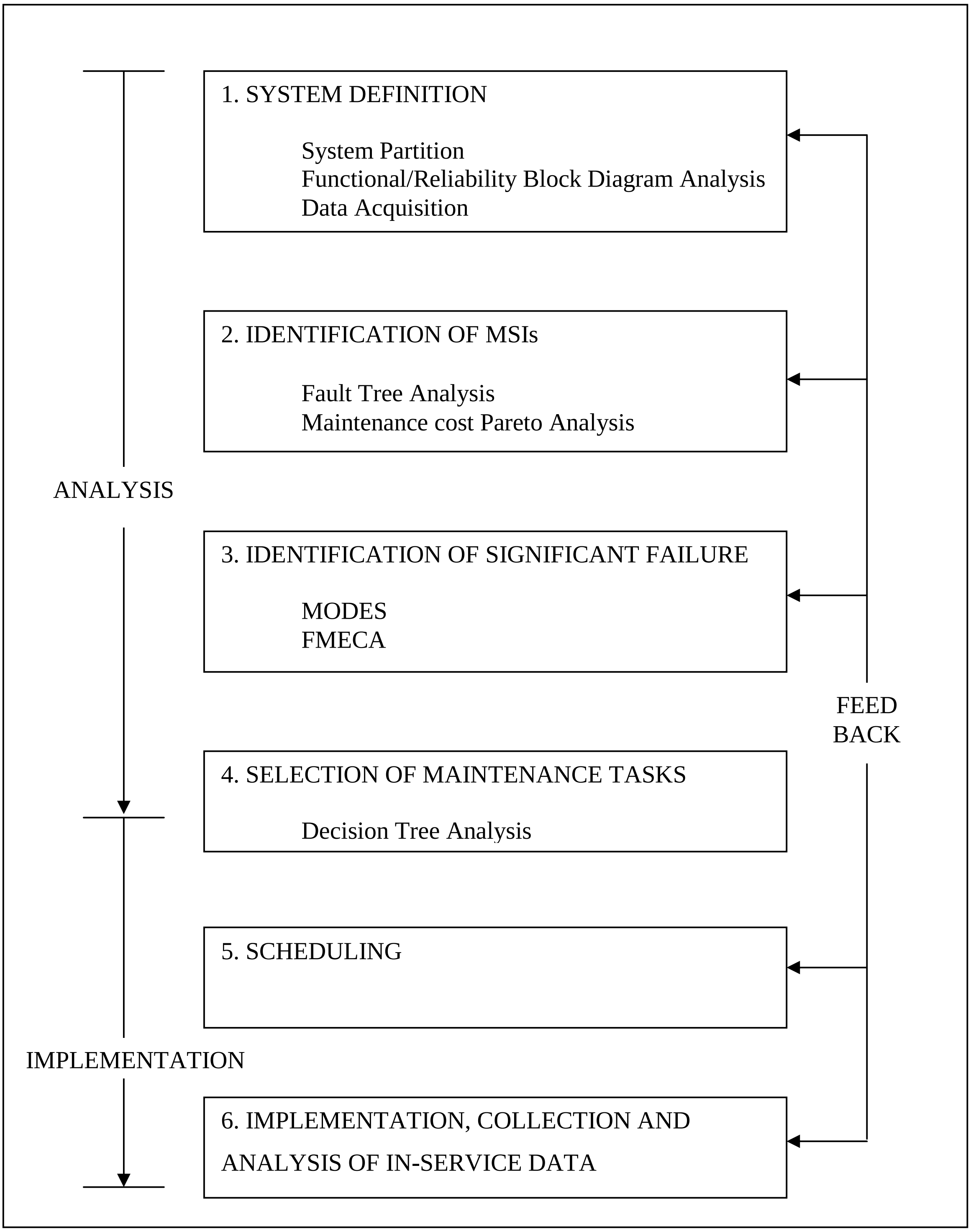
Figure 8: Example MSG-2 Decision Tree Logic (Adapted from Jones, 1995)



MSG-2 presented a tool that would form the basis of future RCM application. Many practitioners still work from MSG-2 guidelines rather than the succeeding MSG-3 document. The presented tool was that of Decision Tree Logic. The tool uses a series of questions using discreet answers (Yes or No) in order to assess the nature of a failure and the most effective maintenance action. The first use of the phrase “Reliability Centred Maintenance” came from Nowlan and Heap (1978) who based their workings on MSG-2 and presented a three pronged approach to logical application of RCM:

(i) What caused the failure?
(ii) What effect did the failure have on operability and safety?
(iii) Could RCM work to avoid this type of failure?

Figure 9: Basic Structure of RCM (Adapted from Kelly, 1997)



Moubray (1997) presents the concept of Reliability Centred Maintenance, which bases the methodology on the reliability modelling of critical components. “The objectives of maintenance with respect to any asset are defined by the functions of the asset and its associated desired standards of performance” (Moubray, 1997). It stands to reason that in order to define the maintenance strategy, it is first required to identify the functions and performance parameters.

“RCM maintenance strategy is formulated via a structured framework of analysis aimed…at ensuring the attainment of a system’s *inherent reliability* i.e. the reliability it was *designed* to attain.” (Kelly, 1997) RCM is not therefore, an approach designed to increase the reliability of plant hardware, but a case of understanding the reliability profile of the particular configuration and approaching maintenance in the most effective way to maintain reliability. Figure 9 above shows the formulaic approach recommended by Kelly (1997). He proposes six distinct stages in order to formulate and deploy a maintenance strategy but utilising RCM. Most significantly, the model includes the use of feedback looping at many points of the process, which allows reformulation and enhancement of the selected strategy through the incorporation of the system user’s own views and observations.

The applications of RCM lean predominantly towards primary industries. Jones (1995) lists Military, Nuclear Power, and Maritime as examples of prime case studies. As RCM originated from civil aviation, the benefits are equally transferable to military aviation, and moves were made in the 1970’s by the U.S. government to do just that. Despite opposition, the programme was successful at a level similar to that experienced by the FAA. RCM was also successfully transferred to nuclear power facilities based on the premise that it was similar to aviation in the lack of system redundancy in design principles. It is also similar in the need for government regulation and monitoring. The programme deployed in the 1980’s showed effective results particularly on application to auxiliary systems, as nuclear reactors had little flexibility in maintenance approach. RCM has also been deployed to auxiliary systems for Solar Receiving plants.

RCM systems have also been successfully deployed to maritime auxiliary systems, on the same premise that maritime engines or reactors (for nuclear maritime applications) have little flexibility in maintenance approach, similar to the nuclear power application listed above. RCM can potentially be applied to conveyor based systems. Jones (1995) highlights Grain Terminals and Coal Mining as two examples. The advantage of RCM deployment to these applications is the relatively simplistic nature of the overall systems, the use of RCM methodology is straightforward and less complicated, which lowers the cost of programme design compared to its civil aviation origins. This proved advantageous in reducing costs within industries with may traditionally have run conveyor equipment to point of failure, performing only corrective maintenance.

Kelly (1997) presents five generic advantages of RCM;

1. Traceability. The documentation of maintenance procedures and the related data that was used for decision making provides accountability and traceability for all decisions. This means that the root cause for failures arising from incorrect maintenance can be identified.
2. Cost Saving. The key benefit as realised from initial RCM deployment in aviation was cost savings, by eliminating unnecessary maintenance. This remains true across all applications.
3. Rationalization. Unnecessary maintenance regimes are eliminated, often showed by a reduction in required man hours. This means that only that which is achievable is planned.
4. Plant Improvement. The use of RCM can improve the plant by reducing recurring failures and increasing maintainability.
5. Education. The design of an RCM system educates the workforce by enforcing understanding of the engineering principles.

“Improvement activities are not undertaken without profit motivation” (Jones, 1995). The use of RCM, while it carries distinct advantages from deployment, carries high initial start-up costs for even the most simple of systems. The required financial input, as well as the amount of human capital deployment in order to commence the use of RCM form the key drawbacks for those organisations considering using it. The lack of a ‘one-size-fits-all’ approach for RCM is a further disadvantage, in order to see benefit of RCM deployment, it is necessary to tailor the principles of RCM to the particular application. This requires the training of human capital in understanding the principles, tools and algorithms that form RCM if it is to be deployed in a manner which adds value to the organisation. This incurs further costs.

The application and study of RCM and gas turbines has been examined by Carazas and de Sousa (2009) who presented a recent article in the International Journal of Thermodynamics, which presents a system reliability methodology based on a project undertaken with the Brazilian Electrical Energy Agency (ANEEL). They present a Reliability and Availability analysis based on the Mean Time to Failure and Mean Time to Repair figures taken from two gas turbines within a combined cycle plant. As part of the recommendations they recommend RCM as a methodology to reduce unexpected failures and improve existing maintenance policies.

RCM combines the fields of Predictive Maintenance and Preventative Maintenance in a manner which manages to draw on the best elements from both typologies. RCM utilises this to reduce costs for the required performance level for organisational success.

V) Other Maintenance

"One of the major trends in European industry is the adoption of the Japanese technique (and underlying philosophy) of Total Productive Maintenance (TPM)." (Kelly, 1997). Nakajima (1988) originally presents the concept of Total Productive Maintenance, which draws on Japanese human resource concepts such as Total Employee Involvement (TEI) in order to incorporate maintenance on a day to day level. This approach derives from motor manufacturing, and is based on the principle of employee involvement in maintenance at each point of the production chain. This is not appropriate in power generation because of the fact they are not chain systems, and so the system is controlled as whole, not a series of chains.

Zhu et al (2002) present an alternative view; of Object/Objective Oriented Maintenance, which uses Behaviour Based Maintenance in order to design maintenance scheduling around organisational objectives. This emphasises the value of each piece of equipment in achieving organisational objectives. This approach carries weight to power plant maintenance because of the ultimate business objective of a plant is its sole method of revenue generation. The use of OOOM on its own is not enough; the use of industrial scale engineering in power generation means that OOOM must be combined with PM or RCM to consider the risk of engineering failure when meeting organisational objectives.

VI) Concluding Remarks

In reality, many organisations will draw on different aspects of the above defined maintenance strategies, using different elements to fit their specific needs. In power plants, where many of the maintenance practices are based on historical activity and moulded by the culture of the plant, different elements of the above strategies will be combined to present a strategy unique to that particular unit. Often, influences will also be drawn from parent company practices. While RCM would appear to be the best overall maintenance strategy, the high costs associated with implementation means that a combination PM and PdM can be more cost effective where the required systems are already in place.

Chapter 6: Case Study: Best and Worst Practice Operators

I) Background

The results below are derived from a combination of questionnaire completion aided to the researcher's interview notes. To protect operator identity many of the details have been anonymised; while any descriptive data rounded up or down to prevent reverse engineering of the analysis to establish operator identity. The completed questionnaires and notes are not attached to the document but are available upon request and only with the express permission of the participating plant. In total four plants were surveyed.

II) Primary Investigative Results

Power Station A is a combined cycle gas fired plant operating three turbines. The plant operates a combination of base load and two shifting, as required by market conditions. Typically one turbine will operate on base load with the other two shifting. The station has an ISO Megawatt rating of over 600 MW and was commercially operationalised over 15 years ago. The output from the plant is sold to the plant's parent group customers.

Plant maintenance is undertaken by a combination of the operator's own maintenance team with the further use of 3rd party contractors to perform large scale management (for example turbine overhaul). The planning itself is performed by a combination of the plant level maintenance planners allied to the turbine OEM management team. The maintenance strategy is based on a combination of the following factors:

- The EOH for each turbine allied to life expectancy figures from the OEM.
- Engineering opinion as to the overall status of the plant derived from day to activity and measurement.
- Financial considerations.
- Market forecasting, including the spark spread within the market.
- The effect of maintenance on contractual conditions with the output purchasers. This includes the ability to meet demand when requested while balancing the amount of gas purchased to fire the turbines.

In planning the maintenance activities the plant uses a number of data sources. Data output from both the plant Enterprise Resource Planning (ERP) system and Distributed Control System (DCS) is utilized to form the core of planning data. The data is contextualized through the use of descriptive statistics. The effectiveness of maintenance is measured through calculation of Reliability and Availability and the use of Root Cause analysis. The effectiveness is also examined through regular plant status reviews and performance testing. The plant also implement quality control procedures to form the basis of risk mitigation and management, highlighting the large number of exclusions in OEM turbine warranty as one of the influencing factors for its deployment.

The plant uses a data management system to record operational data, event data and counter readings. When an event occurs, a Noteage of Outage Occurrence (NOO) paper form is completed by the operational team. This is then entered into the system by the Production Support officer who is the sole collector of the data within the plant. The type of event is monitored via a set of event reporting codes, while the duration is captured to the nearest second via readings from the Circuit Breaker Sensors. Information relating to the outage mechanism is captured via the NOO form. The Outage Cause is determined through engineering inspection. The event data is subjected to Root Cause analysis and the Megawatt impact (Expected vs. Actual Output) is also calculated. MTTF and MTTR are not calculated but the Revisit to Defect rate is. The long term event data is reported through Technical Incident Reports, KPI Reports and Event Logs, and is further analysed through monthly trend reviews.

All counter readings are collected by daily queries run from the Data Management System. Readings are captured in high detail as they are queried electronically from the counters. The data is collected by Production Support Officer and reported on a monthly basis for use in efficiency calculations The readings are also reported to the Finance Team (for depreciation calculations), Engineering Team, and to plant and parent company management. The Production Support Officer uses a spreadsheet for long term tracking, although it requires manual data input. Reliability and Availability are regularly calculated as part of the analysis. Traditionally, the plant has used Parent

Company definitions. However, inconsistencies with the guidance material means the plant wishes to switch to the IEEE business planning definitions. Equipment hours are not currently tracked and monitored. Instead, Condition Monitoring systems are used, however issues exist with the radio signal capture as the system is not integrated with the Data Management System.

All the operational data is collected at turbine level. The data is collected in reference to the fuel (gas) used and the amount of power produced. Data is captured with high detail as it is queried electronically from the counters. The data is collected by Production Support Officer and is reported alongside the counter readings and sits in many of the same documents, being distributed to the same recipients. The operational data is further reported in Monthly Efficiency Calculations to Plant Dispatch. The plant must comply with the EU Emissions Trading Scheme, DECC, and the Environment Agency. All compliance is monitored and reported through the Data Management System.

Up until 2007, the plant undertook benchmarking through a 3rd Party RAM (Solomon – A U.S based firm). The plant sees the advantages of benchmarking in that the tools are useful in assessing market position and to understand relative, contextualised plant performance. They also feel that there are number of disadvantages that need to be resolved to make benchmarking effective. Firstly, the tools that exist are only as strong as the quality of data held. Poor quality data based RAMs are of little value. Secondly, the plant feels that many of the RAMs are also complicated for use by the plant. For example, in order for the plant to input the data into the RAM input tools there may be manual formatting required, which can be some distance from the original data capture process.

There are number of areas of further data capture as identified by the plant. Condition Monitoring Systems output is not currently reported due to incompatibility between radio signallers and the Data Management System. Defect Reporting Systems output is available for capture but not currently collected. Alarm setups for sensors are also required for the new DCS. At present the new system has a number alarms across equipment areas not covered by the previous DCS, and thus the output is unmanageable.

Once setup these should be collected and reported. Lube Oil readings, Operator Logs and data from Switches should all be made available for collection. The operator logs are currently recorded on paper, and thus during times of high operator activity gaps appear in the logs. This means that complete logs are difficult to fill in during failed starts, as the operator is does not have the time to complete the relevant procedures and manually log their observations. Finally, data that cannot be captured due to HSE guidelines would be useful to collect from the plant's perspective (e.g. measurements from inside gas turbines).

Power Station B is a combined cycle gas fired plant operating a single turbine plus a steam turbine and heat recovery boiler. The plant operates on base load, being the last in its fleet owner's priority list for two shifting during times of low demand. Its output is sold as part of the parent company's portfolio of commercial contracts. The starting mechanism is performed by a static frequency changer. The plant has an ISO Megawatt rating of between 300 – 500 MW and was commercially operationalised nearly 10 years ago.

Maintenance at the plant is carried by a combination of the operator, the on site team, and 3rd party contractors. Turbine maintenance is carried out by the OEM, who have a permanent team of two engineers based on site. The planning itself is performed by the on site engineering team. The maintenance strategy is designed based on a combination of factors. These include the OEH (which remains relatively stable and predictable due the high percentage of operating time at base load), and the OEM life plans and scheduled maintenance requirements. This means that for turbine maintenance a predictive based methodology is used with fixed period time based inspections. Condition monitoring is linked to preventative maintenance for the auxiliary support systems. Maintenance effectiveness measurement is performed quantitatively by the turbine OEM, who have their own independent analysis system in place linked to fleet data. The data required for OEM maintenance is extracted the OEM fleet reporting system. The condition monitoring is performed through the operational management dashboard, and as such is reliant upon the engineering opinion of the planners. Warranty management is performed by the operations maintenance software, and is based predominantly on time cycles.

Event reporting is performed through a number of reporting codes assigned to the various outage mechanisms. The outage mechanism is determined through examination of the operator logs, and the outage cause is extracted from the DCS alarm system. If the outage is a turbine issue, the OEM has their own remote monitoring system for outage cause identification. Outage duration is captured in days for planned outages, and to the nearest minute for forced outages as identified by the data management system. The event data is collected by the Production Manager and reported via a set of spreadsheets, including separate sheets to the parent company and a performance based scoring system disseminated throughout the plant. Long term event data is analysed by the turbine OEM, who have fleet calculations for MTTF and MTTR. Parts inventory is linked only for repeated failures or known issues. Although the plant has a small amount of auxiliary spares on site, they also have access to parent company stock, while turbine spares are provided from OEM stock.

The counter readings are collected every 7-10 days, and captured in a high level of detail, to two decimal places in the case of the service hours and MW generation figures. The counter readings are performed by the turbine OEM. The readings are disseminated monthly through availability reporting which resides on shared access systems across the plant. They are also validated through manual cross checking operational data. The long term analysis is again performed by the turbine OEM. Reliability and availability are calculated in two ways; first, by the production manager to communicate to the parent company, and also by the turbine OEM for their own contractual calculations. This also provides an opportunity for manual validation checking. The equipment hours are tracked by the OEM using a spreadsheet.

Operational data is backwards calculated from base load operating figures minus outages. The level of detail is the same as the counter readings – to two decimal places. The data is collected by the Production Manager who adds the key figures to the performance based scoring spreadsheet that also contains the event data. The data is also included in a set of high level standardised weekly and monthly reports to parent company management. At plant level the information is disseminated through team meetings. The data is analysed long term in twelve month periods. Legislative compliance is performed through Business Support division, who utilize the internal reporting mechanisms to manually populate the compliance forms for site specific reporting.

The power station currently benchmark through a third party provider, as well as engaging in fleet benchmarking for its parent company. The general view is that benchmarking is of value to the business; most notably the ability to reflect on the benchmarking output by driving queries as to the reasoning behind plant performance. However the problems of differing bespoke engineering profile from plant to plant means that direct comparison is difficult.

The plant currently has all required data available and sees little or no value in collecting further data.

Power Station C is a CHP plant that is operated as combined cycle (due to contractual changes post commission) using a single GT and an ST. The plant is run as base load with two shifting undertaken as required, being started by a starter motor. The plant has an ISO Megawatt rating of under 50MW and was commercially operationalised in the last ten years. The plant output is sold as part of parent company contracts.

Plant Maintenance is performed through a combination of the owner, the GT OEM and the on site maintenance team (in conjunction with 3rd party subcontractors). The maintenance is planned by the Site Maintenance Coordinator. The strategy draws on data feeds from the DCS as well as the GT OEM Control Systems, and is utilised in conjunction with GT OEM recommendations. Auxiliary systems maintenance is performed as and when required as identified by the electronic operator logs. The site uses predefined service intervals over various different levels. The service intervals are tracked by spreadsheet, utilising DCS data linked to the EOH and EOC, which use the GT OEM algorithm for calculation. The spreadsheet also uses the EOH and EOC to establish a set of in house ratios used to rationalise operational decisions. The service intervals are not rigidly applied to; they can be overridden by commercial decisions or altered in order to synchronise plant downtime.

Where regular two shifting means the GT may exceed its EOH or EOC for a defined financial period, operational decision making is performed based on either load or risk management. Counter readings from the DCS are added to the spreadsheet daily and aid in the regular tracking. Post maintenance, effectiveness is not currently measured – although the parent company are looking to introduce a fleet wide scheme to perform this. The GT OEM is reliant on monthly site reporting for GT data; remote monitoring is not currently utilised. Warranty management is performed using GT OEM reporting proforma – any warranty claim is subject to scrutiny by the GT OEM.

Event Data is collected in one of two ways. Planned outage data is extracted from the maintenance planning spreadsheet and is then reported upwards through parent company management as part of submitted business plans. Forced outage data is collected by the electronic shift log, with the exception of the event duration which is read from the DCS. As the data is extracted direct from electronic systems, the level of detail is high. The event data is collected initially by the shift operator before being collated by the production coordinator. Event data is reported through a set of proformas that show loss of availability and are available through a set of shared electronic folders throughout the site. The event data is also reported to the GT OEM and to the parent company. Long term event analysis is performed on site but is also performed further up the parent company hierarchy. MTBF and MTTR are not calculated on site, only by the GT OEM for fleet wide data. The event data is not directly linked to onsite parts inventory, as the majority of major maintenance is performed through the GT OEM.

Counter Readings are regularly collected from the DCS; again as they are collected electronically the level of detail is high. The readings are collated and stored in the data management system to facilitate future queries and reporting. The counter readings are collected by the shift operator and are reported in a set of weekly and monthly reports to differing levels of parent company management. The reliability and availability are not calculated on site, but are calculated through the parent company CHP division for fleet wide reporting and analysis. The equipment hours are also tracked and calculated by a similar method. Operational data is collected alongside counter readings and follows much of the same reporting framework. The plant is subject to a number of environmental legislation, including EA, IPPC and DTi regulations. These are monitored and reported through the parent company environmental division. This is essential in order to facilitate continual improvement programmes in line with the changing specifications of the various environmental bodies.

The plant uses third party benchmarking with a specific provider. In the past they have participated in benchmarking schemes with other providers. Benchmarking is also performed internally through parent company performance and technical reporting. The overall view is that benchmarking holds benefit for the plant due to the facilitation of informal fleet discussion. The plant also points to GT user groups representing numerous plants, which are useful in providing quick wins for the plant and the resolution of common turbine problems in order to improve efficiency, reliability and availability. The plant sees the application of user groups as something that should sit alongside benchmarking, citing examples in the US where some GT user groups have formed steering committees to work alongside the GT OEMs.

The plant sees few opportunities for further data capture – stating that the information required to perform robust decision making is all currently available. The main area of consideration is application of algorithms or modelling for supplementary maintenance deployment, for example performance recovery through compressor washing. The application of modelling into this and other related areas would benefit the plant in planning activities which would increase or maintain turbine efficiency.

Power Station D is a combined cycle multi turbine plant running two gas turbines that was operationalised over 10 years ago. The plant produces between 500 – 1000MW operating predominantly on base load. When required to start the plant is restarted using a starting motor incorporating a frequency converter. The plant output is split between the plant’s own contracted partners and the parent company contracts, as part of a worldwide fleet.

Plant maintenance is performed by the gas turbine OEM, with auxiliary systems maintained via subcontractors. The planning is performed by the Maintenance Manager in conjunction with Production Support. The planning is performed based upon a number of factors. These include:

- The service agreement with the GT OEM, and the OEM historical and fleet maintenance data algorithms for service interval calculation.
- The calculation of EOH using figures from the operator logs and DCS alarm systems.
- Defined service intervals for oil changes, sampling, different inspection levels and statutory calibration.
- Data from condition monitoring systems allied to predictive maintenance calculations.

The key data sources for maintenance planning come from operational data and the GT OEM. Maintenance effectiveness measurement can be performed through the Performance Monitoring System, which drills down operational data to calculate effectiveness, but is not performed routinely. Warranty management is performed through the SLA with the GT OEM, and covers OEM maintenance labour and parts for one year post installation.

Event data is captured by the alarm handler data management systems, which collects data on event type, duration, outage mechanism and outage cause. The GT OEM also has its own remote event monitoring system which used by onsite OEM staff. Event duration is calculated from the time of dispatch, or for forced outages timings are used from the circuit breakers. The trip algorithm from the DCS provides the basis for a follow-up inspection to find the outage cause. The data is therefore captured in high detail as it is collected electronically. The data management system automatically calculates daily reports which are then manually checked. This is performed by the

Production Manager. The data management system also generates weekly, monthly and annual reports which use performance measures as part of the output. The event reports are disseminated across the plant (and can even be accessed by blackberry) and to parent company commercial division, as part of the overall fleet data. Any outage is also discussed during loss of load meetings post event which ensures effective management of forced or scheduled outages. Long term event data is analysed through performance optimisation. For catastrophic failures, the figures are reverse analysed to understand the nature of the large scale outage. The key risks are also calculated and may then be submit to a condition monitoring programme. The plant also takes part in GT user group conferences, and share event information so as to understand worldwide turbine events and known problems.

MTBF and MTTR are calculated by the data management system, but not calculated routinely. The most commonly used calculations by the plant relate to electrical systems (pumps, motors, bearings, transformers etc). Event data is not directly related to parts inventories, but is used in justifying capital expenditure in business planning. The plant benefits from having access to parts inventories from its sister plant.

Counter readings are queried manually from the data management systems and then cross checked. They are collected by the Production Manager, who reports them through manual population of spreadsheets. A separate reporting mechanism is used to report the readings to the GT OEM. Reports are made the parent company energy management division, with separate reporting mechanisms for the gas. Long term the counter readings are analysed through monthly efficiency runs. Reliability and availability are both calculated. Availability is calculated based on fourteen primary factors using ISO standard calculations. The availability must be defined as it forms the basis of the service level agreement between the operator and GT OEM. One of the key inputs for availability calculation is the use of weather reporting four times a day linked to a ambient correction algorithm which adjusts the MW production values accordingly. Equipment hours are tracked manually through daily reports which also go to the GT OEM. The plant had previously attempted to implement an operational data counter systems but trials found elements of unpredictability, so it was not operationalised.

Much of the operational data is collected manually and reported alongside the counter readings. The regulatory and legislative structures are monitored and reported manually by the production manager, who draws the figures required for compliance reports from the counter reading/operational data reports. The plant is subject to various legislation by the Environment Agency, European Union (for pollution regulations), and also to sewer control agencies for their sewer discharge. The carbon dioxide reporting is calculated automatically but is then subject to manual check before reporting to the relevant bodies. The plant is also subject to various H&S regulations for CCGTs.

The plant currently partakes in benchmarking schemes with third party benchmarking providers. They use both internal and external benchmarking and see numerous benefits from taking part, most notably in business planning. The GT user group that the plant takes part in shares benchmarking data as part of its activities. Some issues the plant has with benchmarking are to the level of contextualisation required, as current benchmarking does not allow for direct comparison between differently configured plants. They would prefer the removal of those variables. The views of the plant are that informal sharing is beginning to be utilised in what was a previously closed industry, which serves to benefit plant operators.

The plant feels that all data used to make operational decisions is currently collected and utilised appropriately. The only improvement they would like to see is the use of further dashboard systems for real time reporting across the plant.

III) Plant Analysis

Plant A has a KM system in place that appears to facilitate the basic plant requirements. The use of ERP and Data Management Systems is aiding the plant in driving information to the right people. The use of these systems is embedded into workflows and thus their importance to the plant cannot be overemphasised. The manual population of spreadsheets is performed predominantly through manual interrogation of these systems. The EOH graph is key to the plant because of the amount of two shifting performed. This two shifting means that the need for reliability and availability are high because failure to synchronise with dispatch requests exposes the plant to price spiking for both electricity and gas. This is further exacerbated by the fact that they are at the top of the priority list for two shifting as part of the fleet (while those at the bottom of the list run predominantly on base load and would be the last in the fleet to be two shifted). Although the plant is part of an overall fleet (which aids mitigation in light of risk and financial exposure) their ability to operate independently is paramount.

The plant makes full use of appropriate reporting mechanisms to the different stakeholders in the plant; however the lack of centralised and standardised reporting means that often reports to different stakeholders are required in different formats, which puts pressure on the production support officer. The plant is at a disadvantage for operational data capture as the operator logs are still manual. This means during periods of interruption or outage the logs are often unpopulated as the operators are busy attempting to rectify the problem. Ideally, running on combined cycle (multi), having three turbines, Plant A should have more robust systems in place in order to operate more effectively, using its current systems as the basis; however these systems require more effective setup and integration.

Plant B operates on combined cycle (single) having a single gas turbine, and as such requires a less complicated system. The plant benefits from an extensive relationship with the GT OEM, having OEM presence and monitoring systems on site. The plant has a small operational team, and the close knit nature of the staff makes reporting mechanisms easier to distribute; the management hierarchy is relatively flat within the plant. Extensive use of shared folders provides the basis for reporting across the site. The use of simple systems with manual input is not an issue due to the fact that all systems have undergone extended setup ensuring that each system (DCS, Data Management etc) is utilised in the most effective way possible.

As the plant is last on the fleet priority list for two shifting, the constant calculation of EOH is not required – instead turbine performance is tracked via a series of performance measures that are reported throughout the plant. The plant is embedded as part of the fleet, meaning that its risk is diluted; already risk of financial exposure is low due to predominant baseload running. The relative simplicity of Plant B means that its systems are appropriate to effective plant operations.

Plant C has the smallest ISO Megawatt rating of all plants surveyed, but benefits from its fleet operator’s experience with larger plants, utilising a range of systems. Being a small plant means that the plant can plan its maintenance almost exclusively from GT OEM recommendations and regulatory requirements. The use of a single point of reference for service intervals in spreadsheet format ensures transparency in service interval decision making. The plant use GT OEM planning requirements for the majority of their maintenance decisions and this helps simplify the planning process. The small amount of staff onsite promotes the building of relationships – that between the shift operator and production coordinator is essential to plant operations.

The use of EOC in conjunction with EOH allows effective tracking of equipment lifecycles which is required as the plant does perform two shifting, mostly during the winter. Using both these measures allows better tracking of life cycles; the data is fed into the service interval calculator to provide an accurate picture of plant operations. The plant has effective internal reporting systems – which are relatively simple with such a small team, but has to deal with differing reporting requirements to the operator. The key issue is that the contractual division of the operator primarily wants to know how many hours and two shifts the plant performs, but are not interested in EOC or EOH. This means that decision making at operator level can conflict with that at plant level as it is based on different variables and influencing factors. The plant is commencing benchmarking for the first time, using internal and external benchmarking and as such is on a learning curve as to the effectiveness of benchmarking output at plant level. Overall, the plant has effective KM systems in place to facilitate its operations; the final reporting structures appear to be the only area of improvement.

Plant D is the largest plant in terms of ISO Megawatt rating, but has only two gas turbines as opposed to Plant A which has three. Plant D has an extremely effective set of systems that complement the SLA in place with GT OEM. The use of elements of different maintenance is allied by the presence of a performance monitoring system.

The use of a dedicated report sharing system to distribute reporting mechanisms is very effective, particularly the ability of plant personnel to access the system remotely via Blackberry. Although there is the use of some manual population of spreadsheets and informal reporting structures this is not a drawback as the reporting system distributes the correct information to the correct individual. The use of real time reporting complements the fixed period reporting systems which all seem to be handled effectively, there are no noted disparities between reporting formats. Here the benefit of centralised fleet reporting is apparent; the plant's relationship with its fleet owner functions well in managing operations without intrusion.

The calculation of availability by the plant is key as it forms part of the SLA with the GT OEM; this focuses the plant personnel on the availability regularly. The most commendable of the plant's operations is its benchmarking activities. By taking part in two different benchmarking schemes, as well as fleet benchmarking, the plant is actively aware of it relative performance in the market. The participation in GT user groups also benefits the plant; by using the outputs of user group conferences to attempt to improve turbine efficiency and performance, and also through better understanding common GT problems. Overall the plant benefits from appropriate use and semantic interoperability of the deployed systems which adds value to organisational decision making. The reporting structures in place are effective and combined with the plant focus on the GT through its SLAs and user groups means that it is running smoothly and effectively.

IV) Best Practice

The best practice in maintenance of the plants studied is Plant C. This is primarily because of its extensive relationship with the OEM, who have their own onsite control systems, providing cross checking facilities for gas turbine overhaul. Predefined service intervals are more or less the standard within all CCGTs, however Plant C manages these most effectively. This is done through the calculation of EOH and EOC, which facilitates more accurate decision making than just EOH alone. The use of both of these measures also aids decision making, as it provides a number of ratios for decision justification. The combination of preventative and predictive maintenance serves the plant function extremely well. Preventative maintenance is used for the GT, while predictive maintenance is used for auxiliary systems. The flexible use of service intervals to synchronise equipment downtime where possible represents intelligent applied use of preventative maintenance. While most of the plants undertake maintenance in a similar fashion, the use flexible service interval calculators combined with the use of EOH and EOC elevates Plant C over the other case studies.

Plant D represents the best practice in its collection and reporting of event data. While the collection of the event data is similar to the other studied plants, the reporting mechanisms are where the plant stands out as a best practice operator. First, the DCS trip algorithm provides leverage in detecting failure cause. The calculation of automated event reports combined with manual checking means that event awareness on a daily level is significantly heightened. The shared data management system, accessible from PC or Blackberry, also aids event awareness among staff. The use of loss of load meetings post event also sets the plant apart as the use of these meetings forms the basis for more effective event management.

Of further benefit is the identification of key risks (which is performed across the majority of plants) but allied to condition monitoring systems, which helps prevent repeated failure through understanding of the failure mode. Finally, the plant participation in user groups represents the biggest advance in event data practice as it disseminates the event data across the whole cross section of those particular turbine users, which provides feedback as to the key risks worldwide which can then further be fed into the plant’s own identified risks for condition monitoring. This set of systems sets Plant D apart from the others studied.

Plant D also represents the best practice in the handling of counter readings, primarily due to its availability calculations. The readings are queried manually from the data management systems (automatic querying with manual checking would be advantageous). The separation of reporting mechanisms for the GT OEM, parent company energy management, and gas provider means that those parties only receive the information pertinent to them, without the need to trawl through unneeded report content. The use of a defined availability levels as part of the SLA with the GT OEM means that the calculation of availability is done in very high detail. The use of ISO standard calculations matched to weather reporting and ambient correction algorithms means the calculation is more accurate than other plants studied. This use of counter readings to define SLA agreements represents the best use of counter readings and as such sets Plant D apart from other plants, who do not all calculate reliability and availability with the same level of detail, thus not maximising the use of counter readings.

Plant B represents the best practice in the collection and reporting of operational data. The calculation of operational data is performed in a similar way to the other plants studied, however the reporting mechanisms are what sets the plant apart. The population of a performance based scoring system, distributed across the plant through a set of shared folders aids plant awareness of operational performance to a higher degree than the other plants studied. The plant is also disseminated at informal team meetings, which further enhances awareness. The plant handles its compliance through a specific support division, instead of through the production manager, reducing the production manager’s workload by taking the figures from existing reporting mechanisms rather than requesting specific reports. These measures, in particular the use of shared performance scoring, represents better reporting functions than other plants, the majority of whom simply distribute operational data alongside the counter readings.

The best practice in benchmarking comes from Plant D. The plant sets itself apart from those studied by participating in two different third party benchmarking schemes, as well as fleet benchmarking, where other plants use a single benchmarking scheme. However, the best practice ultimately comes from the plant’s participation in a GT user group, being the only one of the plants studied who do so. Simply participating in a benchmarking scheme offers only a performance centric view of the plant. It does not take into account the differing configurations of the plants and so does not facilitate direct comparison. By taking part in a GT user group, the plant can undertake direct comparison with similar plants utilising the same turbine, and provides heads up to known issues. Of even more use is the potential influence of the user group on the GT

OEM through the use of steering committees. This provides huge benefit to the plant, and this represents the best possible practice in benchmarking.

VI) Maintenance Strategies and the Use of Knowledge Management

Gas turbines are heavy duty engineered components worth tens of millions of pounds. As such, their maintenance and associated warranties are subject to strict maintenance guidelines from the OEM, which take the form of preventative maintenance schedules. This will include different levels of inspection and service. The service intervals are normally calculated using the OEM's own algorithm for OEH, and as such the power plant has little control over the maintenance of their turbines. If the OEM service intervals are not followed, then the plant runs the risk of invalidating their warranty until the next service interval is performed. A plant cannot afford to cut maintenance costs of intervals in light of the risk of generating outage.

The power plant does however have control over its knowledge management tools in relation to GT maintenance. These KM tools are required in order to track the required capital expenditure for maintenance, and will form the basis of business planning for the plant, which will often be reported and challenged through various levels of parent company (fleet owner) management. The relationship between the plant maintenance planners and the OEM is critical – the use of KM tools can aid this relationship by providing tools that accurately track the OEH and other GT maintenance influencing factors. The KM tools will draw on feeds from the plant DCS as well as GT OEM control systems to calculate the intervals. Ultimately there is little scope for changing the functions of these KM tools – their primary function remains the tracking of equipment life cycles in order to comply with OEM maintenance recommendations.

Power plants have more control over maintenance strategy for auxiliary systems. A plant can choose to implement predictive, preventative or RCM based strategies, and as such the use of KM tools can be used to interpret data that is used for decision making, regardless as to the maintenance strategy. If a plant uses predictive maintenance, then the KM tool that captures and disseminates the condition monitoring sensor data is important in that it captures the sensor data at the correct time.

Where KM tools can leverage business value is the tracking of unscheduled outages or random failures. In this instance, KM tools can be used to detect modes of failure through the DCS system, in the form of an inbuilt trip algorithm that will indicate to the shift operator and inspection engineer where the root cause of failure occurred. Likewise for small scale events and failures the use of alarm systems in the DCS will alert the operator to any problems. This is useful for small events such as a circuit breaker failing to open or a water pump failing to operate. The use of these alarm systems, when setup correctly can then be used to drive automated event reporting and also then be logged for historical trend analysis in data management systems. KM tools can then be used to identify repeated failures or risks and the output used to drive inspection scheduling or condition monitoring.

KM tools can also be used to perform market forecasting, which is essential knowledge, particularly for those plants which perform two shifting. These can include the spark spread within the market, the price of the electricity and the price of gas, both of which are essential to plant operation.

Another KM tool is weather forecasting. Understanding ambient plant conditions is important because differing ambient conditions can affect the maximum MW output. This is important as a drop in capacity must be accounted for, particularly where contractual obligations are present. A final KM tool is the use of performance monitoring systems, which can calculate the efficiency and performance of the plant through analysis of operational data. These are not widely used but the technology is available for plants to use.

VII) Concluding Remarks

In summary, while there is a relatively narrow range of practices employed by the plants studied, there are different applications of the same practices. The calculation of engineering ratios is not standard across the plants studied, illustrating that the different standards for calculating availability has left plants unsure as to the value of such calculations. The findings also show that while plants have little or no influence over

GT maintenance, they have much more control over auxiliary systems maintenance, which is where the deployment of different maintenance programmes influence reliability or availability.

Chapter 7: Recommendations and Conclusions

I) Best Practice Methodology

The replicable methodology can be found in Appendix 3. The methodology draws on the findings of the primary investigation, utilising the best practices found from the case studies of plants A, B, C and D. The methodology also draws on elements of the literature review, incorporating engineering principles and KM practices. In particular the use of Knowledge Acquisition and subsequent reporting mechanisms forms the basis of the methodology.

The methodology is designed to operate as a static “TO-BE” model, and such illustrates an idealised KBS for use by power plants. A replicable methodology would usually be taken to illustrate a series of steps that an organisation should take to realise a defined objective. The methodology provided instead seeks to illustrate the steps the organisation (the power plant) should take in utilising the available knowledge. This focuses on three distinct stages:

1. The capture of the data and knowledge in the power plant, considering the different KA mechanisms already utilised as standard (such as a DCS).
2. The KM that is performed, in order to utilise the knowledge available in the most effective way.
3. The reporting of the knowledge in its various formats to satisfy the different stakeholders in plant activities in a timely and efficient manner.

These three stages are represented along the X axis at the top of the matrix. It is important that each is considered both in isolation and as an overall part of the KBS. Knowledge acquisition tools should be considered in terms of the specific data they are designed to capture and what KM functions they feed. Each KM component should be designed and installed bearing in mind its primary function. However, the way that a particular component reports its knowledge to the end reporting mechanisms should be defined in terms of timing and formatting.

These three stages each have five sub-sections, as illustrated by the Y axis. These sub-sections are designed based around five distinct knowledge flows. These are the event data, counter readings, operational data, maintenance strategy planning data and benchmarking input data. While some data flows will overlap, the identification and separation of the different flows must be performed in order for KM to take place effectively. All in all, the matrix has fifteen subsections when considered in terms of KA, KM, and Reporting Mechanisms. This illustrates the number of different activities that must be performed in order to enhance decision making and increase the efficiency of stakeholder reporting.

Sat within the matrix are thirty different tools that facilitate and properly service the above sub-sections. While this may seem complex, many of the tools proposed already exist within a power plant or can be adapted from other tools. Some of the tools cross sub-section boundaries and as such will take inputs from multiple subsections. Key KA for Event, Operational and Counter Readings is the use of a DCS (with associated alarm system) linked to electronic shift logs. These may be operated in tandem with GT OEM remote systems. The maintenance strategy uses GT OEM recommendations linked to Condition Monitoring data based on PdM principles. The benchmarking KA takes the form of a specified proforma which covers all benchmarking undertaken (both internal and external).

The KM tools will also utilise or existing practices within plants. These include manual engineering inspections linked to root cause analysis modeling to understand the nature of failures and outages. The operational data and counter readings will feed through an ambient correction algorithm before being subject to the relevant availability algorithm (as defined by the GT OEM and forming part of the SLA). The maintenance planning data will be considered in light of a PM programme, or if financial resources allow, an RCM programme allied to a service interval calculator in order to plan for the most effective synchronized maintenance downtime. Benchmarking data should be fed through internal and external benchmarking mechanisms and also through GT user groups for the particular turbine.

The reporting mechanisms are further defined by the need for business and financial planning. This may also be required to a parent company where a plant operates as part of a fleet. These include business planning at the heart of outputting. Event data should be reported by daily, weekly, monthly and yearly automated event reports and should also be reported through outage meetings with key personnel. The output of these should be an identification of the key risks. Operational data should be reported through a performance based scoring system that identifies the relative performance level of the plant. Also included is a separate legislative and regulatory reporting system. Counter readings are distributed to three different stakeholders (gas supplier, fleet owner and GT OEM) and should also sit within the business planning justifications. Maintenance data is reported through a performance measurement system linked to effectiveness reporting in line with the defined availability and reliability figures. The output from both third party and internal benchmarking should be reported back through the organization.

The use of the different tools and components listed above should ideally feed through a shared management system, as illustrated on the matrix. This should form the basis of the electronic elements of the system and provide the necessary feeds between those components. The reporting mechanisms should be shared and distributed automatically and available remotely either through the internet or by a Blackberry based system.

The proposed best practice methodology carries a certain number of intangible benefits. The designing of the system based on data flow means that the system focuses on the requirements and functions of data, eliminating that which is duplicated or not required. This results in a system that performs only what is expressly required, reducing information overload on the users (most notably Production Support). The use of an overall shared management system should also reduce the need for the manual transposition of data, saving time and eliminating mistakes, which should increase the timeliness and efficiency of the final reporting mechanisms. The system will increase the power of decision making through providing the right knowledge to the right person at the right time, thus resulting in better decisions in terms of maintenance deployment that will, through the maintenance programmes, increase reliability and availability.

The method of the study conducted means that the tangible benefits of the best practice methodology cannot be identified due to the absence of performance measurement data collected. This requires address through further study.

II) Further Study

The need for further study is critical in progressing the research. Linking KM and KA to performance measurables (E.g. Availability/Reliability, Profitability, and Maintenance Costs) will enable the measurement of the system in increasing reliability and availability, which are at present only theoretical advances of the intangible benefits. However, the commercial confidentiality required makes this difficult in the public domain. The furthering of the study is best performed by plants or fleet owners.

III) Conclusions

In conclusion, the above study of practice linked to the literature available shows that effective KA can influence reliability and availability by providing leverage for auxiliary systems maintenance (rather than GT maintenance, over which the plant has little control). An example of this is the use of Flexible Service Interval Calculators – using preventive life cycles allied to condition monitoring. Likewise, the harnessing of effective relationships with GT OEMs through the use of GT User Groups (harnessing industry wide tacit and explicit knowledge) can serve to benefit plants which up until recently have operated in a predominantly closed marketplace. This opening up of the industry can only serve to increase the knowledge available to plants, thus increasing the scope for decision making.

If the KM processes in a plant can help to harness organisational effectiveness, then this can be further increased through the use of tailored KA and KBS as discussed. The effect of this on understanding the nature of the equipment and associated failures and mortality rates can aid problem detection and resolution through the use of systems which distribute data in a timely fashion, using KM tools to contextualise the data from DCS, Event Logging systems and so on. The use of KM into a primary based industry to build on IS systems is critical to future power plant operation in reducing financial exposure and risk through the impact on increasing reliability and availability.

References

Awad, E., M and Ghaziri, H., M. (2004) Knowledge Management. Prentice Hall, New Jersey.

Brewster, C., Ciravegna, F,. and Wilks, F (2001) Knowledge Acquisition for Knowledge Management: Position Paper. In *Proceeding of the IJCAI-2001 Workshop on Ontology Learning.* Seattle WA: IJCAI.

Bryman, A, Bell, E (2007). *Business Research Methods*, 2nd Edition, Oxford University Press, Oxford, UK.

Carazas, J., G., C., and de Sousa, G., F., M. (2009) Availability Analysis of Gas Turbines Used in Power Plants, Int. J. of Thermodynamics, Vol. 12 (No. 1), pp. 28-37.

Daley, D., T. (2007) The Little Black Book of Reliability Management, Industrial Press, New York

de Grosbois, J. (Date Unknown) Linking Knowledge Management Practices to Nuclear Power Plant Organizational (sic) Performance. Atomic Energy Canada Limited [Online] Available from: http://www.iaea.org/inisnkm/nkm/documents/nkmCon2007/fulltext/FP/IAEA-CN-153-2-K-02fp.pdf Accessed on [Jul, 14, 2009]

Easterby-Smith, M, Thorpe, R (2008). *Management Research*, 3rd Edition, Sage Publications, London

Ebeling, C., E. (1997) An Introduction to Reliability and Availability Engineering. McGraw Hill, Singapore.

Ekstrom, T. E. (1995). "Reliability/Availability Guarantees of Gas Turbine and Combined Cycle Generating Units." Transactions on Industry Applications 31(4): 691-707.

Faucher, J., B., P., L., Everett, A., M. and Lawson, R. (2008) Reconstituting knowledge management. Journal of Knowledge Management, 12, 3, pp 3 - 16

Federal Energy Management Program (2007) Operations and Maintenance: Predictive Maintenance [Online]. Available from: http://www1.eere.energy.gov/femp/operations_maintenance/om_predictive_main.html Accessed on [Aug, 30, 09]

Grzymala-Busse, J., W. (1991) Managing Uncertainty in Expert Systems. Kluwer Academic Publishers, Massachusetts. P44-45

Handzic, M. (2004) Knowledge Management – Through the Technology Glass. World Scientific Publishing Co. Pte. Ltd. Singapore.

Jankowicz, A., D. (2005) Business Research Projects (4th Edition). London, Thomson Learning

Jardine, A., K., S. (1970) Operational Research in Maintenance. Manchester University Press, Manchester.

Jones, R., B. (1995) Risk Based Management: A Reliability Centred Approach. Gulf Publishing, Houston

Kelly, A. (1997) Maintenance Strategy: Business Centred Maintenance. Butterworth-Heinemann, Oxford.

McCall, H., Arnold, V. and Sutton, S., G. (2008) Use of Knowledge Management Systems and the Impact on the Acquisition of Explicit Knowledge. Journal of Information Systems; Fall 2008, 22, 2; ABI/INFORM Global.

Mobley, R., K. (2002) An introduction to predictive maintenance, Butterworth-Heinemann, New York

Moubray, J., (1997) *Reliability-Centered Maintenance*, Industrial Press Inc, New York.

Nakijima, S. (1988) Introduction to TPM: Total Productive Maintenance, Productivity Press, New York

Niebel, B., W. (1994) Engineering Maintenance Management. Marcel Dekker, New York.

Nowlan, F., S. and Heap, H. (1978) Reliability Centered (sic) Maintenance. National Technical Information Service, Virginia.

Patton, J.,D. (1983) Preventive Maintenance. Instrument Society of America, North Carolina

Pigford, D., V., and Baur, G. (1990) Expert Systems for Business: Concepts and Applications. Boyd and Fraser Publishing, Boston. P98.

Saunders, M, Thornhill, A, Lewis, P (2007). *Research Methods For Business Students*, 4th Edition, Prentice Hall, Harlow, UK.

Shepherd, D., G. (1948) Introduction to the Gas Turbine. Constable and Company, London.

Shreve, D (2007) Organizing a Successful PdM Program (Online). Available from: http://www.reliabilityweb.com/art07/successful_pdm.pdf Accessed on: [September 01, 09]

Skyrme, D., J. (1991) Knowledge Networking. The Intelligent Enterprise, Vol 1, No 9.

Smith, A. M. (1992). Preventive-Maintenance Impact on Plant Availability. Annual Reliabilty and Maintainabilty Symposium. IEEE

Smith, A. and Hinchcliffe, G., (2004) *Reliability-Centered Maintenance: a gateway to world class maintenance*, Elsevier Butterworth-Heinemann, New York.

Stargardt (2008) Condition-Based Maintenance Using Wireless Monitoring: Developments and Examples [Online] Available from: http://www.reliabilityweb.com/art08/cbm_wireless.htm Accessed on [Aug, 31, 09]

Tiwana, A. (2002) The Knowledge Management Toolkit. Prentice Hall, New Jersey.

Yu, J., Hunter, J., Reiter, E., and Sripada, S. (2001). An approach to generating summaries of time series data in the gas turbine domain. In *Proceedings of ICII2001*, IEEE Press, New Jersey.

Zhu G., Gelders L., Pintelon L. (2002) Journal of Quality in Maintenance Engineering, Volume 8, Number 4, 2002 , pp. 306-318(13) Emerald Group Publishing Limited

Appendix 1: Questionnaire

MSc Organisational Knowledge – Primary Investigation

Assisted Questionnaire – Knowledge Acquisition in Power Plants

Cranfield UNIVERSITY

General Plant Information

Plant Owner						
Plant Operator						
Configuration	Simple Cycle		Comb Cyc (Sing)		Comb Cyc (Multi)	
	CHP		Steam Turbine		Heat Recovery	
Operating Cycle	Continuous		Base Load		Peaking	
	Cycling		Standby			
Starting Mechanism	Diesel		Starting Motor		Hydraulic	
Application	IPP		Cogeneration		Industrial	
	Other					
ISO Megawatt Rating						
Commercial Ops Date						

Plant Maintenance

Maintenance Provider	Owner		Operator		3rd Party	
	OEM					
Maintenance Planner						

Maintenance Strategy Influencing Factors

Maintenance Effectiveness Measurement	Yes		No		

If Yes, how?

Maintenance Planning Data Requirements

Warranty Management Practices

Event Data

How are the following collected?

- Type of Event
- Duration
- Outage Mechanism
- Outage Cause

What level of detail is captured?

Who collects the event data?

How is the event reported?

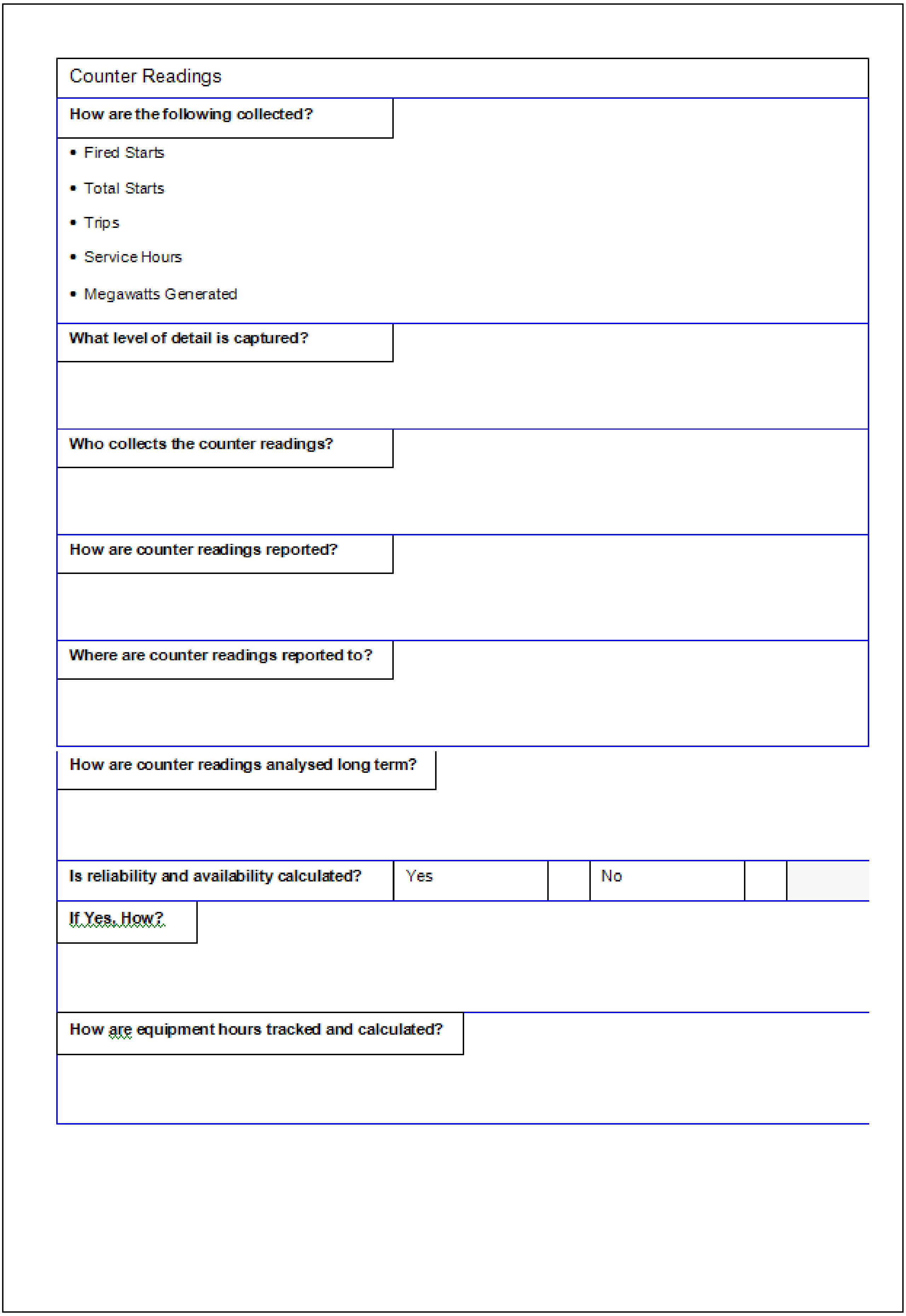
Where is the event report disseminated?

How is long term event data analysed?

Are the following calculations performed?

- Mean Time to Failure
- Mean Time to Repair

Is event data analysis linked to parts inventory?	Yes		No	



Counter Readings

How are the following collected?

- Fired Starts
- Total Starts
- Trips
- Service Hours
- Megawatts Generated

What level of detail is captured?

Who collects the counter readings?

How are counter readings reported?

Where are counter readings reported to?

How are counter readings analysed long term?

Is reliability and availability calculated?	Yes		No		

If Yes, How?

How are equipment hours tracked and calculated?

Operational Data

How are the following collected?

- Period Hours
- Reserve Hours
- Service Hours
- Unavailable Hours
- Attempted Starts
- Successful Starts

What level of detail is captured?

Who collects the operational data?

How is operational data reported?

Where is operational data reported to?

How is operational data analysed long term?

What regulatory/legislative structures apply to your plant?

How are these monitored and reported?

Benchmarking

Do you benchmark against the market?	Yes		No		

If Yes, How?

What are your views on the advantages and disadvantages of benchmarking?

Further Data Capture

What other data is available for capture but not collected?

Is there further data that should be made available for collection?

Appendix 2: Risk Assessment Matrix

	Potential Risk Factors	*Risk Probability (H/M/L)*	*Project Impact (H/M/L)*	*Risk Indicators*	*Control Mechanisms*	*Overall Risk (H/M/L)*
Financial	- Primary research costs exceed agreed budget	Low	Low	- Regular budgetary reports indicate increasing costs. - Extra project elements arise through research.	- Complete comprehensive planning and budget prior to project launch. - Signoff required from sponsor for additional research elements.	Low
Legal/Contractual	- Non compliance with operator Health & Safety regulations	Low	High	- Concerns expressed by site H&S staff	- Clarification of all H&S regulations prior to primary research visits	Med
	- Commercial confidence is compromised	Low	High	- Concerns expressed at thesis review meetings prior to submission	- Definition of commercially sensitive items prior to thesis submission. Adherence to NDA's at all times during thesis completion	Med
Reputational	- Project submission does not fulfil requirements, loss of reputation for author	Low	Med	- Concerns expressed by supervisor at point of submission	- Provision made by university for thesis correction	Low
Resource	- Illness to author resulting in delay to thesis submission	Low	High	- University absenteeism process	- Use of change management for deadlines and timescales	Med
	- Difficulties in accessing power station operators	Low	High	- Deadline for primary research exceeded	- Use of resource access agreements with operators	

Appendix 3: Replicable Methodology