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ANALYSIS OF MANAGEMENT METHODS AND APPLICATION TO MAINTENANCE OF GEOTHERMAL POWER PLANTS

MSc thesis
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by

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INTRODUCTION

The Geothermal Training Programme of the United Nations University (UNU) has operated in Iceland since 1979 with six month annual courses for professionals from developing countries. The aim is to assist developing countries with significant geothermal potential to build up groups of specialists that cover most aspects of geothermal exploration and development. During 1979-2008, 402 scientists and engineers from 43 countries have completed the six month courses. They have come from Asia (44%), Africa (26%), Central America (15%), and Central and Eastern Europe (15%). There is a steady flow of requests from all over the world for the six month training and we can only meet a portion of the requests. Most of the trainees are awarded UNU Fellowships financed by the UNU and the Government of Iceland.

Candidates for the six month specialized training must have at least a BSc degree and a minimum of one year practical experience in geothermal work in their home countries prior to the training. Many of our trainees have already completed their MSc or PhD degrees when they come to Iceland, but several excellent students have made requests to come again to Iceland for a higher academic degree. In 1999, it was decided to start admitting UNU Fellows to continue their studies and study for MSc degrees in geothermal science or engineering in co-operation with the University of Iceland. An agreement to this effect was signed with the University of Iceland. The six month studies at the UNU Geothermal Training Programme form a part of the graduate programme. Six UNU-GTP MSc Fellows completed their MSc degree in 2008, the biggest group to date.

It is a pleasure to introduce the fifteenth UNU Fellow to complete the MSc studies at the University of Iceland under the co-operation agreement. Mr. Clety Bore Kwambai, BSc in Mechanical Engineering from the University of Nairobi in Kenya, of KenGen – Kenya Electricity Generating Co., is the seventh Kenyan to complete an MSc degree under this agreement. He completed the six month specialized training in Geothermal Utilization at the UNU Geothermal Training Programme in October 2005. His research report was entitled “Exergy analysis of Olkaria I power plant, Kenya”. A year later, in September 2006, he came back to Iceland for MSc studies in Mechanical Engineering at the Department of Mechanical and Industrial Engineering within the Faculty of Engineering of the University of Iceland. In July 2008, he defended his MSc thesis presented here, entitled “Analysis of management methods and application to maintenance of geothermal power plants”. His studies in Iceland were financed by a fellowship from the Government of Iceland through the UNU Geothermal Training Programme. We congratulate Mr. Clety Bore Kwambai on his achievements and wish him all the best for the future. We thank the Department of Mechanical and Industrial Engineering of the University of Iceland for the co-operation, and his supervisors for the dedication.

Finally, I would like to mention that Clety’s MSc thesis with the figures in colour is available for downloading on our website at page *www.unugtp.is/yearbook/2008.*

With warmest wishes from Iceland,

Ingvar B. Fridleifsson, director
United Nations University
Geothermal Training Programme

DEDICATION

I would like to dedicate this work to my late parents; my father Kwambai Chebore for allowing me to go to school instead of looking after the family's goats and cows as was the tradition at the time and to my mother Toyoi Kwambai for sacrificing her meagre savings to send me pocket money while I was at high school.

ACKNOWLEDGEMENT

I would like to express my gratitude to the Government of Iceland and the United Nations University geothermal training programme (UNU-GTP) for funding my Master of Science studies at the University of Iceland. I am very grateful to Dr. Ingvar Fridleifsson, the director of UNU-GTP and Mr. Lúdvík S. Georgsson, deputy director of UNU-GTP, and to the staff of UNU-GTP; Thórhildur and Dorthe, for their support throughout my studies. I sincerely thank my employer, KenGen for granting me the study leave to pursue this course and to the staff of Olkaria for their support throughout my study.

I am indebted to the maintenance staff of Krafla power station in particular Mr. Peter for his resourceful information on maintenance at Krafla and the staff of Svartsengi power plant, in particular Mr. Geir Thórólfsson for providing me with valuable information towards this thesis. And to my special friend Tómas Haflidason and his family for taking me as a member of their family during my stay in Iceland, thank you so much.

I wish to thank my supervisors Professor Magnús Thór Jónsson and Associate Professor Gudrún Saevarsdottir for their tireless effort in advice and guidance to make this research successful. I extend my thanks to Professor Gudrún Valgerdur Bóasdóttir, the administrator at the Faculty of Engineering for always ensuring that my administrative requirements were conveniently fulfilled.

I am indebted to my family, to my dear wife Dinah Kiyeng and our children for enduring my long absence and their constant calls and messages of encouragement that enabled me bear the long duration. Finally to all my brothers and their families and to my friends who gave me moral support through telephone, e-mail and SMS. God bless you all.

ABSTRACT

The unit cost of geothermal energy depends on the capital investment, operations and maintenance (O&M) costs. The capital costs are substantial but are incurred only at the inception of the power plant and can be optimized at the inception stage. The O&M costs are incurred throughout the life of the plant and determine the economic operation of the power plant. The greatest part of O&M costs goes to maintenance cost. To make geothermal power plants (GPPs) economical, the maintenance functions should be optimized by carefully selecting and planning the maintenance strategies that will address the maintenance needs of the plant at the least cost. This research was carried out to obtain a clear understanding of the modern management concepts and to assess their suitability to management of maintenance in geothermal power plants. The objective of the study was to propose a methodology that can be used to compare the management methods and determine a method that can optimize maintenance of GPPs to make the plants operate economically.

The research involved literature review of maintenance and management methods. The maintenance methods analysed were preventive maintenance (PM), condition based maintenance (CBM) and corrective maintenance (CM). The management methods analysed were Six Sigma, Reliability Centered Maintenance (RCM) and Lean method. To understand the maintenance needs of GPPs, a failure mode and effect analysis was performed. The methods were assessed to determine their suitability in management of maintenance of geothermal power plants. The management methods were then compared by using analytical hierarchy process (AHP) and cost model.

The research showed that not one maintenance or management method can effectively address maintenance needs of any system hence a combination is always desirable. It was found that the formal management methods have been widely applied in the aviation industry, nuclear plants and some power systems but not much is written on its application in GPPs. During informal discussions and observation in GPPs, it was found that most of the plants applied in-house developed management methods to model their maintenance procedures using equipment maintenance manuals for guidelines.

It is concluded that to optimize maintenance of GPPs, a suitable combination of the management methods should be designed. RCM should be applied to design the appropriate maintenance strategies, six sigma to address chronic problems and lean to identify and eliminate wastes. A successful combination has great potential to optimize maintenance processes in GPPs and make the plants economical.

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1. INTRODUCTION

Maintenance is defined as the work of keeping an operating system in good condition or putting it in working order again after it fails. Maintenance refers to the collection of activities that include inspections, overhauls, repairs, preservation of parts and replacements carried on an operating equipment to preserve its functions, avoid consequences of failure and ensure its productive capacity. Maintenance of engineering systems is responsible for keeping the equipment healthy, safe to operate and suitably configured to perform their tasks efficiently. Maintenance functions in production plants have major impacts on product delivery, product quality and production cost. The article 'What is the added value of maintenance?' (Haarman, 2004) explains that maintenance, far from being a cost centre is actually a major economic value within the overall business performance of an organization. The true value of maintenance can only be realized when maintenance activities for each maintained equipment are optimized. Over the past few decades, there has been considerable interest and research in the field of maintenance modelling and optimization (El-Ferik and Ben-Daya, 2006). Maintenance actions affect the cost of operating a system and whether the system will be operated economically or not. The book 'engineering maintenance: a modern approach' (Dhillon, 2008) explains that 80% of the billions of dollars spent on operation and maintenance in the American industries go to correcting chronic machine failures that can be avoided with a well designed maintenance system.

To optimize maintenance, the individual maintenance needs and activities are carefully assessed and assigned into a maintenance method. Maintenance methods refer to the procedures in which the maintenance activities are planned, scheduled and executed. Maintenance methods that are commonly used in practice include preventive maintenance (PM), condition based maintenance (CBM) and corrective maintenance (CM) also known as operate-to-failure or no scheduled maintenance. The procedures and methodologies for assessing and assigning of the maintenance activities into maintenance methods constitute a maintenance management system. There are several formal management methods used in the industrial and service organizations. The ones considered in this research are six sigma, reliability centred maintenance (RCM) and lean method. Other management methods in practice include total quality management (TQM), total production maintenance (TPM), good to great (G2G) among others. These management methods have been widely applied in the manufacturing and service industries but not much has been published on application in the power production sectors including GPPs.

Geothermal power plants (GPPs) are mainly operated as base-load stations in most countries. This means that their safety, reliability and availability are critical to the power systems for the countries with GPPs in their power system. High reliability and availability of GPPs can be achieved by carefully optimizing maintenance practices. The nature of the working fluids found in most geothermal fields present maintenance challenges for GPPs because the fluids contain dissolved and suspended elements such as silica, chlorides, carbonates, sulphurs, gases and rock cuttings which are responsible for maintenance problems such as corrosion, erosion, scaling, acid attacks and fouling in the equipment in the plants. These problems require a maintenance approach that is suitably designed to address them and to ensure high plant reliabilities, availability and utilization. The maintenance practices in most GPPs is related to maintenance used in conventional power plants such as thermal and hydropower plants, manufacturing and service industries in addition to the recommendations from the vendors of the equipment as contained in maintenance manuals. The problems faced in GPPs are different from those in the above plants. Recommendation of maintenance manuals assume equipment is operated according to design conditions which is not always the case. To address these unique challenges, formal design of a maintenance system for GPPs is necessary to ensure high plant performances.

In this research, three management methods; six sigma, RCM and lean maintenance were analyzed to understand the underlying objectives, strengths and weaknesses of each method. In addition, the maintenance methods of preventive maintenance, condition based maintenance and corrective maintenance were analysed. The maintenance needs of GPPs was determined using a failure mode, effect and criticality analysis (FMEA) process in order to understand the potential failures, their likely causes and the effects of such failures in GPPs. The maintenance practices of Olkaria GPPs in Kenya, Krafla, Svartsengi and Reykjanes in Iceland were reviewed to establish how maintenance management is actually carried out in reality and how it differs from the formal methods. A theoretical evaluation was done on the application of the management methods to manage maintenance of geothermal steam gathering system (GSGS) as a case study. Finally, the methods were compared analytically using AHP and quantitatively using a cost model using assumed plant performance values to set up the AHP and cost model since real plant data was not available. In the presence of real plant data, the models can give realistic indications on the strengths and weaknesses of the methods

The AHP analysis gave RCM as the best overall method when compared analytically followed by six sigma. The cost model ranked six sigma as the best management method ahead of RCM, when compared quantitatively. Both AHP and the cost model ranked lean method as the least preferred. In both AHP and cost model, the methods showed individual strengths in meeting specific objectives of maintenance, which indicates that, no single method can optimize maintenance. It was concluded that the appropriate management method to optimize maintenance in GPPs is to combine the methods whereby RCM is applied to design the optimum maintenance tasks, six sigma to address chronic maintenance problems and improvement projects and Lean maintenance to identify and eliminate wastes in maintenance.

Literature review in this research showed that there are limited publications on maintenance and in particular on maintenance of GPPs. Existing literature mainly describes the maintenance and management methods, their advantages and disadvantages but do not make a comparison of the methods. Most GPPs generally adopt maintenance systems based on the recommendations of the manufacturers of equipment or on some established maintenance traditions such as PM. Under this approach, parts will be maintained driven by the maintenance system and not by the actual need for maintenance. This research attempted to develop a management tool that can be used by GPPs to determine the maintenance management methods that can adequately address their specific problems. The approach is to determine the management methods suitable for all equipment in GPP so that the plants can achieve their objectives at most optimum costs, time and resources.

The thesis is structured into six chapters. In Chapter 1 (introduction), an overview of the research problem and the approach taken is presented. In Chapter 2, the background to geothermal power plants and analysis of literature on maintenance and management methods is presented. Chapter 3 presents descriptions of the formal maintenance and management methods. In Chapter 4, the maintenance needs of GPPs are determined using FMEA and the maintenance practices in three GPPs described. In Chapter 5, the management methods are evaluated when applied to the maintenance of geothermal steam gathering system and their theoretical performance compared and discussed. Chapter 6 presents an overall discussion of main findings of the study and presents the main conclusions and recommendations.

2. BACKGROUND AND LITERATURE REVIEW

Geothermal is defined as the heat energy that originates from the hot rocks deep beneath the surface of the earth (GEO, 2008). The shallow-lying magma, beneath the surface of the earth, heat up the deeply circulating ground water to form hot water and steam. Geothermal energy reaches the surface in the form of hot water, steam or its mixture mostly at high pressures when a borehole is drilled into the geothermal reservoir. Geothermal resources are classified into low temperature (< 90°C), medium temperature (90-150°C) and high temperature (>150°C) (Geoheat Center, 2008). The uses of geothermal resources depend on their temperature; high temperature resources are mainly used for electricity production or as combined heat and power (electricity) production, medium temperature resources are used for electricity production in binary units and for direct uses while low temperature resources are mainly for direct uses (heating).

Geothermal power plants (GPPs) transform the heat energy in the geothermal fluids into a form of energy suitable for human uses, mainly electricity and useable heat. In typical single flash GPPs, the naturally heated steam and water is brought to the surface by a well drilled into the geothermal reservoir. The hot water is flashed and the liquid is separated from the steam. The steam is used to drive a steam turbine which in turn drives a generator that produces electricity. In a double flash GPPs, the hot water is further flashed to produce low pressure steam which is used to drive a low pressure steam turbine. In combined heat and power GPPs, the separated water is further used to supply heat for direct uses such as space heating. Where the geothermal fluid is of low temperatures, binary system GPPs is used where the geothermal fluids is used to superheat a low boiling point secondary fluid which is used to drive a binary turbine. In modern GPPs, the used geothermal water is eventually re-injected to the ground for environmental reasons and also as a means to manage the geothermal reservoir. In all these processes, there are hundreds of equipment and components that need to be maintained to keep the GPPs in good operating conditions. Figure 1 shows a simplified schematic flow diagram for geothermal power cycle showing the fluid path from a production well through the plant to a reinjection well.

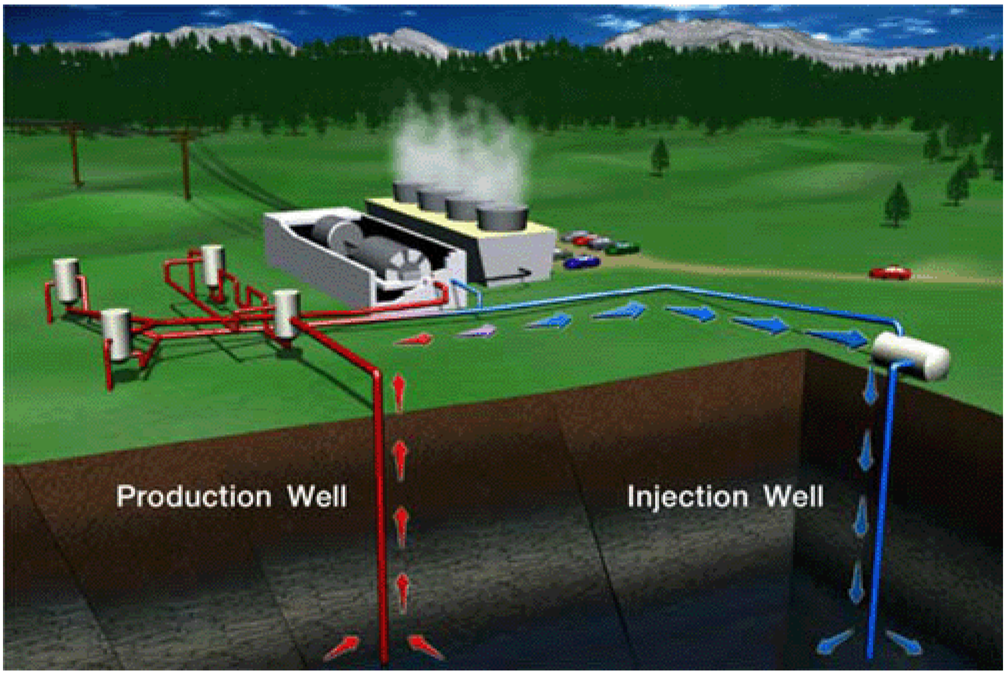

FIGURE 1: Typical flow diagram for a geothermal power plant
(Courtesy: NGP, 2008)

Geothermal fluids contain dissolved and suspended solids, gases and variety of chemical elements which result from the rock-water interaction that take place during the formation and movement of the fluids within the geothermal reservoir. The chemical and physical properties and composition of the fluids affect the way the fluids can be used, the type of design of the GPPs and the maintenance needs for the power plants. GPPs are faced with specific maintenance challenges related to the nature of geothermal fluids. Unlike in nuclear or fossil-fired steam power plants where the water quality is under control throughout the cycle, the quality of waters in geothermal power plants depend on the formation processes in the reservoir. The silica, hydrogen sulphide (H_2S), calcites and chlorides among other chemical constituents put specific maintenance challenges for GPPs which are not found in the fossil or nuclear steam power plants. Attempts have been made in recent past to control certain elements of the composition of the fluid in particular silica and chlorides by chemical dosing procedures which are costly.

Geothermal energy and other renewable energy sources have continued to gain greater attention and importance in the recent years in the world energy sector because of the increased awareness of the detrimental effects of burning fossil fuels on the environment (Fridleifsson, 2003). The recent increase in the cost of fossil fuels in particular crude oil (World Press News, 2008) is set to increase the interest in geothermal energy and other alternative sources of energy. The growing interest in geothermal energy and the fact that most GPPs are operated as baseload stations will to put greater challenges to maintenance teams in GPPs to ensure high availabilities and reliabilities of the power plants to ensure sustainability of geothermal resources and meet the growing expectations. In addition, GPPs have relatively low capital costs compared to other power plants such as hydro stations but their O&M costs are high. To operate them economically, the maintenance costs have to be minimized.

The management of maintenance in production systems have evolved over many years from the time of industrial revolution to the modern times. The evolution in maintenance management was probably been driven by the desire to reduce maintenance costs, improve productivity, quality of work and ensure high human, machine and environmental safety. Substantial literature exists with regards to development of modern day maintenance and management principles. Henry Fayol is famous for his 14 principles of management. The principles included division of work, chain of command, unity of command, motivation by remuneration and order in the business among others (Wren et al., 2002). Fredrick Taylor who is also known as father of scientific management invented the use of scientific techniques to design and manage work in industry. His work gave rise to the division of work between planning and execution. This has led to specialization at expense of multi-skilling and has been criticised by a number of researchers (Taylor, 1998). Henri Ford is another household name in the development of management philosophies. He is credited with establishing the mass production concept and pioneering what is called a $/day incentive to motivate workforce.

The quality drive of the 1950s led to improved productivity in the industry which positively affected maintenance. The article 'The quality gurus' (Mabbett, 2002) give brief discussions of the contributions from known quality gurus including Edwards Deming, Joseph Juran, Bill Crosby, Henry Taguchi and Kaoru Ishikawa who contributed extensively to the development of quality management practices in the manufacturing and service industry. Edwards Deming is known for his famous 14 points on quality management and the seven deadly quality diseases. Joseph Juran came up with the trilogy of quality being quality planning, quality control and quality audit. Philip Crosby is credited with coining the term 'quality is free' to emphasize the importance of quality while Kaoru Ishikawa is known for his fish bone diagram for tracking causes of defects (cause and effect diagram). Taguchi developed the use of design of experiments for testing alternative solutions. Quality plays important role in the maintenance of GPPs to ensure reliability, safety and efficiency of the plants.

Maintenance methods have been presented by different authors in different perspectives. In this research, maintenance management method is used to refer to the analysis and decision making processes used to design maintenance procedures. Maintenance methods refer to the way the maintenance tasks are planned and scheduled. The maintenance methods reviewed are preventive maintenance (PM), condition based maintenance (CBM) also known as predictive maintenance and corrective maintenance (CM) also called operate to failure. The management methods reviewed are *six sigma, lean maintenance* and *reliability centred maintenance* (RCM). The formal management methods were compared to classical management methods which are the informal management practices used by most organizations to manage their maintenance processes. Many articles and publications and a considerable number of books have been written to explain or promote specific methods to the industry. The competitive marketing of the methods often cause confusion and a procedure to compare and select the appropriate method is necessary. Derrick Anderson of plant maintenance resource centre presents different scenarios of the modern maintenance management theory jungle (Anderson, 2001).

Preventive maintenance (PM) is the most common method of maintenance used in industry and in power plants. Preventive maintenance is build on the concept of scheduling maintenance activities at predetermined time intervals based on calendar days, running hours, machine output or other triggers. According to the article 'optimum preventive maintenance policies' (Barlow and Hunter, 1960), PM is a logical choice if, and only if (i) the component in question has an increasing failure rate and (ii) the overall cost of the preventive maintenance action is less than the overall cost of a corrective action. The article argues that preventive maintenance will result in savings due to an increase of effective system service life. The method allows for planning for spares and therefore a better inventory management. The main disadvantage with the PM method is that it results in some unnecessary maintenance works and downtime.

Condition based maintenance is where the condition of the equipment is used to determine when to carry out maintenance. The paper 'preventive maintenance basics' describes condition based maintenance (CBM) to consist of scheduling of maintenance activities only when a functional failure has been detected. The article argues that by employing CBM, the equipment would be stopped only at a convenient time for repairs.

Corrective maintenance or run to failure is where maintenance is carried out after failure has occurred. The paper 'preventive maintenance basics' (Girdha and Scheffer, 2004) explains that the basic philosophy behind the run to failure is to allow the equipment to run until it breaks down and only repair when the machine has come to a stop. This approach works well if the equipment failure has negligible safety and operational effects and if the resultant cost is minimal. In such circumstances, this method becomes the most efficient way to do maintenance.

Six sigma is commonly defined as a comprehensive and flexible methodology driven by close understanding of customer needs, disciplined use of facts, data and statistical analysis and focused to improve and reinvent business. Six sigma was developed by Motorola company and made popular by application at the general electric company (GE) and has been applied by many companies to manage their processes to great success (Pande et al., 2000). The 'six sigma way' book lists a number of companies who have reported great financial success through implementation of six sigma method. They include General Electric, Motorola (who are the inventors of six sigma), Honeywell, Kodak, Toshiba, Black and Decker among other highly successful companies.

The RCM method first developed in the aviation industry (Boeing) before being adopted by the United States military aviation and has recently been introduced to the nuclear power plants (Overman and Collard, 2003). The method is also being tried in Aluminium smelting companies such as Alcoa and Alcan in Iceland (via interviews, telephone and email correspondences), power transmission systems and other industrial sectors. Discussions with maintenance managers at Svartsengi GPP revealed that the plant made attempts to use RCM in its maintenance (Geir Thórólfssson, maint. eng., pers. comm.). The society of automotive engineers (SAE) standard defines RCM as a 'specific process used to identify the policies which must be implemented to manage the failure modes which could cause the functional failure of any asset in a given operating context'. The goal of RCM process is to ensure that the right people perform the right maintenance, at the right time, in the right way, with the right training and tools.

Lean maintenance is a maintenance philosophy aimed at eliminating wastes associated with maintenance activities. The article 'lean maintenance for lean manufacturing' (Cooper, 2002) explains that the problem of maintenance is in reliability and uptime and can be optimized by eliminating downtime by preventing it happening. This can be achieved by identifying the causes of stresses that cause down time and then eliminating them. According to manufacturing extension partnership, lean operating principles started in the manufacturing environment and are also known by different names like lean manufacturing, lean production or Toyota production systems. According to national institute of standards and technology manufacturing extension partnership, lean is a systematic approach to identifying and eliminating waste through continuous improvement, modelling the product at the pull of customer in pursuit of perfection. Lean method presents benefits in terms of operational, administrative and strategic improvements (Kilpatrick, 2003).

The discussions have shown that each of the maintenance and management methods has its strengths and weaknesses and is suited to given maintenance scenarios. Maintenance of geothermal power plants has their own challenges and it is important to establish a maintenance approach that can effectively and economically address them. This has been done by obtaining an understanding of the methods and relating the methods to maintenance needs of the geothermal power plants. Finally, the methods are compared to determine the methods that are suited for given maintenance problems.

3. DESCRIPTION OF MAINTENANCE AND MANAGEMENT METHODS

Any operating equipment can fail by means of complete breakdown, operational malfunctioning or decreased performance rating. The types of maintenance activities required will depend on the type of actual or potential failures, the effects of the failure on the equipment and entire system, the costs of repairs, safety and environment concerns and other failure consequences. The way maintenance activities are organized, scheduled and executed constitutes the maintenance method. Maintenance methods include preventive maintenance, condition based maintenance and corrective maintenance or run to failure. The processes used to design, select and optimise the combination of maintenance activities to achieve a given maintenance objective constitute maintenance management process. Formal management processes discussed in this research are reliability centred maintenance, six sigma method and the lean maintenance. Most maintenance organizations design their own maintenance measures using a combination of the formal methods and their experiences in addition to recommendations of equipment manufacturers. The maintenance and the management methods are discussed below.

3.1 Description of maintenance methods

The maintenance methods discussed here are preventive maintenance (PM), predictive or condition based maintenance (CBM) and corrective maintenance (CM) also known as run to failure. These are discussed below.

3.1.1 Preventive maintenance

Preventive maintenance (PM) is a time based maintenance method in which the maintenance activities are planned and scheduled based on predetermined counter intervals in order to prevent breakdowns and failures from occurring. The book ‘applied reliability centred maintenance’ (Jim August, 1999) defines PM as any scheduled preventive tasks intended to reduce the probability of failure of equipment. The scheduling process can be done by a computer system, human memory, wall charts or other scheduling methods. The interval counters include calendar time, running hours, operational cycles or production and seasons shown in Table 1.

The primary goal of PM is to preserve and enhance equipment performance and reliability by preventing failure of equipment before it failure occurs by such actions as replacing worn components. PM is commonly used where equipment failure is age related or where the equipment failure rates follow what is called bath-tub curve (Figure 2). The PM activities can be carried out while the equipment is in operation, on restricted load or during a planned stop. The article ‘building a PM brick by brick’ (Brown, 2003) observes that because PM jobs are pre-planned, the quantities of labour, material and tools needed for the tasks are estimated and known in advance. It is recommended that for new maintenance organizations, PM should be started in small steps and move to next step when the previous is successful. When building a PM system, equipment with high downtime, high number of repairs or repetitive breakdowns should be targeted. The PM should find root cause of common failures, review work order history, brainstorm with operation and maintenance (O&M) employees in order to develop PM procedures to address the root causes of failures.

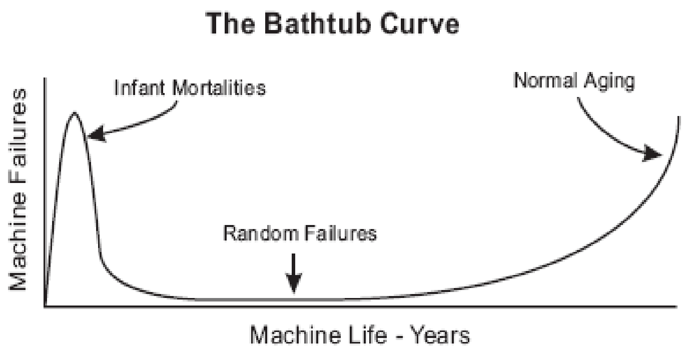

FIGURE 2: The bathtub curve for preventive maintenance

The maintenance tasks done under a PM program are illustrated in Figure 3. The routine tasks carried out in a PM include inspections, adjustments, tests, calibrations, rebuilding and replacements. Inspections start with a checklist of the equipment to be inspected, the symptoms to be looked for and the equipment location. Adjustments involve changes on certain operating parameters in order to optimize equipment performance. Tests are done to verify status of conformance of equipment operations to specifications. Calibrations are done to verify or correct accuracy of critical instruments. Rebuilding includes checking critical dimensions and replacing worn parts to restore equipment to as good as new and would require longer downtime and a detailed report of what was done, what was found, what was replaced and what should be checked in the next rebuilding. Periodic replacement is where disposable parts and inexpensive but critical parts are replaced. The long term objectives and benefits of PM programs are:

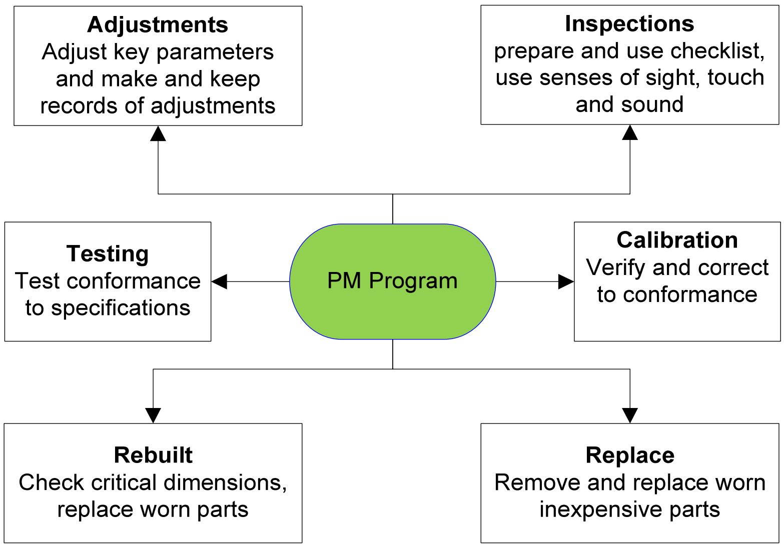

FIGURE 3: Preventive maintenance procedures

- Improved system reliability.
- Decreased cost of replacement.
- Decreased system downtime.
- Better spares inventory management.

The requirements for a good PM procedure include the following:

- A list of tools, spare parts and instruments required.
- A form to record the measurements to be made.
- Limits or ranges for the parameters to be measured.
- Required safety procedures such as isolation and locking out.

When preparing PM programs, the potential sources of information and resources include:

- Vendor recommendations which are commonly contained in equipment maintenance manuals.
- Experience of the operations and maintenance staff borne out of many years of doing maintenance.
- Generic PM programs in the market which can be adjusted to suit the plant or equipment needs.

After a PM program has been developed, it must be tested and corrected and the frequency of activities adjusted. PM activities are scheduled meaning there is some basis to schedule. PM scheduling is commonly done by computer maintenance management software (CMMS) but can also be done using a wall chart, job allocation book and maintenance habits among others. Table 1 shows the commonly used counters for scheduling PM activities.

PM is most suitable in conditions where the failure rate of the component keep increasing with time implying wear-out. Components that have constant failure rates and random failure are not suitable candidates for a PM program. PM programs should be directed at equipment with high downtime, high number of repairs and repetitive breakdowns. The overall cost of the PM actions must be less than the overall costs of a corrective action which should include costs such as downtime costs, loss of production costs, lawsuits over the failure of a safety-critical item, loss of goodwill, etc.

TABLE 1: Types of scheduling counters for preventive maintenance

Calendar time	Running time	Operational cycles	Seasonal cycle
Daily Weekly Monthly Quarterly Semi annual Annual	Number of revolutions made Total units produced Total hours run	Number of start-ups Number of operations Number of switching	Peak load cycles Weather cycles

The common tool used in implementation and analysis of PM programs is the Weibull distribution density function used for calculating the mean time between failure (MTBF) for equipment and to determine the most appropriate maintenance interval and variety of CMMS such as MMS, DMM and enterprise asses management (EAM) used to schedule the maintenance tasks, generate work orders, track equipment maintenance history, keep records of costs etc. The spares are commonly managed using stores management software.

3.1.2 Condition based maintenance

Condition based maintenance (CBM) is a set of maintenance actions based on the evidence of need for maintenance obtained from real time assessment of equipment condition obtained from embedded sensors and external tests and measurement taken by portable equipment. Predictive maintenance (PdM) involves comparing the trends of measured physical parameters against known engineering limits for the purpose of detecting, analysing and correcting problems before failure occurs (Brown, 2003). Figure 4 shows a predictive maintenance cycle which includes measuring critical performance parameters periodically or online and when the measurements exceed an established limit, the condition must be analysed further and action taken to forestall failure. PdM is part of CBM practices because the maintenance actions are related to measured parameters. CBM is a technology that strives to identify incipient faults before they become critical which enables accurate planning of PMs. Under CBM, the asset is assessed while in operation and a decision is made as to whether it needs maintenance or not and if so, when it should be done to forestall failure. Assessment can be simple visual inspection or fully automated system to sense, receive and process performance data, monitor, diagnose and predict failure.

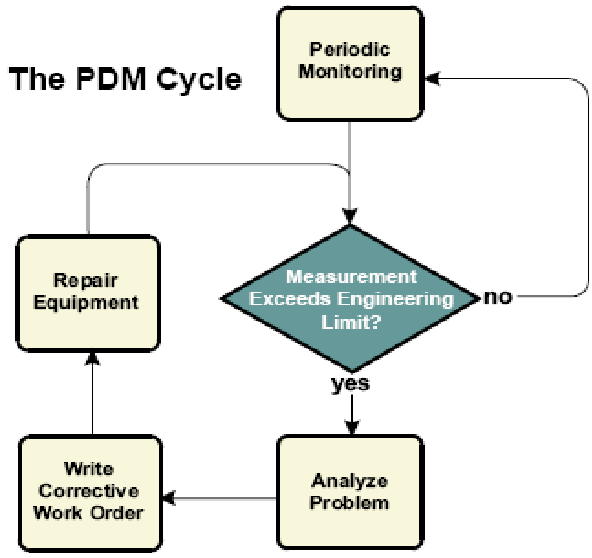

FIGURE 4: Predictive maintenance cycle

The main objectives of CBM or predictive maintenance (PdM) is to improve system reliability and availability, product quality, security, best programming of maintenance actions, reduction of direct maintenance costs, reduction of energy consumption and meeting standards. The paper 'technical design of CBM system' (Bengtsson et al., 2004) shows that most equipment failures are not related to the length of time of service or age and therefore PM actions are not effective. The paper presents six time-related probability failure curves to proof that most failures are not age related (length of time in use) but are rather random failures. Random failures cannot be predicted but their onset can be detected through change in certain performance parameters and failure can be forecast. Common parameters to monitor to detect changes in condition of equipment include: vibration, power consumption, temperature, noise, chemistry of fluids and visual observation. It is important to spot the tell-tale signs in advance (condition monitoring) then follow up to establish and remove the failure cause.

The open system architecture for CBM (OSA-CBM) presents the essential modules that are required for a CBM system. The modules include a sensor, signal processing, health assessment, prognostic, decision support and presentation modules (Bengtsson et al., 2004). The process flow in the OSA-CBM system is illustrated in Figure 5 below.

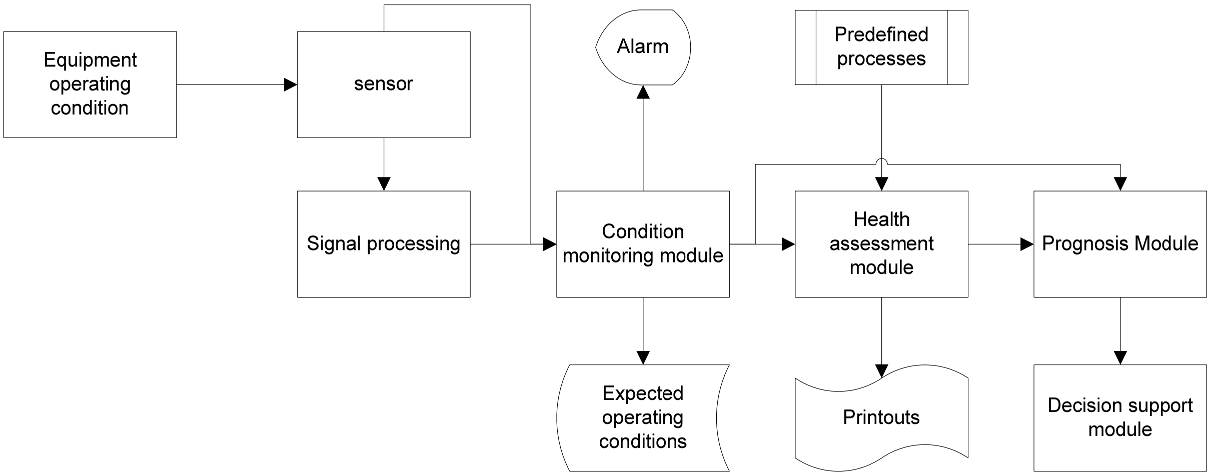

FIGURE 5: OSA-CBM condition based maintenance process flow

CBM is suitable where the cost of failure is high and if the cost of installing a CBM system is economical. CBM is mainly used on costly equipment and those whose failure has serious effect on production and safety. The common maintenance procedures carried out under CBM include vibration analysis, thermography, Ultrasonic and oil analysis. Table 2 gives a summary of the CBM actions and their applications. The first four are the common procedures and are described in detail.

TABLE 2: Condition monitoring techniques and their applications

No	CBM procedure	Applications
1	Vibration analysis	Misalignment, out of balance weights, wear of bearings etc
2	Thermography analysis	Overloading, excessive friction or wear, abnormal electric resistance
3	Ultrasonic analysis	Steam leakage, corona discharge, excessive friction or wear, lubrication breakdown
4	Oil analysis	Contamination, breakdown of lubrication properties, signs of wear
5	Current measurement	Electric overloads, faulty bearings, current leakage
6	Laser alignment tests	Misalignment of rotating shafts, checking level of surfaces
7	Visual inspection	General defects that can be detected by human senses of sight, hearing and feeling
8	Insulation tests	Check status of electric insulation
9	Power rate	Bearing failures, damaged turbine blades, vacuum loss
10	Voltage measurement	Brush failure, excitation faulty, insulation failure

Machine vibration refers to the back and forth movements of a machine or its components. Vibrations are mainly caused by repeating forces which include rotational imbalance, misalignment, wear and improper installation of a piece of equipment. Other possible causes of vibration are looseness of assembled parts and resonance. Resonance is where the frequency of a machine vibration is in harmony with the natural oscillation of the machine. Vibrations are undesirable because they result damage and eventual failure of the equipment. Vibration monitoring and analysis is important means to detect onset of failure in rotation machines and can be used to prevent costly failures (Comtest Instruments Ltd., 2006).

Ultrasonic technology is among the new technique for condition monitoring. New ultrasonic techniques make it possible to 'hear' friction and stress in rotating machines which can predict the onset of deterioration much earlier than conventional monitoring techniques. This is possible because the ultrasonic technology is sensitive to high-frequency sounds that are inaudible to the human ear and distinguishes them from lower-frequency sounds and mechanical vibration. Machine friction and stress waves produce distinctive sounds in the upper ultrasonic range. Changes in these friction and stress waves can suggest deteriorating conditions. With proper ultrasonic measurement and analysis, it's possible to differentiate normal wear from abnormal wear, physical damage, imbalance conditions and lubrication problems based on a direct relationship between asset and operating conditions. This allows amble time to prepare for maintenance and helps to manage spares on just in time basis. By monitoring stress levels and correlating with load, the machine loads and operating parameter can be adjusted to eliminate stresses (Kennedy, 2006).

The applications of ultrasonic include detecting of mechanical wear, detecting of air and steam leakages, detecting of corona discharge from faulty electrical systems such as bushings, transformers and generator stators, analysis of status of lubrication and locating leaks in heat exchanger tubes (Rienstra, 2002). All plant machinery produces sound patterns – both sonic and ultrasonic. Characteristics of those patterns change relative to the health of the machine. Subtle changes in the ultrasonic range can be a sign of wear, changes in lubrication properties and structural degradation of mechanical components (bearings, couplings, gears, valves, etc). Leaking pressurized fluids such as compressed air and steam create noise that has both an audible and ultrasonic component. The ultrasonic component of a leak is very useful for leak detection because of its directional properties and the ability of a quality detector to filter out ambient plant noise. Corona effects, arcing and tracking in electrical systems do not always generate significant increases in temperature and high ambient temperatures can mask hot spots from the infra red camera. However, corona arcing generate distinct noises in the ultrasonic range and are detectable using ultrasonic listening equipment. Ultrasonic detection systems can be used to detect noise defects produced by faulty insulators, line bushings, transformers, potheads, and arresters. Poor lubrication result in increased acoustic sounds which is an indication of lubrication breakdown. By trending bearing acoustic sounds against baseline, the onset of lubrication breakdown can be detected. Ultrasonic can also be useful in detecting leakages in heat exchangers.

Oil sampling and oil analysis is an important condition monitoring procedure for rotating equipment that require lubrication. The article 'Oil Analysis 101' (Walsh, 2005) describes the importance of oil analysis for rotating machines and compares it to blood tests in humans. The process of oil analysis involves taking a sample of lubricating oil and carrying out selected tests to establish if its properties are still suitable for continued use or not and to determine the possible sources of problems. The Oil laboratory service (USA Industrial Group, 2002) in their website lists close to twenty different types of oil tests and their purposes. They include water tests, sulphur tests, viscosity, flash point and elemental analysis among others.

Infrared thermography is another CBM technique which detects heat 'signature created by abnormally faulty mechanical equipment, high electrical resistance or high current flow in electrical systems. High resistance is commonly associated with poor conductor connections which may lead to fire hazards or unplanned shutdown. Abnormally high current though the electrical system can be caused by overload of the circuit when the equipment draw excessive current. Most mechanical systems generate heat during operation due to friction. It is usually possible to find rated temperature values for different types of equipment (from the manufacturer's datasheets) compare those values with the inspection results to detect abnormalities.

3.1.3 Corrective maintenance

Corrective maintenance (CM) is the maintenance strategy in which equipment is allowed to run until it fails after which maintenance is scheduled and executed. It is also known as run to failure or no scheduled maintenance. This strategy is cost effective when the failure has negligible safety, environment and functional impact and the repair of the failed component is cost effective. Modern system designs incorporate a fail-safe mechanism where the equipment will safely shut itself out when it fails (August, 1999). In addition, some modern systems designs incorporate redundant capacity which allows for a run to failure.

According to reliability solutions (Plucknette, 2002), the run to failure strategy is suitable in conditions where:

- Failure cannot be predicted through the use of condition monitoring such as where failure occurs too quickly to be predicted.
- Failure cannot be prevented by using a PM task.
- Failure cannot be eliminated through redesign such as where the component has been in service several years with no failures and there is no justification for redesign.
- Failure has no or limited consequences on safety and production and the cost from failure are low.

3.2 Description of management methods

This section describes the formal management methods used by institutions to run their business processes and by maintenance to determine and select maintenance strategies that can optimize maintenance. The ones considered in this report include reliability centred maintenance (RCM), six sigma and lean maintenance. In addition, the methods representing the informal decision and planning processes used by various maintenance organizations are to manage their maintenance processes are discussed under classical management methods.

3.2.1 Reliability centred maintenance (RCM)

Reliability centred maintenance (RCM) is an analytical method used to determine appropriate failure management strategies to ensure safe and cost-effective operations of a physical asset in a given operating environment. RCM involves understanding the plant goals and needs, understanding the equipment (how it serves, ages and fails) and then developing maintenance strategies to optimize the plant goals. The RCM approach requires an extensive knowledge of the reliability and maintainability of the system and its components. The important elements in RCM are the mean time between failure (MTBF), mean time to repair (MTTR) and failure rate (FR). Some guiding questions used in RCM development include:

- What are the functions and associated performance standards of the asset in its present operating context?
- In what ways does the asset fail to fulfil its functions?
- What causes each functional failure?
- What happens when each failure occurs?
- In what way does each failure matter?
- What can be done to prevent each failure?
- What should be done if a suitable preventive task cannot be found?

The objectives of an RCM approach include safety, preservation of functionality in the most economic manner, improve efficiency of the system being maintained and the related systems and optimize the maintenance by foreseeing downtime and scheduling other activities in response to the foreseen downtime. RCM aims to orient the thinking of an organization in line with its strategic mission statement. Under an RCM method, the focus of maintenance is on functional failure of systems and equipment. RCM puts emphasis on the understanding of the processes and in identifying, understanding and studying of failure modes and the root causes of failures. RCM applies statistical analysis of failures and making decisions based on facts. Table 3 is a summary of the main objectives of an RCM system.

TABLE 3: Summary of the key objectives of an RCM method

No.	Main objectives	How they are achieved
1	Ensure equipment reliability	Reliability modelling
2	Ensure safety through appropriate PM actions	Classify types of failure Analyze failure consequences
3	Ensure equipment functionality in the most economic manner	Effectiveness of PM Economic viability of PM Preservation of function

According to the articles reliability tips (IDCON Inc., 2006), RCM is very useful method when designing, selecting, and installing new systems in a plant, setting up preventive maintenance for complex equipment and systems whose functioning is not clearly understood and when teaching people the basics of reliability. RCM is not be very useful when defining PM procedures for typical plant equipment like pumps, motors, couplings, cylinders and hydraulics since their failure modes are well known and tedious RCM procedure cannot be justified. RCM is suitable for newly installed equipment and complex systems where failure modes are not clear but their reliability and safety requirements are high.

The implementation of **RCM** follows a systematic procedure. The IBM asset management group (IBM Corporation Software Group, 2007) presents seven main steps in RCM development. These are illustrated in Figure 6 and are described below:

Step 1: *Develop an overall RCM program plan.*
This step involves carefully selecting the target equipment for RCM analysis in order to get maximum benefits. The aim is to identify the equipment in which maintenance yields most benefits.

Step 2: *Breakdown and group equipment for RCM analysis:*
Classify equipment into main system to subsystem and within unit levels in a way that is consistent with the existing maintenance strategy, tasks, routines and levels of unit replacement.

Step 3: *Carry out a failure mode, effects and criticality analysis (FMECA):*
Do an FMECA to isolate ways in which the equipment can fail and seek to identify the significance of these failures in terms of their impact on safety, environmental risk, operations and costs. In doing this, FMECA evaluates both probability and consequence of failures, providing the basis for making risk-based decisions to optimize maintenance activities. While engineering judgment is a key element of FMECA, its full potential can only be delivered with strong data support.

Step 4: *Perform a criticality ranking of the potential failures according to the probability and the severity of consequence for the organization:*
Determine whether the loss of equipment function resulting from each failure is significant or not, and hence whether further consideration of the failure by the RCM process is justified. This is a key stage

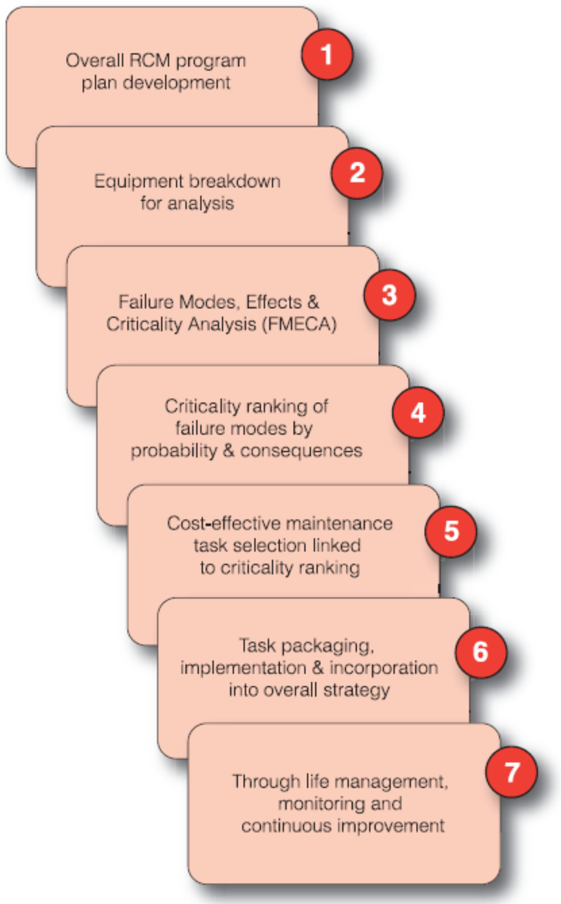

FIGURE 6: Steps followed in developing and implementing RCM

in determining how effective RCM can be in removing non-productive work activities. At this stage, all the failures that have insignificant effects are removed from RCM analysis and can be candidates for a run to failure strategy.

Step 5: *Cost-effective maintenance task selection linked to criticality ranking:*
List all the maintenance options and select the most cost-effective mix from these task options. Where there are CBM practices already in place, condition based tasks will offer the most cost effective task ranks. Integrating CBM practices and directly interfacing with plant-based data acquisition systems and hardware such as programmable logic controller (PLC) and supervisory control and data acquisition (SCADA) systems and capabilities to manage data from multiple meters/counters including volume, pressure, transactions and distances. It is also possible to integrate data from industrial engineering systems and components such as controllers, digital communication, displays, power supplies, barriers, samplers, recorders and isolators.

Step 6: *Task packaging, implementation and incorporation into overall strategy.*
The individual tasks determined as a result of the RCM analysis are packaged and integrated within existing maintenance programs. A successful integration results in changed maintenance practices that incorporate a more focused and effective approach, with less wasted effort. The new tasks should integrate easily with existing work programs and should be easily supported by local skills, resources, knowledge or culture. The new maintenance tasks can be selected with the full knowledge of existing in-house or contractor skills and resources so that they are supportable within the existing approach and are easily integrated.

Step 7: *Ongoing monitoring and continuous improvement.*
The most important first step in establishing successful on-going monitoring and continuous improvement processes is to understand the situation as it is. This can be established in Step 1 of the RCM process by setting out the underlying logic for the areas targeted by the program in terms of their impact on key factors such as security, health and safety, environmental risk, operations and costs. This can help ensure that the best results are achieved in return for the expenditure and resources employed in carrying out the RCM program. Managing the entire RCM process helps ensure not only that the most beneficial plant areas are targeted, but also that the best choices are made among maintenance task options, and that the outputs of the RCM work program become an integral part of plant maintenance strategy and execution. The implementation results of the RCM program can be monitored and quantified through the use of utilizing key performance indicators (KPI) and becomes part of a continuous maintenance strategy and performance improvement.

The reliability engineer employs a number of *analytical RCM tools* to optimize reliability relative to mission goals. Some of the more common tools include:

Reliability statistics - Reliability statistics differ from conventional experimental statistics. They provide the means with which to estimate the likelihood that a system will achieve its mission given a stated duration and operating conditions. It is important to become knowledgeable about the methods of reliability engineering in advance of undertaking an RCM project.

Reliability block-diagrams - Once sub-system's reliability is determined, the system can be effectively modeled from the reliability perspective. Once modelled, the weak links usually become evident and can be addressed with reliability growth measures to eliminate the deficiencies.

Failure modes effects and criticality analysis (FMECA) - FMECA is the inductive process of identifying Primary functional failures, their related failure modes or states, the effect of the failure modes on the operation of the system and the associated criticality of the failure mode as a function of impact and likelihood. This valuable analytical tool enables the removal or better management of failure modes through application of advanced maintenance techniques, redesign or redundancy.

Root cause failure analysis (RCFA) - RCFA assesses a failure after it has occurred with the intent to determine the root causes for occurrence. Once the root causes are ascertained, the engineer can assess the risk of recurrence, the success with which the root cause might be controlled and the cost to control it. With this information, a decision can be made to deploy control measures or to let it go.

There are several commercial reliability analysis software available in the market for analysis of plant reliability and executing RCM programs. Reliasoft Corporation (www.reliasoft.com) presents ten types of commercial reliability software in their web page. Their selection depends on the needs of the user and the tasks to be accomplished.

3.2.2 Lean maintenance

Lean maintenance is the application of lean philosophy, lean tools and lean techniques to manage and execute maintenance functions. Ricky Smith of Life Cycle Engineering (LCE) defines lean maintenance as 'a proactive maintenance operation employing planned and scheduled maintenance activities through *total productive maintenance* practices using maintenance strategies developed through application of *reliability centred maintenance* (RCM) decision logic and practiced by *empowered (self-directed) action teams* using the *5S process*, weekly *Kaizen improvement* events, and *autonomous maintenance* together with *multi-skilled*, maintenance technician-performed maintenance through the committed use of their *work order system* and their computer managed maintenance system (CMMS) or enterprise asset management system' (Smith, 2004).

From this definition, the key elements of a lean maintenance method are:

- Proactive maintenance means that lean maintenance uses PM and CBM strategies to prevent and predict failure instead of reacting to it.
- Planned and scheduled means that the maintenance activities are documented in such a way that the required activities, labour needs, spare parts and time needed to complete the tasks are known in advance. By being scheduled, the maintenance activities are prioritized and assigned a designated action time.
- Application of RCM decision logic means lean maintenance tasks are optimized.
- Self empowered teams' means lean teams are designed so that a maintenance team has all the skills required to execute all the tasks within the team.
- Application of 5S: sort (remove unwanted items), straighten (organize), scrub (clean), standardize (make routine), spread (expand to other areas).
- Kaizen means that lean focuses on continuous evaluation and improvement of the maintenance processes in terms of time, resources use and quality of work.

The practice of lean maintenance is centred on the separation of "value-adding" from "non-value-adding" maintenance activities with the objective of eliminating the root causes of non-value adding activities and their related costs. Lean method encompasses philosophies of several maintenance and production concepts. Figure 7 illustrates the concepts and beliefs on which lean philosophy is build.

FIGURE 7: Illustration of building concepts of lean philosophy

The objectives of the lean maintenance method are to give equipment a near 100% uptime and reliability and to cut down maintenance costs by identifying the stresses that affect the machine and protecting the machine from those stresses. Howard Cooper of Amemco (Cooper, 2002) concludes that 'Lean Maintenance is basically reliability and reduced need for maintenance troubleshooting and repairs. Lean Maintenance comes from protecting against the real causes of equipment downtime, not just their symptoms'. He identifies causes of down time as:

- Down time due to operator or program error.
- Downtime due to inadequate PM and downtime due to chronic wear and stresses.
- Downtime from chronic wear & stress to circuit boards, hydraulic components and other system components.

The stresses that cause downtime include heat, vibration, oxidation & corrosion, dirt build-up, electrical voltage transients and current surges, hydraulic contaminations of dirt, water & acids, etc. Howard emphasizes that the last cause is generally neglected in most maintenance management method and is what a lean maintenance method focuses on.

Many authors have highlighted several benefits from application of lean maintenance. The benefits cited include reduction in lead time, cost of poor quality, waste, production costs and inventory size. Other benefits are increased productivity of manpower and competitive market position. The article 'lean principles' (Kilpatrick, 2003) classifies the benefits of lean maintenance into three types:

1. Operational gains– reduced lead time, increase productivity, reduced inventory, and improved quality.
2. Administrative improvements – reduced paperwork, reduced staffing, reduced process errors, streamlined customer care, cost reduction, job standardization.
3. Strategic gains in achieving overall company goals.

A white paper from Infor Global Solutions (2007) identifies four areas that can benefit from lean maintenance as optimization of spare parts inventory management, achieving quality preventive maintenance through better management, cross training of staff for multi-skilled task force and a continuous improvement drive in the maintenance spectrum.

Lean organizations reduce costs by eliminating maintenance activities that don't add value to the product. There are several types of lean wastes that have been identified by several authors. Table 4 is a summary of 8 types of wastes encountered in maintenance as pointed out by Daryl Mather of Plant Services ltd (Mather, 2007). Lean maintenance can be effective in conditions where the kinds of wastes in the table exist.

TABLE 4: Types of wastes identified by a lean maintenance system

Waste type	Description
Unproductive work	Efficiently doing work that is not needed
Delays in motion	Delays waiting for spares, outage, isolation, people etc.
Poor inventory managem.	Excessive inventory, not having the right parts when needed
Rework	Having to repeat maintenance tasks due to poor workmanship
Underutilized staff	Using people to the limits of their qualification, not to the limits of their abilities
Ineffective data managem.	Collecting data that is of no use, failing to collect the data that is needed
Unnecessary motion	Unneeded travel to the to tool stores, workshop, looking for items, etc
Misapplication of machinery	Incorrect operational strategies that lead to maintenance work being done when it need not be done

Some authors refer lean maintenance as lean six sigma and apply similar phases as those used in six sigma improvement methodology (DMAIC). The article 'lean maintenance for lean manufacturing' (Cooper, 2002) discuses the lean six sigma steps applied to maintenance of manufacturing systems. The activities in lean six sigma steps are discussed below.

Define the problem: In lean maintenance, the problem is any activity that does not add value to the maintenance function, a waste and should be eliminated. In the lean define phase, the non-value adding maintenance efforts and wastes are identified. These will include unnecessary human movements, excessive inventory, unplanned downtime and repeated maintenance (rework) among other wastes as shown in Table 3.

Monitor and measure the waste: In this step, the problem is monitored with the objective of determining how they occur and calculating the actual costs of the resulting wastes. This step is used to establish the size of wastes in the system.

Analyze how to solve or eliminate the problem: this will involve analysing the processes to determine the most cost effective way to eliminate the wastes involved. The possible ways to eliminate the causes of wastes are analysed and the most optimum ways are identified and evaluated to find the best option.

Implement the lean improvement actions: Put in place the actions that will protect the equipment from the stresses that cause downtime and wastes. This involves implementing the activities that are aimed at eliminating the wastes as identified in the analyze phase.

Control to sustain the improvement: Most lean improvement projects are single step protective procedures that may not require control once the project has been implemented successfully. When the causes of stresses that result in wastes have been identified and eliminated, the control tasks are limited.

Figure 8 illustrate some of the systematic steps followed in reaching a decision to implement lean maintenance in an organization.

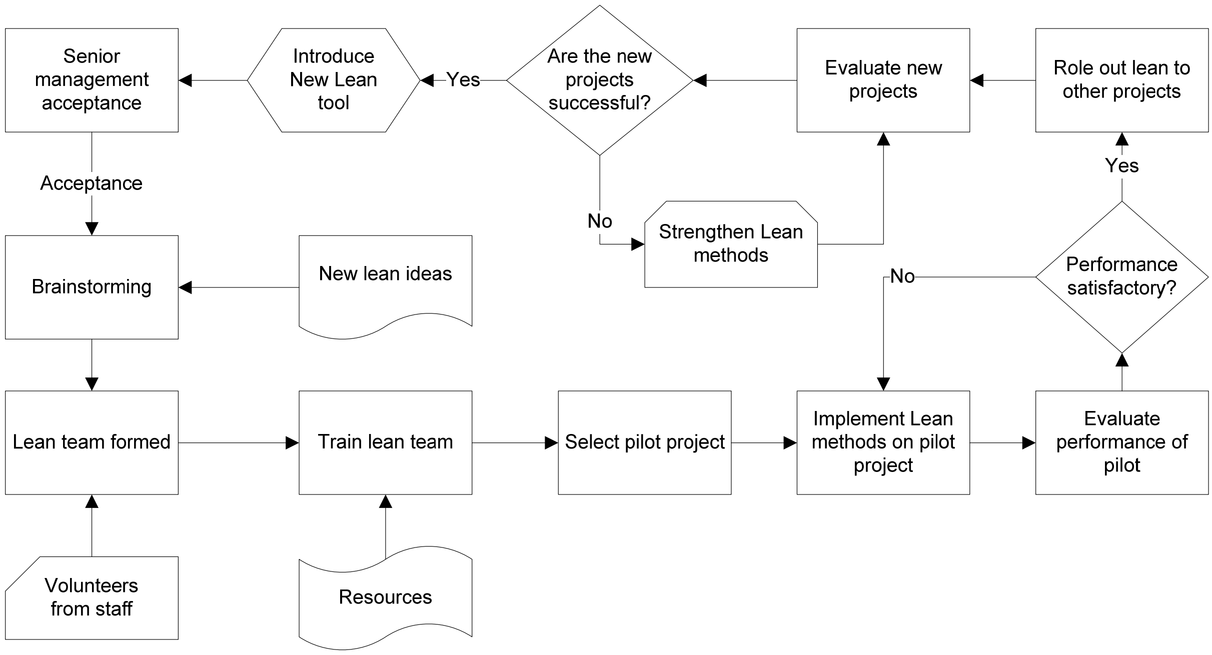

FIGURE 8: Decision flow process for implementation of lean maintenance

There are a number of barriers that can inhibit the success of lean maintenance initiative. The lean principles article (Kilpatrick, 2003) discusses several 'barriers to successful lean implementation' which include failure by the company to tie the improvement metrics to financial statements, implementation of lean building blocks in the wrong sequences, poor selection of lean improvement projects and overlooking of administrative areas in lean improvement initiatives. It is important that these barriers are not considered when designing and implementing lean. A number of tools used to implement lean principles in the manufacturing field also apply to application of lean in the maintenance field. These tools include but not limited to the following:

- The 5S: Sort, Straighten, Shine, Standardize and Sustain.
- Elimination of Deming's seven deadly wastes: management by fear, short term thinking, lack of consistency of purpose, hiding weak sides, job hopping by management, excessive medical and litigation costs.
- Kaizen – continuous improvement.
- Jidoka - Quality at source.
- JIT - Just in time.
- TPM – Total productive maintenance.
- Value stream mapping – process control and planning material flow.

3.2.3 Six-sigma

Wikipedia, the free encyclopadia website describes six sigma as a system of management practices originally pioneered by Bill Smith at Motorola in 1986 as a metric for measuring defects and systematically improving processes by eliminating defects and is also a registered trade mark of Motorola Inc. The book 'the six sigma way' describes six sigma as a comprehensive and flexible management system for achieving, sustaining and maximizing business success, a process driven by closely understanding customer needs, disciplined use of facts, data and statistical analysis and and build on diligent attention to managing, improving and reinventing business processes (Pande et al., 2000). The core elements of the six sigma method that emerge from the various definitions and explanations include:

- Close understanding of customer needs
- Diligent use of statistical analysis for analysis and support decisions
- Systematic, structured approach to issues affecting processes
- Continuous and sustained improvement.

The objectives and benefits of the six sigma initiative are given in Table 5.

TABLE 5: Objectives and benefits of a six sigma maintenance approach

	Objectives	Benefits
1	Sustaining business success	Increased market share
2	Setting a performance goal for each staff	Increased productivity
3	Enhancing value to the customer	Retention of customers
4	Accelerating rate of improvement	Developing new products and services
5	Promoting the culture of learning	Reduced costs
6	Achieving a better understanding of company processes and procedures	Reduced defects, reduce cycle times

The term sigma (σ) refers to statistical standard deviation which is a measure of the degree of variation from the mean in a population. A deviation from the population mean represents a defect or non-conformity. A six sigma standard is equivalent to six standard deviations corresponding to 3.4 defects per million opportunities (DPMO). The importance of variation in processes from the mean is illustrated in Figure 9. It is seen that the level of variation from the mean represent the level of defects or the sigma level. The relations between the sigma level and the number of defects is shown in Table 6. It is seen that defect level reflects the spread of the variable (X) about the mean value. A narrow spread of a population about the mean value is most desirable as it corresponds to less defects. This spread about the mean (desirable) value reflects the status of a given process and is often used as basis to correct the process. A population mean outside the expected mean indicates a process that is out of control.

The required inputs and tools for implementing the six sigma process are shown in Figure 10.

The advocates of six sigma recommend the method for any organization that thinks there is a better way that they can carry out their functions (a room for improvement). There are four ways in which six sigma guides and helps organizations. These are:

1. Understand and manage the requirements of their customer by defining who their customers are and determining what their requirements are and how the requirements can be met
2. Identify the key business processes that contribute to meeting the customers requirements and aligning organizations business processes to the customer needs
3. Utilize rigorous data analysis to minimize variations in the key business processes so that the customer needs are met consistently
4. Drive to rapid, sustainable and continuous improvement of their business processes.

The standard steps in implementation six sigma in an organization are depicted in Figure 11 where the main processes in the application of six sigma are shown.

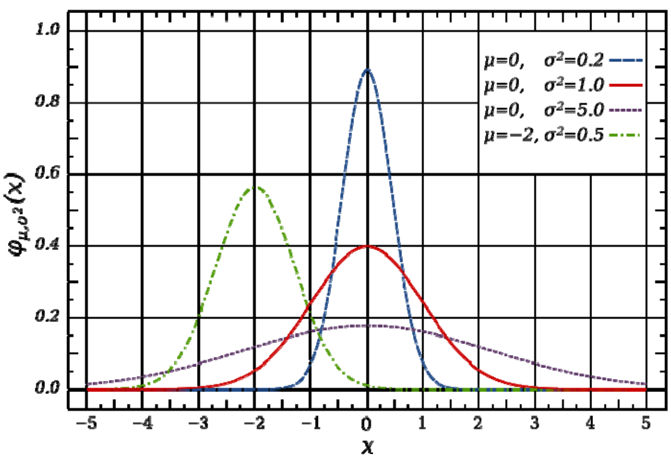

FIGURE 9: Illustration of the effects of variation of processes about the mean

TABLE 6: The number of defects for different sigma levels

Sigma Rating	Number of defects per opportunities	
6	3.4	per million
5	230	per million
4	6210	per million
3	67	per thousand
2	31	per hundred
1	69	per hundred

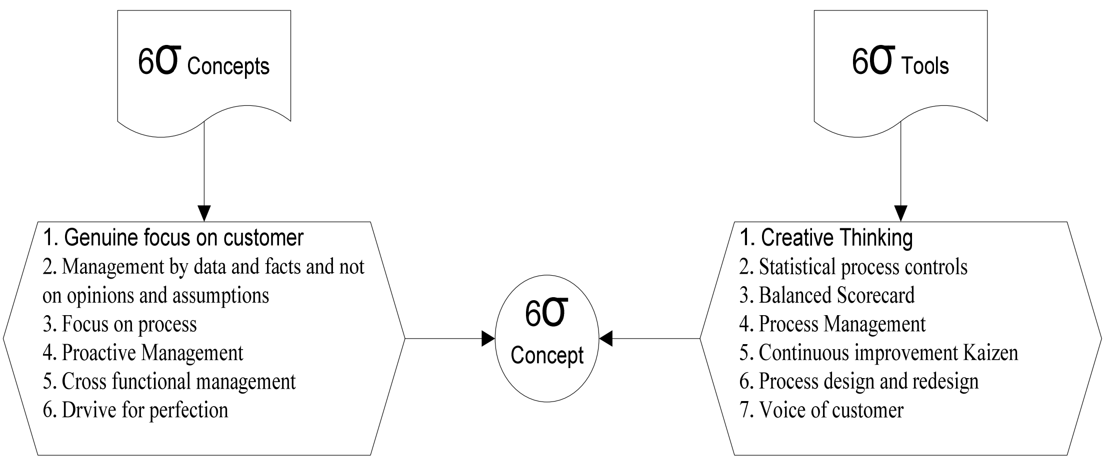

FIGURE 10: Inputs into a six sigma concept

Six sigma has two kinds of methodologies, namely:

1. An improvement methodology consisting of the phases define, measure, analyse, improve and control (DMAIC) which is used to improve existing processes or systems.

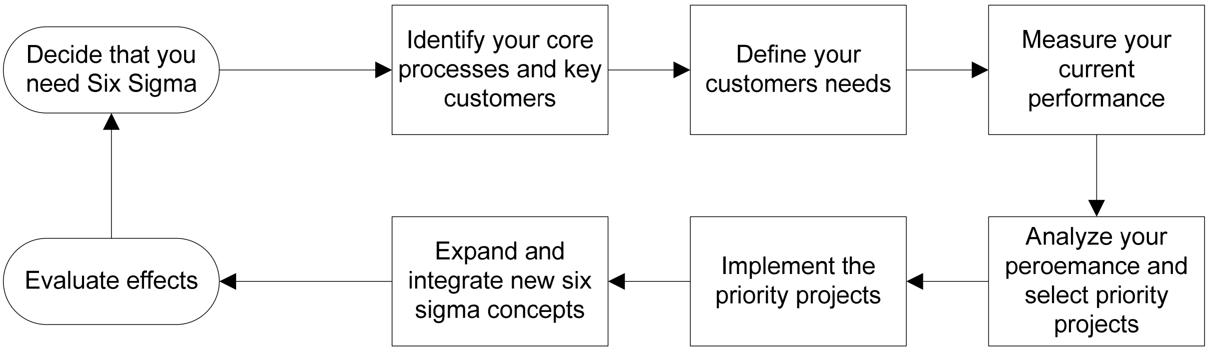

FIGURE 11: Steps in the implementation of the six sigma method

2. A design methodology consisting of the phases define, measure, analyze, design and verify (DMADV) which is used to create new product or process designs or inventions in such a way that the new or improved process or product is predictable, mature and defect free.

The most appropriate methodology for management of maintenance processes is the DMAIC improvement method. The DMAIC phases are described below following a model contained in a presentation called 'the six sigma tools for early adopters' (Hefner and Siviy, 2006).

Define phase: The purpose of the define phase is to identify the major problems within the organization or a section of the organization. In this phase, the problem and goal statements are refined and the scope of the project and boundaries are defined. The problems can include excessive downtime, frequent failure of critical equipment, high maintenance costs and poor quality of maintenance work among other maintenance related problems. The define step clearly describes the processes associated with the problem and identifies the key issue that require to be solved.

Measure phase: The purpose of the measure phase is to gather information and data on the existing situation related to the problem. This step determines and obtains the data necessary for the analysis of the problem which include accumulation of existing procedure, equipment histories and baselines.

Analyze phase: The purpose of the phase is to identify the causes of the problems. The phase explores the data obtained in the measure phase, generates some hypothesis and updates the goal and scope of the improvement project. In this phase, the characteristics of the data are determined and the driving forces evaluated, the cause effect relationship is explored, failure causes and consequences are evaluated.

Improve phase: In the improve step, the possible solutions are identified and evaluated and the optimum solution is selected. Each solution selected must be feasible and cost effective. Tools used in the phase include brainstorming, benchmarking and decision matrix. The selected solution is then implemented and the outcome evaluated to determine if it yielded the desired results. Some authors recommend a separate phase of implementation in which the resources are assigned and responsibility and accountability conferred.

Control phase: The purpose of the control phase is to ensure that the maintenance improvement projects are implemented effectively and the gains of the improvement projected are achieved and additional improvements are sought. The phase involves determining the improvement method needed, implementing and documenting.
Figure 12 describes the six sigma DMAIC process steps and the main activities in each step.

In implementing and managing six sigma, leadership is very important. The method has a leadership hierarchy. The roles of top company management are emphasized. The leadership structure and roles of top leaders is illustrated in Figure 13.

There are several tools used in six sigma method. Each phase has a set of tools applied in the phase. The most common tools in each phase are given in Table 7.

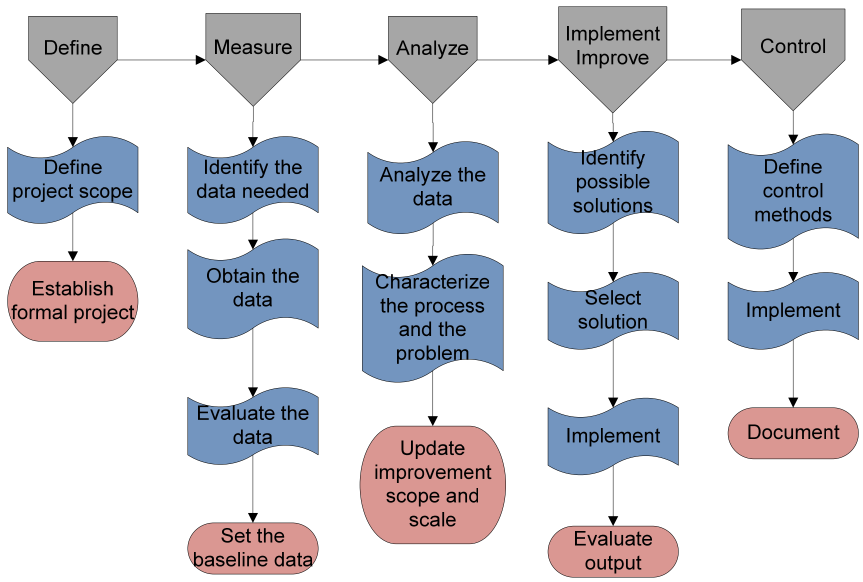

FIGURE 12: The six sigma DMAIC steps and key activities

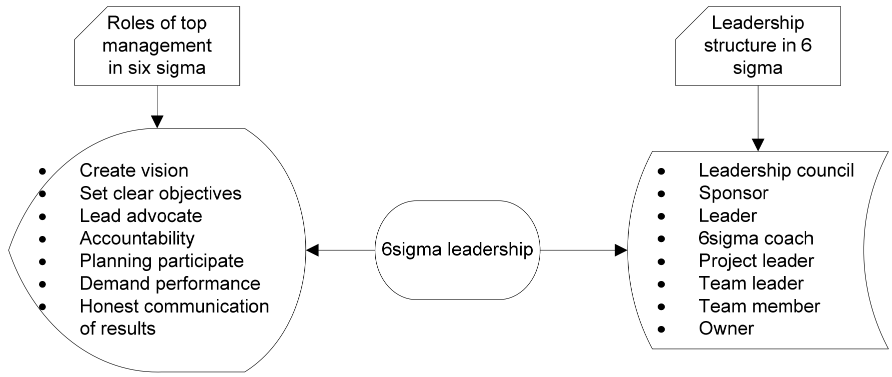

FIGURE 13: The roles of top management and leadership structure of a six sigma

TABLE 7: Summary of main tools for each phase of six sigma DMAIC

Six sigma phase	Tools
Define	Benchmarking Voice of customer Quality function deployment Process mapping
Measure	Measurement system evaluation Data collection methods Defects measurement
Analyze	Cause and effect diagram Failure mode effects analysis Statistical inference Pareto diagram Root cause analysis
Improve	Design of experiments Decision and risk analysis Systems thinking
Control	Control charts Time series Performance management Preventive measures

3.2.4 Classical management models

The classical management models are the non informal models that are used by maintenance organizations to plan and execute their maintenance functions. Most organizations build their own maintenance management systems depending on their maintenance needs, their intuitive judgement and experiences and supported by recommendations of the vendors of equipment. Most manufacturers of equipment recommend maintenance practices accompanying their equipment in the maintenance manuals. Their recommendations assume a standard application and operation of equipment according to design conditions. In reality, equipment are seldom operated according to design. For example, equipment can be overloaded or underutilized and the operating environment is not always according to design criteria and these render the maintenance recommendations in the maintenance manual ineffective when the equipment is operated different from design.

Visits to several geothermal power plants, hydropower plants and some aluminium smelting plants revealed that the classical maintenance management approach is widely practiced. None of the geothermal plants was found to apply any of the conventional management methods to their maintenance. At Olkaria geothermal power plants in Kenya, vendor recommended preventive maintenance procedures are widely used to design and schedule maintenance activities. An informal interview with the maintenance staff at Svartsengi geothermal power plant in Iceland showed whereas the management there had planned to implement an RCM method for their maintenance, the implementation was found difficult due to the high cost and the complexity of an RCM procedure and in the view that their traditional approach was still effective, the plan was shelved. During discussions at the power plants, it was found that certain maintenance activities carried out at the power plant fitted well with some procedures of the formal management methods such as process improvements for six sigma, fault tracing procedure for RCM and waste elimination actions for lean. At Krafla geothermal power plant in Iceland, it was found that most decisions are based on experience, ventor recommendations and condition based. During telephone interviews with one maintenance staff at Alcoa aluminium plant in Iceland, it was seen that the company recently implemented RCM as principle maintenance management method but they were yet to measure the performance results. Discussions with personnel at ISAL aluminium plant in Iceland showed that they use RCM to design maintenance strategies and also six sigma for improvement projects and lean method for waste cutting measures.

In this research, it was found that the most common reasons given by organizations for not adopting the formal methods include high costs to implement the methods, the tedious tasks in the methods and the high skills and training required to implement and run the formal methods. Some organizations argued that their classical maintenance methods were working well and they did not need to experiment the new methods.

4. MAINTENANCE NEEDS AND PRACTICES IN GEOTHERMAL POWER PLANTS

The processes that give rise to geothermal waters take place naturally deep beneath the surface of the earth and involve water-rock interactions at high pressures and elevated temperatures. The resultant fluids contain varying concentrations of dissolved and suspended rock-based elements such as silica, chlorides, carbonates and sulphur compounds among others in varying quantities. The fluids reach the surface equipment with varying quantities of these elements and quantities of gases depending on the geothermal field. The presence of these elements in geothermal fluids presents major challenges in the maintenance of equipment in geothermal power plants (GPPs). The suspended solids which include silica, chlorides and rock cuttings are transported in the hot water and can settle at the bottom of equipment and can cause blockage on the hot water equipment and drains. The dissolved solids like silica, chlorides and sulphur precipitate when the saturation conditions are reached and cause scaling on the walls of equipment. The scaling causes blockages, sealing and impedes normal functioning of equipment. Dissolved and mixed gases which include hydrogen sulphide (H_2S), oxygen and carbon dioxide (CO_2) can make the solution acidic which can cause accelerated corrosion in the presence of heat, water and oxygen.

To understand and determine maintenance needs of GPPs, a failure mode and effect analysis (FMEA) was performed. All the potential failures for each equipment in the plant were established together with the all the possible causes each potential failures. All the possible consequences are determined and the maintenance actions needed to prevent the potential failure or mitigate after failure has occurred can be determined by analysing the failure mode. A detailed FMEA for a GPP is presented in Appendix 1. A summary of potential failures and corrective and preventive maintenance needs for GPPs are given in Table 8.

The maintenance practices in GPPs vary from vary from one field to another depending on the nature of field, the plant design and the inherent practices. Each plant has its own method of doing maintenance based on experience and unique problems in the plant in addition to recommendations by manufacturers of equipment. Visits and interviews were contacted in selected GPPs in Iceland, in addition to experience from Olkaria GPPs in Kenya. An overview of maintenance practices in these power plants in relation to properties of the geothermal fluids is discussed.

4.1 Evaluation of maintenance needs of a GPP

4.1.1 Main equipment in of a typical GPP

A typical GPP has hundreds of operating equipment that have to be maintained to preserve their functionality, maintain plant safety and improve plant efficiency. A generalized flow diagram for a typical electricity producing GPP is shown in Figure 14 below. Only major processes and equipment are shown. A complete assembly of a GPP consist of thousands of components that make it a complex.

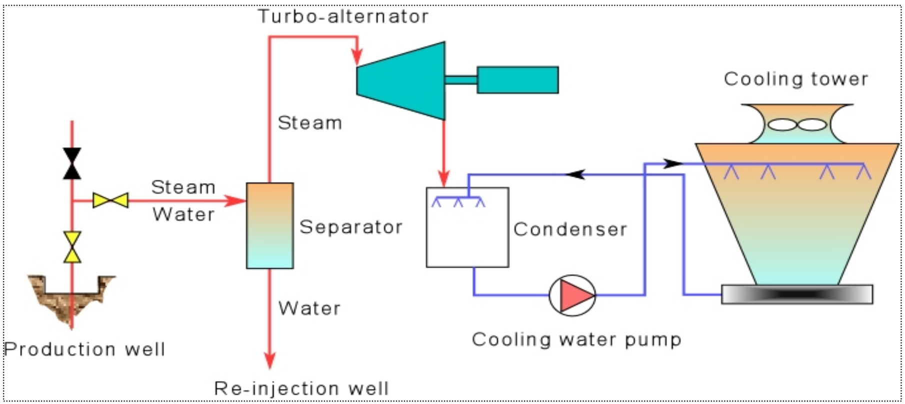

FIGURE 14: A simplified process flow diagram for a GPP

In a typical electricity producing GPP, the main processes are steam gathering and transmission, turbine and its auxiliaries, generator and electrical, Gas extraction, cooling processes and instrumentation and controls. A summary of the main components in the processes is shown in Table 8. Only the major components under each system are presented.

TABLE 8: Equipment in a typical an electricity producing GPP

System/process	Main equipment	Main components
Production and transmission	Wellhead Separator station Steam transmission Water transmission	Master valves, flow control valve, two-phase pipeline Separator vessel, pressure relief device, level control Steam pipe, condensate drains, steam pressure, controllers, steam driers, steam flow meters Hot water pipeline, hot water pressure relieve
Turbine and auxiliaries	Inlet devices Steam Turbine Oil system	Steam strainer, emergency valves, governor valves Rotor, nozzles, diaphragms, bearings, casing, gland seals Oil pumps, servomotors, oil tanks, oil pipes
Cooling system	Cooling towers Water pumps Condenser	Fans, motors, gear reducers, structure, fills, cold water ponds, strainers Large hot well pumps and motors, auxiliary pumps Condenser heat exchangers, nozzles, gas cooling
Gas extraction system	Steam jet ejector Vacuum pump	Control valves, isolating valves, nozzles, intercoolers Vacuum pump, water seal, motor
Generator and electrical	Generator Transformers Protection	Rotor, stator, exciter, bearings, coolers Step up transformers, station transformers Relays, switchgears,

4.1.2 Failure mode and effect analysis (FMEA) for GPPs

Failure modes define the ways that failure of equipment occurs and the circumstance associated with the failure. The causes of failure refer to the likely originators of the failure while the effects of failure define what happens if and when failure occurs. The effects of failure include functional, the safety, operational and the economic consequences. The effects of the potential failure affect the maintenance approach to be adopted for the particular equipment whether to prevent the failure from happening or correct the failure after it happens. In doing a FMEA for GPP, the main equipment was grouped into steam gathering and transmission, Turbine and accessories, Cooling and the non-condensable gas extraction system, the generator and electrical system and Instrumentation, control and protection. The FMEA analysis for each of the systems in a GPP is discussed below:

FMEA for the steam gathering and transmission equipment
The main equipment in the steam gathering and transmission system consist of different types and sizes of valves which include master valves, service valves, drain valves and control valves; pipelines which include two phase pipelines, hot water and steam pipelines; separators that include steam separators, mist separators and condensate drains; silencers and hot water disposal system. The FMEA for main equipment for this system is illustrated by the cause and effect diagram in Figure 15. The diagram shows the potential failures, possible causes and the effects.

FMEA for turbine and auxiliaries
The turbine equipment consists of the turbine rotor and rotor bearings, the casing and diaphragms and the steam glands. The auxiliaries include steam control valves, emergency steam valves and the steam strainers. The turbine rotor is one of the most expensive equipment in GPPs and requires well designed maintenance processes to minimize the risk of failures. A summary of FMEA for a turbine system is illustrated in Figure 16 where the possible failures are given at the roots, the possible causes as links and the effects at the head of the diagram.

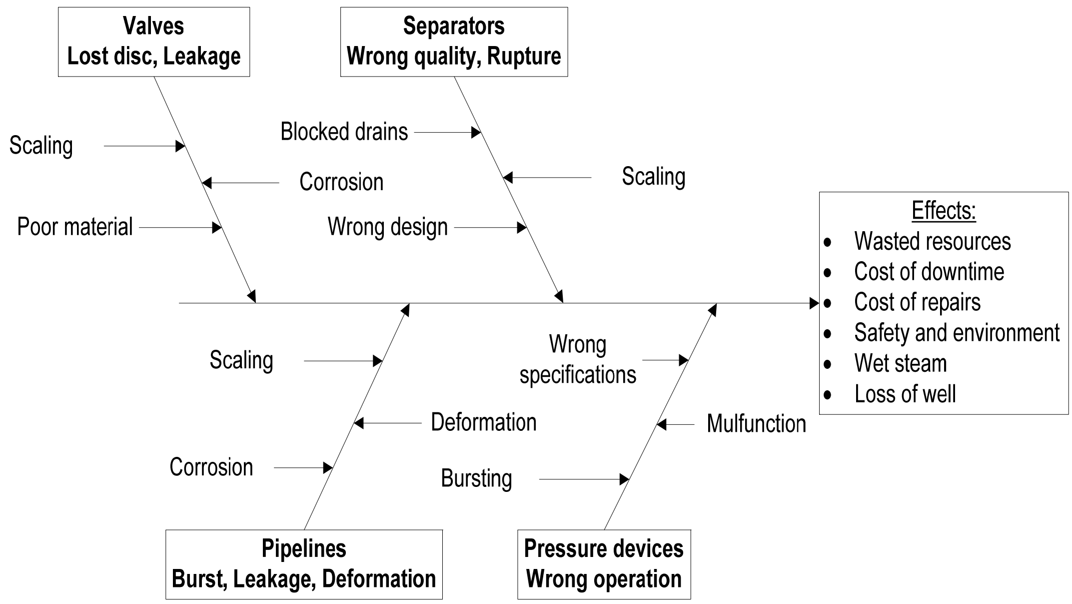

FIGURE 15: Cause effect diagram for a geothermal steam gathering system

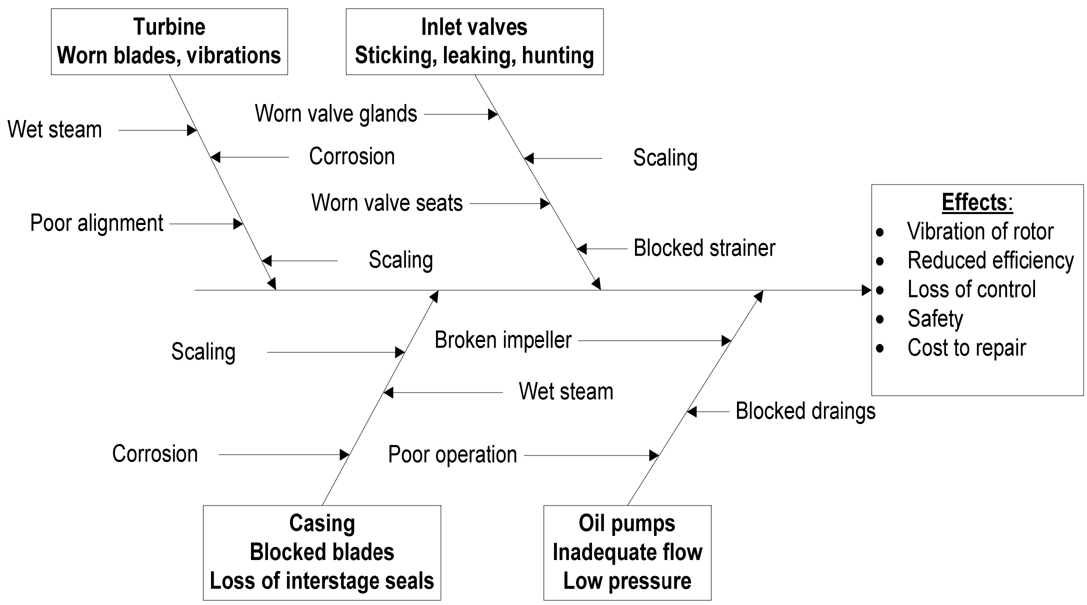

FIGURE 16: Cause effect diagram for a geothermal turbine and main accessories

FMEA for the cooling and NCG extraction system

The cooling system in a GPP is consists of the cooling towers made up of cooling fans and cooling tower structures, hot well pumps and pipes and the steam condenser. The NCG extraction system consists of the gas cooling section in the condenser, the steam jet ejectors and vacuum pumps and the inter-condensers. A summary of the FMEA for the system is summarized in Figure 17.

FMEA for the generator and electrical system

The generator consists of the generator rotor and stator, rotor bearings, generator air coolers and the excitation system. The equipment grouped as electrical system consisting of power cables, switchgear, transformers, motors and relays and several electrical gadgets. Figure 18 is an illustration of the failure cause effect diagram for the generator and electrical system which shows what can fail, the causes and what happens when the failures occur.

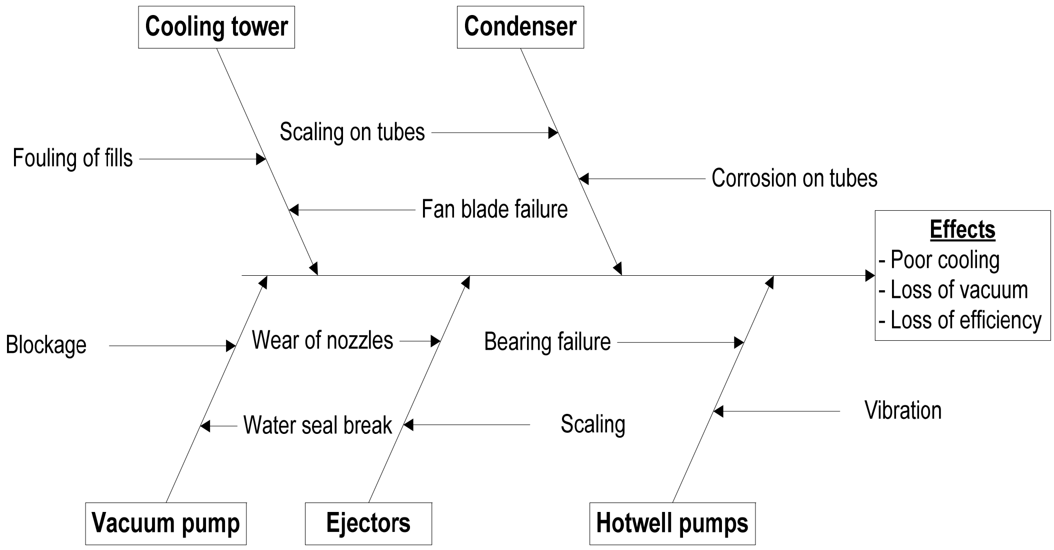

FIGURE 17: Cause effect diagram for geothermal cooling and gas extraction systems

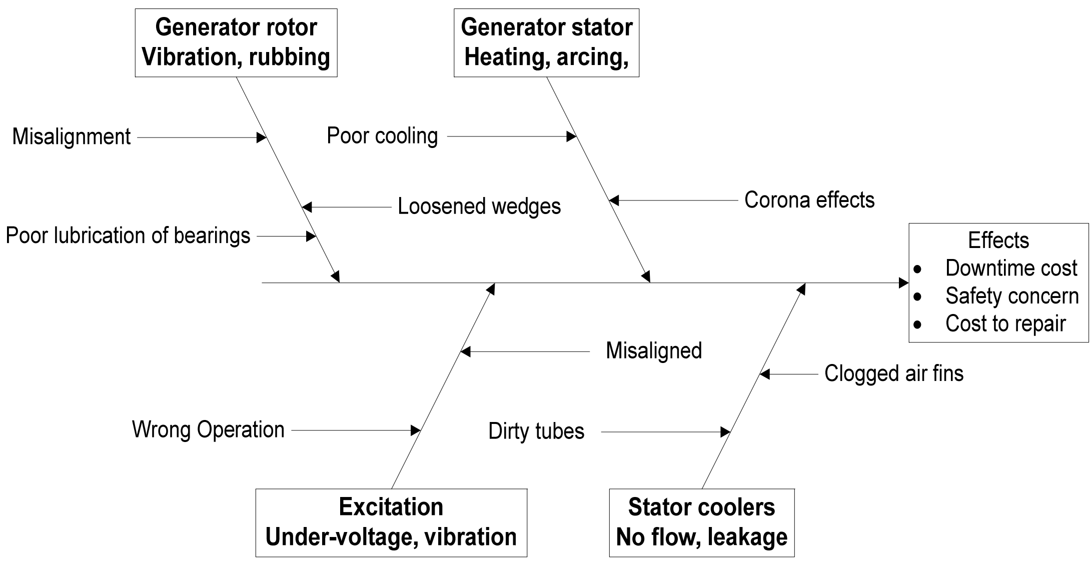

FIGURE 18: Cause effect diagram for the generator and electrical systems

FMCEA for instrumentation, control and protection system

The instrumentation, control and protection are very important parts of a GPP. The instrumentation covers a wide variety of instruments installed in the GPP. The type of instruments depends on the level of technology in the design of the plant but they all serve the purpose of monitoring and communicating the performance of the GPP. The instruments include pressure gauges, temperature gauges, vacuum meters, flow meters etc. The control function is important to ensure the GPP operates within the required limits. Control system receive measured parameter signal and use the value of the signal to generate a control signal to keep the performance within what is desired. One common control system in GPPs is the supervisory control and data acquisition (SCADA) system. The protection systems include all the systems installed to ensure the plant components are protected. They include the protection relays for the generator, transformers and the turbine protection. Because of the sensitivity of these systems, their sound operation is critical. A FMEA for the system is presented in Figure 19.

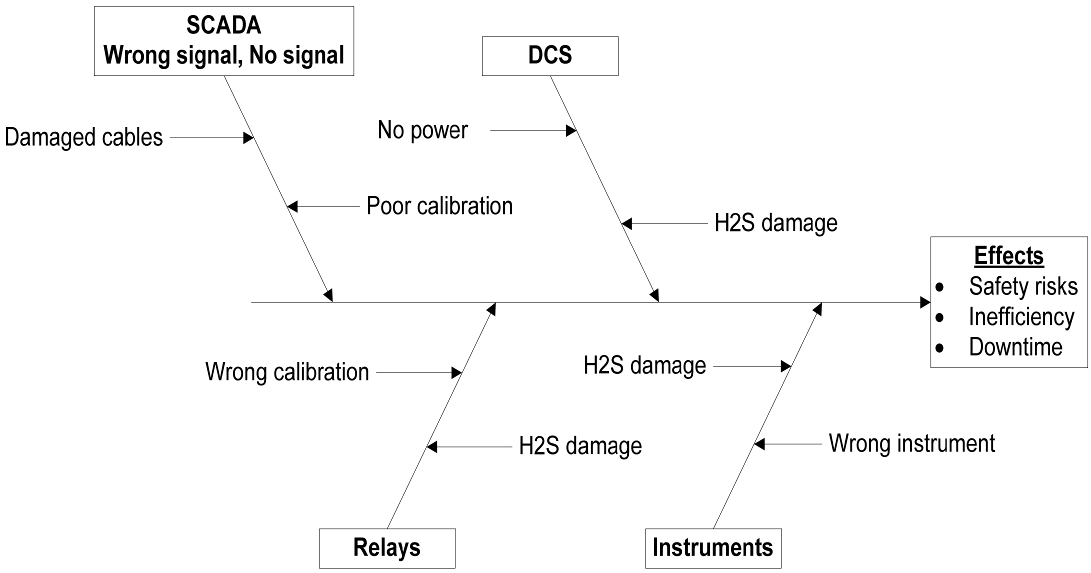

FIGURE 19: Cause effect diagram for instrumentation and control system

4.1.3 Summary of maintenance needs for a GPP

From the findings of the FMEA for each component, the maintenance actions needed to prevent or correct the failures are deduced. The mode of execution of the maintenance needs will depend on the maintenance approach applied and will be guided by the management method applied. Corrective maintenance actions will be required to correct equipment failure that has occurred. In some cases, it is effective to perform a failure preventive maintenance instead of corrective maintenance. The preventive maintenance actions are guided by measured indicators of potential failure or based on interval period derived from experience or vendor recommendations. From the FMEA, it is seen that most of the potential failures in GPPs are linked to the chemical and physical properties of the geothermal fluids. The effects of failures range from safety to performance loss. The nature of potential failures affect the type of maintenance procedures adopted whether to prevent or respond to the failures. A summary of preventive and corrective maintenance needs for each failure modes in a GPP are shown in Table 9.

4.2 Description of maintenance practices in selected GPPs

4.2.1 Olkaria 1&2 GPPs, Kenya

Olkaria 1&2 Geothermal power plants are located in the Olkaria geothermal system in the Rift Valley region of Kenya. The geothermal system in this field is a high temperature system. The plants have installed capacity of 115 MWe from two power plants. Olkaria 1 power plant has three generating sets each rated 15 MWe. Olkaria I steam field has 26 production wells and 1 reinjection well. Olkaria 2 power plant has two generating sets each rated 35 MWe. Olkaria 2 steamfield has 20 production wells and 4 re-injection wells. The mean chemical properties of the geothermal fluids for the scaling and corrosion causing elements in both Olkaria 1&2 steamfields are shown in Table 10, summarized from Kizito Opondo (2006):

The common maintenance problems related to the physical and chemical properties of the geothermal fluids in Olkaria power plants include the following:

- Silica scaling on steam pipes, valves, separators and turbine nozzles
- H_2S attacks on exposed copper material of switchgears, transformers, motors etc
- Extensive surface corrosion of ferrous metals of pipes, pipe supports, structural frames
- Blockage of drains due to deposits of suspended solids and silica in the fluids

- Sticking of valves as a result of scaling cement
- Leaking of valves due to worn valve discs
- Failure of steam traps and condensate drain devices
- Bursting of pressure safety discs due to pressure fluctuations

TABLE 9: Summary of preventive and corrective maintenance needs of a GPP

Failure mode	Preventive actions	Corrective actions
Steam gathering		
Sticking valves Leaking glands Blocked pipes Worn valve discs Failed traps Dislodged pipes	Review operation of valves Redesign maintenance schedule Inhibit scaling agents like silica Redesign of steam traps Check pipe designs	Replace glands Overhaul Replace
Turbine accessories		
Scaling on rotor and diaphragms blades Wear and corrosion Sticking of valves Rotor vibration	Review operating pressures and flow Check the steam drying processes Check the turbine alignment Investigate and correct bearing lubrication Regular Stem free test of valves	Detect and identify the problem Address the cause Repair the failed part Redesign the system
Cooling & NCG		
Fouling of condenser tubes Blocking of nozzles Fouled cooling tower fins Scaling of ejector Vacuum pump water seal breaking	Improve quality of cooling water by treatment and adding fresh water Improve steam processing Chemical dosing of cooling tower Check operating pressures for steam ejectors and vacuum pumps	Detect and identify the problem Address the cause Repair the failed part Redesign the system
Generator electrical		
Rotor vibration Loose stator coils Arcing of switch gears Failure of motors Failure of transformers	Ensure turbine-generator-exciter alignment Eliminate causes of corona effects Maintain correct switchgear operations and contacts Monitor all motors performance Regular test transformer oil, contacts and temperatures	Detect and identify the problem Address the cause Replace stator coils Redesign the system
Instruments, protection & controls		
H_2S damage of copper Wrong control signal Failure of protective relay	Use non copper materials Isolate copper parts from H_2S, e.g. air conditioning Install backup safety Install backup control circuits	Replace damaged copper parts Calibrate equipment Repair or replace damaged parts

TABLE 10: Average properties for fluids from the Olkaria geothermal fields (mg/kg)

Chlorides	Calcites	Silica	H_2S	pH	TDS
475	220	644	4.81	9.04	2316

In the company organization hierarchy, both the power plants are headed by a manager while each plant is supervised by a chief engineer. There are about 60 maintenance staff members maintaining both plants. The maintenance teams consist of mechanical, borefield, electrical, instruments and civil teams. Each team consists of an engineer, a technician and craftsmen. There is elaborate level of specialisation where each section performs distinct tasks and the level of multi-skilling is low. The work schedule consists of:

- Regular 8-hour work during normal working days
- Emergency standby hours during breakdowns
- Overtime hours during major maintenance such as overhauls

Most equipment and systems at Olkaria 1 power plant are based on analogue signal system and are largely manually operated. Olkaria 2 power plant operations are automated and most equipment monitored and controlled via SCADA system with most control signal being digital.

The main method of maintenance used in Olkaria is time based preventive maintenance (PM). The PM programs include major overhauls every five years, annual inspections, semi annual maintenance and monthly tasks. There are 5-year major overhauls for turbines, two year overhauls for auxiliary equipment, annual inspection for the whole plant, semi annual quarterly and monthly maintenance for auxiliaries. Maintenance actions can also be based on observed signs of deterioration.

Besides the preventive maintenance, the power plants are regularly inspected and any potential failure indications will be addressed outside the PM programs. The management for the maintenance procedures is based on management maintenance subsystem (MMS). Monitoring in Olkaria 2 are done online using the distributed control system (DCS) and the SCADA system but in Olkaria 1, monitoring is mainly done manually.

4.2.2 Krafla GPP, Iceland

Krafla GPP is located in the northern Iceland on the Icelandic rift system. The power plant has an installed capacity of 60 MWe from two generating sets. The Krafla steam field has 18 production wells and 2 cold water boreholes. Table 11 shows the average composition of main chemical elements that are significant to plant maintenance (Gudmundsson and Arnórsson, 2002).

TABLE 11: Average properties for fluids from the Krafla geothermal fields (mg/kg)

Chlorides	Calcites	Silica	H_2S	pH	TDS
114	230	943	4.81	23.0	1094

During a visit to the plant, the common maintenance problems related to the physical and chemical properties of the geothermal fluids in the power plant were reported to include:

- Silica scaling on pipelines
- Extensive surface corrosion of metals
- Acid corrosion of turbine blades due to extremely dry steam
- Carbonate scaling

There are 6 persons working full time in Krafla who carry out both operations and all maintenance activities. The staff is multi-skilled and perform all the operations and maintenance functions that include mechanical, electrical, civil works, instrumentation and control. The included in the staff are mechanical and electrical engineers and technicians, scientists and craftsmen. The maintenance work schedule is a 12-hour shift operation and maintenance.

The power plant is highly automated with most equipment monitored online. The maintenance system is run on DMMs software. The level of automation of the plant is complete, with all systems control by DCS system via SCADA. The status of the plant is monitored and controlled via computer stations. The maintenance method used in Krafla is mainly time based preventive maintenance. The PM schedules include major overhauls carried out after every five years, annual inspection and maintenance programmes, semi annual, quarterly and monthly maintenance programs. Besides the preventive maintenance, the power plant is monitored online and any potential failure indications will be addressed outside the PM programs. Some failures are also assigned to corrective maintenance actions.

4.2.3 Svartsengi – Reykjanes GPPs, Iceland

The Svartsengi and Reykjanes GPPs are located on the Reykjanes Peninsula in South Iceland. Svartsengi has an installed capacity of 46 MWe from combination of backpressure and binary generating units and 150 MWt (Thórólfsson, 2005). The plant also has an additional form of direct use in the form of blue lagoon in which the condensate from the power plant is used in a natural pond. The field has 12 production wells and 2 reinjection wells. The Reykjanes GPP which is operated and maintained alongside Svartsengi has an installed capacity of 100 MWe in two units of 50 MWe each. The Reykjanes steam field has 20 production wells and one reinjection well. The mean characteristics of the chemical properties of the geothermal fluids that are important to maintenance is given in Table 12 for both plants (Opondo, 2006).

TABLE 12: Average chemical properties of fluids from Svartsengi-Reykjanes fields (mg/kg)

Field	Chlorides	Calcites	Silica	pH	TDS
Svartsengi	13507	1066	490	5.4	23000
Reykjanes	19648	1800	880	5.3	39000

The management and maintenance of the two plants is done by one team based at svartsengi. There are 22 staff members for the two plants who perform the work of maintenance and operations. The staff members are multi-skilled and perform all the necessary maintenance activities. The staff member comprises mechanical and electrical engineers and technicians, earth and environment scientists. The staff members work on a rotational basis from operations to maintenance functions.

The main method of maintenance used is periodic based preventive maintenance. The maintenance programs include major overhauls that are carried out every five years, annual maintenance, semi annual maintenance, and quarterly and monthly preventive maintenance programs. The plant also apply the operate to fail maintenance for the cooling tower fans. The power plants are continuously monitored via the SCADA network and any emerging failure indications are addressed outside the PM schedules. The maintenance programs are managed by DMM system. The level of automation of the plant is high with most operations remotely controlled. The status of the plant is monitored and controlled via computer stations.

TABLE 13: Summary maintenance features for the selected GPP

Parameter	Units	Olkaria 1&2	Krafla	Svartsengi	Reykjanes
Plant production capacity	MWe MWt	115 -	60 -	75 150	100 -
Production wells Reinjection wells	No. No.	46 4	20 Nil	12 2	20 2
Number of maintenance staff	No	60	6	22	
Estimated staff rates per hour	Kr/hr	1000	3000	3000	
MWe/staff ratio	MWe MWt	2 -	10 -	6.6 7	6.6 -
Fluid properties					
H_2S TDS Silica Chloride Calcites pH	mg/kg	4.81 2316 644 671 220 9.04	23.08 1094 943 114 230 8.73	7.54 39000 880 22000 1067 5.0	0.6 23000 493 18000 1467 6.4
Instrumentation and controls		Analogue-Olk1 SCADA-Olk2	Digital SCADA	Digital SCADA	
Maintenance system used		PM CM	PM CM	PM OTF	
Maintenance management software		MMS	DMMS	DMMS	DMMS

5. APPLICATION AND COMPARISON OF MANAGEMENT METHODS AS APPLIED TO MAINTAIN GEOTHERMAL STEAM GATHERING SYSTEMS (GSGS)

In the preceding chapters, the conventional management methods have been described in a general context. In this chapter, the individual management methods are analysed with reference to their application to maintenance of geothermal steam gathering system (GSGS). The discussions include a description of the activities that would be involved in each phase of the methods and the tools that would be applied to maintain a GSGS under each management method. The methods are then analysed and compared both qualitatively and quantitatively on the basis of the predicted performance when applied to maintain a GSGS. The qualitative comparison was done using analytical hierarchy process (AHP) method while the quantitative comparison was done using a generalized cost model. Finally, the results of the application and comparison are presented and discussed. The objective of comparing the methods is to propose a method that can be used for estimating the suitability of the management methods to maintenance of GPPs using GSGS as a case study.

5.1 Description of application of methods in maintenance of GSGS

5.1.1 Six Sigma method in maintenance of GSGS

The six sigma DMAIC is a general purpose improvement methodology that is suitable for improving effectiveness of maintenance of systems. When applied to manage maintenance of GSGS, the activities in the DMAIC phases and the applicable tools are as described below. The procedure follows a model presented by the paper 'applying six sigma to plant maintenance improvement programs' (Khan, 2006).

The purpose of the **define** phase is to identify the major problems within the system being analysed. The problems in a GSGS could include:

- Repeated breakdowns such as frequent sticking of master valves,
- Lack of spare parts for valves, level controllers, pressure controllers etc
- Poor quality of work by the maintenance team
- Excessive down time during maintenance

Under the define phase, the scope of the desired improvement project is defined and a formal project established. In defining the project scope, the current problems that need solution are identified, the improvement goals, targets and success criteria are established and a business case is set for the improvement goals. The stake holders and the process owners need to be identified. In setting the improvement project, a project plan should be established and approved with means of communicating it. The tools that can be applied in this phase are:

- Critical to quality
- Affinity diagram
- Supplier inputs-outputs relations
- Process mapping

The critical to quality uses tree diagrams to organize the needs, drivers and issues. From the improvement goal, the CTQ process drills down to the critical factors to achieving the improvement goal. In a GSGS, one goal can be to eliminate forced outages of the separator stations and master valves by accurately detecting onset of failure and preventing it from occurring.

Affinity diagram is a method used to categorise all the maintenance issues raised from a brain storming session into equipment or communication issues. All the personnel in the GSGS are involved in the brainstorming sessions to exhaustively identify potential problems and and propose solutions which can be assessed further.

The supplier-input-process-output-customer (SIPOC) process involves listing all the stake holders in one page and provides a summary of the key elements in a process. This procedure helps to ensure the links between suppliers such as for spare parts and the maintenance process itself and the product are made clear. In this way, all the stakeholders are involved in improving the maintenance processes.

Process mapping enables a clear understanding of the processes involved in the improvement effort. Each process has inputs, the process itself and the outputs. Process mapping consists of graphically detailing all the relevant components of a selected process showing all the steps in a process until the output.

The purpose of the **measure phase** is to gather information and data on the current situation. In this phase, the data sources are identified and the methods of collecting the data are articulated. The phase involves identifying the data sources, obtaining the data set, evaluating the data quality and summarizing the baseline data. The tools applicable are:

- Data collecting plan
- Measurement system analysis
- Control charts
- Run charts

Data collecting plan is an information sheet in which to record the equipment to be measured, the type of data to be collected, the measurement method to be used, referenced procedures and when the data is to be collected. For a GSGS, such a data collecting plan will cover the equipment such as wellhead, separators or pressure controllers.

Measurement system analysis: The measured data will not be meaningful unless the measurement techniques are consistently applied, are accurate and not subject to variations. The measurement system analysis is used to ensure this is possible. A gauge R&R is used to evaluate repeatability and reproducibility,

Control chart is used to determine the amount of variation in a process being monitored and to ensure the parameters are set within limits as shown in Figure 20. A desired value of the measured parameter (X) is determined and the maximum and minimum control limits selected. The variations of the measured parameters about the norm are monitored and action is taken if the parameters fall outside the control limits or if there is a sign of unfavourable trends.

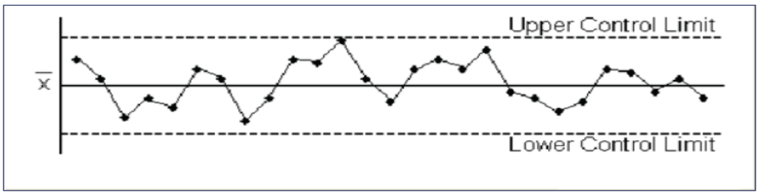

FIGURE 20: Main features of a control chart showing upper and lower limits

Run chart: a plot of process measured versus time used to evaluate data trends and to reveal real patterns. A run chart in GSGS can be like a plot of steam quality against time and using it to detect any changing trend that can signify failure of a process and initiating corrective action.

The goal of the **analyse phase** is to identify the causes of the problems in a system. The step involves analysing in detail the data from the measure phase, explore cause and effect relationships, evaluate failure causes and their consequences and updating the project scope. The tools applied are:

- Pareto charts
- Cause and effect diagrams
- Five whys
- Failure modes and effect analysis
- Fault tree analysis
- Design of experiments

Pareto charts: a bar chart in which the number of occurrences are arranged in descending order and is used to identify the most significant problems on which attention should be focused. In a GSGS, a pareto diagram can be used to pinpoint the most common types of failures in a given system and using it to select targeted solutions to address the problem.

Cause effect diagram or ishikawa or fishbone diagram is used to uncover potential causes of a problem in a pictorial way. In maintenance, the problems are either with the equipment, the process, the people or the procedure related. The diagram seeks to answer the question 'why did the problem occur?'. In GSGS, the method can be used to look for the root causes of failures.

Five whys: a method of reaching underlying causes of a problem by asking 'why does it happen?' five times until the all underlying issues are unearthed. The approach presents an inquisitive method to problem solving leaving nothing to chance.

Failure mode and effect analysis (FMEA): a step by step process to identify potential system or equipment failure, the consequences of such a failure and possible remedial actions. The FMEA steps are:

- Identify the functions of an equipment
- Identify potential functional failure
- Consequences of failure
- Potential causes of failures
- Mitigations
- Risk calculation

Fault tree analysis or logic tree is a methodology used to systematically breakdown the causes of a problem in a tree structure to reach the root causes. You start with the fault and below it are the possible causes downwards until the basic events are described.
Design of experiments also called the cause and effect relationships is a method used to examine the effect of changing any process parameters inorder to determine the true drivers of process variation

In the **improve phase**, possible solutions to the problem are devised and developed so that they can be proposed for approval and funding and the selected solutions are implemented. Some authors separate improve phase into improve and implement phases. Each possible solution must be feasible in terms of resource, time and cost effectiveness. The tools, in the improve phase, are brainstorming, benchmarking and decision matrix. The tools in the implement phase are project charter, gantt chart and work breakdown structure.

Brain storming: in brain storming, team members generate ideas under modest guidelines after which the ideas generated are reviewed and the viable solutions are posed.

Benchmarking is the method of identifying the best practises of similar processes in other businesses and using the data to set goals for improving processes in the organization. The benchmarking targets can be internal, competitor or best in class. From benchmarking result, the gap between the current state and the benchmark is determined and action formulated.

Decision matrix: the method used to evaluate and prioritize action items and potential project that results from benchmarking and brainstorming so that only economically sound projects are pursuit. It involves a criterion to evaluate each project, setting a weighing scale for each project and evaluating of the potential solutions

Project charter: a document to summarize the project which highlights the project title, the team leader and team members, the goals, scope and deliverables, schedule and milestones. The charter is used to get authorization.

The gantt chart: used to detail of the schedule and milestones for the improvement project selected in a graphical way. It shows the tasks, start and end and durations. The Microsoft project is the appropriate software.

Work breakdown structure: method used to divide large project into tasks, subtasks and work packages that can be budgeted, scheduled and controlled. The tools that can be used include design of experiments, systems thinking, decision and risk analysis. In applying design of experiments, the house of quality is used.

After the most feasible maintenance solutions are implemented and the impacts assessed and corrected to achieve desired results, the gains need to be sustained. The purpose of the **control phase** is to ensure that the maintenance improvements are effectively implemented and the gains are realized and to seek to continue to seek additional improvement. The tools are:

- Monitoring process trends and variations
- Monitoring key performance indicators (KPIs)
- Instilling continuous improvement programs

Monitoring of KPIs: a KPI is a trackable process metric that is used to assess progress towards a business target. The kpis are like overall equipment effectiveness, added value of maintenance, profitability, costs of maintenance etc.

Continuous improvement: this is continuous look out for best practices, from within the organization and from outside (benchmarking). The search for continuous improvement is incorporated into the organization culture

5.1.2 Application of reliability centred maintenance (RCM) to maintenance of GSGS

The article 'Enabling the RCM process with IBM Maximo Asset Management' (IBM Corporation Software Group, 2007) presents some main steps used in implementing RCM. A similar RCM approach can be used to lay down the maintenance strategies for a GSGS as discussed below:

Step 1: In developing an RCM program plan, the equipment in the area with the greatest benefits should be identified and selected for RCM analysis. Which equipment of a GSGS would make the greatest savings and overall impacts if their problems are solved? The equipments to be targeted in an RCM approach should be those with high failure rates, high maintenance and failure costs, long downtime, safety and environmental risks. The processes in a GSGS that are potential candidates of an RCM analysis could include leaking master valves, costly repeated puncture steam pipes, scaling on equipment that can cause long outages, failure of pressure controllers etc. It should be planned how the results from analysis of RCM will be implemented, how the results will be measured and how the improvements will be sustained and embedded in ongoing maintenance activities. The activities in this step include establishing the maintenance practices already being performed, the skills available, getting historical maintenance data, collecting and analyzing information on how the systems and equipment operate, collecting and analyzing maintenance data, planning and preparation analysis and definition of company risk criteria.

The potential benefits from an RCM program need to be quantified to justify any investment in the proposed RCM projects. The tools include Computer maintenance management software (CMMS) and Benchmarking. Some of the key performance indicators (KPI) in this stage are mean time between failure (MTBF) and mean time to repair (MTTR).

Step 2: This step involves familiarising with the equipment, their operations and maintenance activities, failure data, risk criteria and classifying the equipment consistent with existing maintenance strategies, tasks, routines and replacement. The classifications will be done based on the function and RCM tool. In a GSGS, operation and maintenance manuals, flow diagrams and steam field drawings and O&M records and failure data should be analysed to familiarise with equipment and how they are operated and maintained and the failure information. The equipments are then grouped in such a way that the grouping is consistent with existing maintenance strategies and also to reflect the RCM tools such as FMEA and fault tree analysis (FTA), Risk analysis etc.

Step 3: In this step, the ways that the equipments can fail are determined and the significance of such failures in terms of impacts on safety, operations, environment risks and costs. Evaluate the probability and consequences of failure and use the results to make risk based maintenance decisions to optimize maintenance by a combination of engineering judgements and data. In GSGS, all the potential failures are determined using plant failure history. The data include sticking of valves, leakages of steam glands, blockage of drains, bursting discs among others. The consequences of each failure are quantified such as safety impacts, down time, environmental damage and the monetary impacts from cost data.

Step 4: The potential failures are ranked according to the probability for failure and severity of the failure consequences (risk based assessment) to the company. This is used to determine whether the loss of equipment from each failure is significant and if further RCM analysis is necessary or not. Failures that are inconsequential (the ones with no adverse on safety and environment and are of negligible costs) can be omitted in the maintenance strategy. This will cut down costs by eliminating non value adding activities. The critical components are then isolated for reliability analysis.

The components of a GSGS are categorized into type reflecting the effects of an individual component failure on overall system reliability. The critical and non critical components are defined. Non critical systems and components can be operated to failure after which they are repaired or replaced. An RCM analysis is performed on critical parts and their maintenance is optimised. Use the historical data maintenance data.

Step 5: When all the potential failures have been identified and analysed, they are ranked according to their probability of occurring and the severity of the consequences of occurrence to the organization. From this ranking, it is determined if the loss of function of equipment as a result of failure is significant or not and if further RCM analysis is justified. The risk should be quantified to enable selection to be done. The application of CBM is investigated. Where CBM is already established it should be integrated with the RCM process and with data acquisition systems such as SCADA and programmable logic controllers (PLC)

Step 6: In this step, the maintenance tasks developed from analysis done are put together and integrated with existing maintenance programs. This should be done in such a way that the new tasks integrate well with the existing work plans and are well supported by the available skills, resources, knowledge and culture. The new tasks are selected in with knowledge of existing skills, knowledge and resources. The new tasks should be traceable (referenced) to RCM decision that created it. A decision to introduce overhaul of a pipeline should fit into existing maintenance strategies for pipeline and should be refer to an RCM decision.

Step 7: RCM analysis results should be implemented and made part of maintenance routines and the results from implementation should be monitored and quantified. This is possible through continuous assessment of work management and workflow capabilities.

5.1.3 Lean maintenance in maintenance of GSGS

Lean maintenance is aimed at eliminating wastes in maintenance processes. The Wastes in maintenance include down time, non-value adding maintenance activities, large inventory etc. Elimination of wastes cuts maintenance costs and improves maintenance effectiveness by cutting down non value adding activities. In essence, it improves efficiency of maintenance. Lean Maintenance focuses on identifying and eliminating the basic stresses that cause machine downtime by protecting the machines from these stresses. In a gsgs, down time constitute lost production. Malfunctioning steam pressure control system and drain equipment result in wasted steam and should be eliminated. The key objective of Lean Maintenance is to give near 100% equipment uptime and reliability it demands while cutting maintenance expense. This is done by systematically surveying or analyzing each machine and control system to determine which basic stresses are affecting each machine, over time, and laying out a scheme to protect each machine, computer, or control system from the stresses to which it is subject. In many companies, maintenance is a constant tightrope walk between guaranteeing adequate system availability on the one hand and the economic efficiency of the production systems, which should not be burdened unnecessarily, on the other. This is because in a lot of companies the maintenance strategies and the organization developed historically. There is no precise orientation to the production system and its requirements. This is where the Lean Maintenance System steps in (Bodo Wiegman). The steps in lean maintenance applied to a GSGS are described below:

Step 1: For each sub-system in GSGS, assess the effects of all potential failures. Use the nature of effect of failure to assign priorities to the systems and to define the recommended actions for the maintenance strategy. Critical systems are given high priority are also given most attention in the maintenance systems and are examined in detail so that a component-specific maintenance strategy can be developed and optimized.

Step 2: Organize the components in the GSGS into damage categories and assess how damage on each component affects the system operation, whether damage can be foreseen, and how often it occurs. Classify the individual components into damage categories and develop component-specific maintenance strategies. Recommend actions for maintenance and stock of spare parts to keep.

Step 3: Distinguish between critical and non-critical systems of GSGS and draw a precisely coordinated plan of action which takes into account of the system priority, the damage category priority and the fault clearance time.

Step 4: Structure the activities and calculate their capacities. The individual results for the various systems are used to calculate the number of employees required for central and decentralized maintenance teams and a pool of specialists on a unit level.

Step 5: Put in place the lean maintenance solution to cut wastes in the GSGS.

Step 6: There is always little to monitor and control after implementing lean maintenance actions because they are mostly single step solutions with instant solutions.

5.2 Comparison of the management methods as applied to maintain GSGS

Each of the methods presented and discussed above have individual strengths and weaknesses together with associated costs and financial benefits. The challenges facing many maintenance organizations are to formulate a maintenance approach that is most beneficial to the organization. Whereas the cost of maintenance remain an important factor in maintenance, qualitative factors such as safety, efficiency and utilization and environmental factors remain equally important. To arrive at an optimal maintenance practices, organizations have to do a ‘delicate balancing’ of these factors.

This research seeks to propose a procedure that maintenance organizations for GPPs can consider when deciding on a cost effective maintenance approach for a given GPP or a system of the plant using the maintenance of a GSGS as a sample. The method presents two methods of comparison; a qualitative approach in which qualitative benefits of the methods are considered and compared using an analytical hierarchy process (AHP) and a quantitative approach in which the potential costs and benefits associated with the management methods are estimated and a cost-benefits analysis performed. The criteria used to assign values in both comparisons are judgemental based on estimations, research and from discussions with maintenance teams of selected power plants.

5.2.1 Qualitative comparison by Analytical Hierarchy Process (AHP)

The analytical hierarchy Process (AHP) is a structured technique that provides a comprehensive and rational framework for structuring the problem, for representing and quantifying its elements, relating those elements to overall goals, and evaluating alternative solutions (Forman and Selly, 2001). It is used in wide variety of decision situations. The AHP was developed at the Wharton School of Business by Thomas Saatyl and allows decision makers to model a complex problem in a hierarchical structure showing the relationships of the goal, objectives (criteria), sub-objectives, and alternatives as shown in Figure 21. Uncertainties and other influencing factors can also be included.

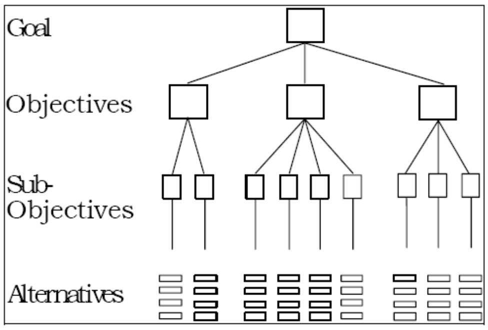

FIGURE 21: The AHP decision hierarchy process

In AHP, the main problem is first decomposed into a hierarchy of simplified sub-problems in which each can be analyzed independently. The elements of the hierarchy can relate to any aspect of the decision problem, tangible or intangible. Once the hierarchy is built, the elements are arranged systematically and compared to one another in pairs using concrete data about the elements or based on human judgments about the elements' relative meaning and importance. A numerical weight or priority is derived for each element of the hierarchy, allowing diverse and often incommensurable elements to be compared to one another in a rational and consistent way. In the final step of the process, numerical priorities are derived for each of the decision alternatives. Since these numbers represent the alternatives' relative ability to achieve the decision goal, they allow a straightforward consideration of the various courses of action.

Ranking of objectives of maintenance of GSGS:
The problem in this research is to determine the management system that is optimum for application to the maintenance of GSGS. The criteria or objectives of maintenance in a GSGS are given in Table 14 below.

TABLE 14: Summary objectives of maintenance of a GSGS

No.	Maintenance objective (criteria)	Abbreviation
1	Flexible, dynamic and proactive	FDP
2	Profitable, production improvement and cost reduction	PPC
3	Quality work, meet standards, minimize defects	QSW
4	Reliability, safety and system security	RSS
5	Availability, minimum down and repair time	ADT
6	Effective organization, motivated staff, documentation	OED

After defining the main objectives in the maintenance of a GSGS, they are then ranked against each other in terms of relative importance to the solution of the problem. In this case, each objective is given a ranking of 1 to 4 relative to the other showing how good one objective is better to the other. The results are shown in Table 15.

TABLE 15: Relative importance of the maintenance objectives (criteria)

	FDP	PPC	QSW	RSS	ADT	OED
FDP	1	1/3	½	1/4	¼	2
PPC	3	1	2	1/3	1	3
QSW	2	½	1	1/2	½	2
RSS	4	3	2	1	1	4
ADT	4	1	2	1	1	3
OED	½	1/3	½	1/4	1/3	1

Ranking of comparison of alternative solutions

The alternative management methods that can be applied to manage maintenance of a GSGS are listed in Table 16 together with the abbreviations used. The three conventional management methods are compared.

TABLE 16: Alternative management methods

No.	Management method	Abbreviation
1	Six Sigma Maintenance	SSM
2	Reliability Centred Maintenance	RCM
3	Lean Maintenance	LCM

The alternative maintenance management methods were ranked relative to each other for each maintenance objective reflecting their perceived strengths in management of maintenance of a GSGS. Based on intuitive judgments, the relative strengths of the alternative methods were evaluated for each of the criteria above. The ranking of alternatives for each maintenance objectives are as shown in Table 17.

Comparing of alternatives steps:

The alternatives are compared by matrix evaluation. The following steps are used:

- The matrix from the relative ranking of the alternatives is squared
- The rows of the square matrix of alternatives is summed to form column matrix
- Sum the column matrix resulting from sum of rows
- Divide each element of column vector by the sum to form eigenvector
- Multiply eigenvectors of objectives by that of alternatives

The result of product of the eigenvectors gives the overall comparison of the alternatives. The results are discussed in next section.

TABLE 17: Relative importance of alternatives for each objective

Flexibility, dynamisms, proactive				**Profitability, productivity, cost reduction**				**Quality work, standards, minimum defects**			
	SSM	RCM	LCM		SSM	RCM	LCM		SSM	RCM	LCM
SSM	1	½	3	SSM	1	1	3	SSM	1	2	2
RCM	2	1	4	RCM	1	1	1	RCM	1/2	1	2
LCM	1/3	¼	1	LCM	1/3	1	1	LCM	1/2	1/2	1

Reliability, safety, system security,				**Availability, minimum down and repair time**				**Organization, motivated staff, documentation**			
	SSM	RCM	LCM		SSM	RCM	LCM		SSM	RCM	LCM
SSM	1	½	2	SSM	1	1	2	SSM	1	3	1
RCM	2	1	2	RCM	1	1	3	RCM	1/3	1	½
LCM	½	½	1	LCM	½	1/3	1	LCM	2	2	1

5.2.2 Results of AHP

The AHP model was created and executed using a simple MATLAB code to execute the matrices. The results from the AHP matrix calculations are summarized in Table 18.

TABLE 18: Results of AHP matrix calculations

	FDP	PPC	QSW	RSS	ADT	OED	Overall
SSM	0.3194	0.4639	0.4961	0.3101	0.3878	0.3859	0.3865
RCM	0.5595	0.3196	0.3101	0.4961	0.4439	0.1494	0.4102
LCM	0.1211	0.2165	0.1938	0.1938	0.1684	0.4647	0.2033

The AHP analysis shows that the six sigma method is superior to the other methods in achieving profitability, process improvement and reducing cost and meeting quality, standards and minimizing defects. This is related to the DMAIC steps of the six sigma method that capture all these objectives and in particular use of data. Several publications show that companies have achieved highly in these objectives with the method. Six sigma scores second in all the other objectives showing that it is impressive management method.

RCM is the preferred method in delivering a flexible, dynamic and proactive maintenance procedures, achieving high reliability, safety and system security and ensuring high availability, minimum down time and repair time. In essence, RCM stands for reliability. The success of RCM is related to its use of risk calculations to determine appropriate maintenance strategies. Because of the reputation of the method, many companies in which reliability and safety are paramount have attempted to incorporate the method in the maintenance. There are several success stories but also some failure stories. RCM is rated poorly in attaining organizational excellence, motivation and documentation probably because of the assumption that a focus on calculated measures shifts the attention away from staff to formulas.

Lean is surprisingly rated least in all the objectives except in the preferred option in attaining organizational excellence, motivation and documentation. This can be attributed to the fact that lean is looked at as a process that focuses on locating wastes through a disciplined approach such as using the 5S, Kaizen, Jidoka, etc.

Overall, RCM scores the highest closely followed by six sigma. Lean comes last.

5.2.3 Quantitative analysis: cost modelling

The required inputs to maintenance activities are financial and manpower resources, machine outage, working tools, spare parts and consumables. Although these inputs cost substantial amounts of money, the maintenance processes are beneficial to the plant in terms of increased availability, increased efficiency, plant safety and high productivity. A successful maintenance process should be cost effective, meaning the benefits should outweigh the costs. The article 'value driven maintenance' (Haarman, 2004) argues that although the value of maintenance comes from delivering maximum availability at minimum cost, present day-to-day operations must involve prioritization. Prioritization involves asking if a 1% increase in availability is as valuable as a 1% reduction of cost, and what of the value of safety? A cost-benefits analysis evaluates and compares the costs of maintenance against the resultant gains. In the analysis, the costs of maintenance have been generalized into four elements:

1. Manpower cost;
2. Machine down time due to planned and forced outage;
3. Spare parts and consumables;
4. Special maintenance tools, equipment and software.

The objective of the cost modelling procedure is to estimate the costs of maintenance for the main cost elements. To estimate the costs for each element, a unit cost was first defined and the quantities of the parameters estimated for maintenance done under the different management methods. To evaluate the benefits of each method, the total costs from the four maintenance elements were evaluated and the costs for the cost elements evaluated for a case not applying the conventional management (classical). The classical case is the common management system adopted in most power plants and the costs are estimates of the actual maintenance costs. The benefits are the differences of the classical costs to the management methods. The benefits are considered to arise from reduced downtime, reduced man-hours, and reduced failure rates resulting in higher reliability, productivity and safety as a result of better management. The assessment and assignment of the cost elements are discussed below.

In this research, the **manpower costs** refer to the payments made to the employees for the hours spend carrying out maintenance tasks. The overhead costs such as housing allowances, insurances, medical allowances and other kinds of allowances are considered as administrative costs and not included in the analysis. Five categories of employees were considered reflecting the functional levels. In Table

19, the estimated per hour earnings in Iceland kroner (ISK) for each category of staff in Iceland (2008) is given based on informal information from maintenance staff in power plants visited.

TABLE 19: Staff categories and gross hourly rates in Iceland (2008 estimates)

Category of manpower	Units	Hourly rates
Top managers (decision and planning) – TM	ISK/hr	5000
Special trained team leader (trained champion) - TL	ISK/hr	4000
Technical specialists (data gathering and analysis) - TS	ISK/hr	3000
Craft trained (specialized tasks) – TC	ISK/hr	2500
General workforce (general tasks) – GW	ISK/hr	2000

To determine the number of hours worked for each category of manpower for each management method, the maintenance tasks were categorized into planning, data collection, decision making, data analysis, execution etc and the % role of each staff category for each task was estimated using intuitive judgement. Table 20 shows the estimated contribution for each category of manpower to each type of maintenance task.

TABLE 20: Estimated contribution of category of manpower to maintenance tasks

Fraction of time spend by each staff category per activity	Units	Distribution of tasks per category (%)				
		TM	TL	TS	TC	GW
Inspection, monitoring and collection of data	%	3	15	25	50	7
Evaluation and analysis of data, identification of wastes	%	5	30	50	10	5
Interpretation of data and defect diagnosis	%	5	30	50	5	10
Study and analysis of defect, causes and solutions	%	5	20	50	10	15
Evaluation of maintenance options and how to eliminate wastes	%	10	30	30	20	10

The fraction of the individual tasks in the overall maintenance process is estimated. The total hours worked by each category of staff is estimated and the manpower costs evaluated as a product of man-hours and per hour rates. Table 21 shows the estimated annual man-hour costs for each staff category

TABLE 21: Estimated annual manpower costs for different categories of manpower

Manpower categories		Manpower costs (ISK)			
		6-Sigma	RCM	LEAN	Classical
Top managers (decision and planning)	ISK	230,880	291,200	305,760	201,760
Special trained team leader (trained champion)	ISK	756,600	882,700	946,400	431,600
Technical specialists (data gathering and analysis)	ISK	1,193,400	1,501,500	1,424,800	556,400
Craft trained (specialised tasks)	ISK	670,800	573,300	1,144,000	722,800
General workforce (general tasks)	ISK	268,320	391,300	339,040	167,440
Total annual manpower costs	ISK	3,120,000	3,640,000	4,160,000	2,080,000

Down time costs refer to costs arising from the equipment being out of operation due to breakdown or while undergoing or waiting for maintenance. The down time cost is obtained by multiplying the unit value of the product processed by the equipment by the rate of production and the duration of outage. For example when a steam line is out of operation, the down time cost will be given by the relation:

$$\textit{Downtime cost} = \textit{unit steam cost} \times \textit{steam flow rate} \times \textit{duration of outage}$$

Downtime hours are based on the estimated the planned and forced downtime under each management method. It is assumed that when the objectives of the methods are achieved, they will help to reduce the planned and emergency down time to a certain % of the annual calendar time as shown in Table 22. The estimated outage time is calculated for each piece of equipment. The cost is calculated by multiplying the production rates of each piece of equipment by the outage time.

The annual **spare parts and consumables cost** was evaluated by identifying the main components in the GSGS and their quantities and estimating their potential rates of failure when managed under each of the management methods using intuitive judgement. The capital cost of the spares is estimated using equipment catalogues of vendors available online. By multiplying the failure rates by the quantities of equipment in the system and the unit cost, the spares cost is estimated. This approach provides a guideline since the actual failure rates are variable and not necessarily related to the way the maintenance is done. A summary of spare parts and estimated failure rates is shown in Table 23 below.

TABLE 22: Estimated annual planned and forced outage hours

Estimated planned outage	**Estimated annual unit outage (%)**				**Estimated annual outage (hrs)**			
	6Sigma	**RCM**	**LEAN**	**Classical**	**6Sigma**	**RCM**	**LEAN**	**Classical**
Wellhead	0.5	1	1.5	2	43.8	87.6	131.4	175.2
Two-phase pipeline	0.5	1	1.5	2	43.8	87.6	131.4	175.2
Separator station	0.5	1	1.5	2	43.8	87.6	131.4	175.2
Main hot water pipeline	0.5	1	1.5	2	43.8	87.6	131.4	175.2
Main Steam transmission	0.5	1	1.5	2	43.8	87.6	131.4	175.2
Estimated forced outage								
Wellhead	0.05	0.1	0.5	2	4.38	8.76	43.8	175.2
Two-phase pipeline	0.05	0.1	0.5	2	4.38	8.76	43.8	175.2
Separator station	0.05	0.1	0.5	2	4.38	8.76	43.8	175.2
Main hot water pipeline	0.05	0.1	0.5	2	4.38	8.76	43.8	175.2
Main Steam transmission	0.05	0.1	0.5	2	4.38	8.76	43.8	175.2

TABLE 23: Estimated failure rates for components

Equipment	**Unit cost (kr)**	**Qty (pc)**	**Estimated failure rates/year**			**Classical case**	**Estimated annual spares usage (pc)**			**Classical case**
			6Sigma	**RCM**	**LEAN**		**6Sigma**	**RCM**	**LEAN**	
Master valve	300000	12	0.15	0.1	0.2	0.3	0.018	0.012	0.024	0.036
Flow control valves	200000	24	0.15	0.1	0.2	0.3	0.036	0.024	0.048	0.072
Small steam valves	50000	1200	0.15	0.1	0.2	0.3	1.8	1.2	2.4	3.6
Steam pipe spares	10000	70000	0.15	0.1	0.2	0.3	105	70	140	210
Steam traps	15000	400	0.15	0.1	0.2	0.3	0.6	0.4	0.8	1.2
Level electrodes	30000	4	0.15	0.1	0.2	0.3	0.006	0.004	0.008	0.012
Insulation spares	300000	70000	0.15	0.1	0.2	0.3	105	70	140	210
Gland packing mat.	200000	1236	0.15	0.1	0.2	0.3	1.854	1.236	2.472	3.708

In performing maintenance using the different approaches, **special tools and softwares** are required as well as training for their use. The required software includes reliability software, six sigma calculators DMM and MMS databases. The special tools include condition monitoring tools such as ultrasonics, vibration analysis and thermography as seen in Table 24. The estimated capital cost includes the cost of hiring of manpower and training of manpower. The annual subscriptions cover any other annual charges including operations for the software. The procedure followed was:

- Determine the possible special tools and software needed for the maintenance tasks
- Estimate the capital cost, annual interest rates, expected lifespan and annual subscription for each tool and software

- For each method, decide if the special tools are applicable or not and assign a 1 or 0 in the Excel worksheet

The annual cost for the special tools and software was then estimated for each method by:

Annual cost = capital cost +capital recovery factor

TABLE 24: The inputs to evaluation of cost of tools and software

Special tool or software	Estimated capital cost	Expected useful life	Annual interest rate	Annual subscription	Application of tool (0 or 1)			
					6-Sigma	RCM	LEAN	Case
Reliability analysis kit	100000	10	20	10000	0	1	0	0
Six sigma analysis kit	50000	10	20	20000	1	0	1	0
Ultrasonic kit	20000	5	20	0	0	1	0	0
Thermography	10000	5	20	0	0	1	1	0
DMMS/MMS	20000	10	20	10000	1	1	1	1

5.2.4 Results of cost model

The cost model was created in an Excel worksheet. The evaluation inputs are contained in the Excel worksheets in Appendix 2. The results of the cost benefits evaluation are presented in Table 25. The negative values show that the methods incur a net cost for the elements considered.

TABLE 25: Estimated cost savings for the management methods

Cost item	Estimated annual cost savings (ISK/year)		
	6-Sigma	RCM	LEAN
Down time costs	86,033,365	72,317,901	49,874,414
Spares parts and consumable costs	33,032,580	44,043,440	22,021,720
Manpower costs	-1,040,000	-1,560,000	-2,080,000
Special tools and software	-53,230	-131,615	-63,230
Total cost benefits from the methods	117,972,715	114,669,726	69,752,904

The cost benefits estimates indicate that the six sigma method would yield the most cost savings compared to the other methods. RCM is the second most preferred method in cost saving while Lean comes last on the basis of the assumptions and estimates used. A true comparison of the methods is possible if the different methods are tested on similarly maintained power plants. The analyses show all the methods give negative cost savings in manpower, special tools and software investment. This is because the formal management methods require well trained specialists to run the method in addition to special tools and software to perform the tasks in the method. The savings on spares and consumables arises from reduced failure rates of equipment which results in reduced consumption. Savings from downtime is achieved when the mean time to repair and mean time to failure is reduced. In the classical model, actual execution of the tasks is often given priority with little emphasis to planning, evaluation and analysis of the existing performance situation or problems. The reasons often cited for not adopting the formal methods by most power plants is the cost and complexity in implementing the methods. This was evident in Svartsengi where RCM was not implemented due to the costs and demands of the method.

5.3 The management methods applied to maintenance scenarios

5.3.1 Six sigma

There are many maintenance problems in GPPs that six sigma method can be the appropriate management strategy to address the maintenance needs. Examples of cases that a six sigma method can be applied include; high rates of failures in the steam gathering and transmission equipment such as sticking of steam valves and leaking of pipes, high levels of forced plant outages, high downtime and low reliability of the plant, high O&M costs and low profits, poor steam quality and frequent turbine trips.

When six sigma is applied to address the high failure rates of the steam field equipment, it works by identifying and eliminating the causes of defects by applying tools such as statistical analysis, pareto analysis and fault tree analysis. The effect of the method will be to reduce the cost of spare parts because few parts will fail. As an example, assume that a GPP has an annual failure rate of 0.3% for its GSGS equipment when under normal maintenance management. Assuming that the six sigma method is implemented and reduces failure rates of the GSGS equipment to 0.15% per year in the cost model presented above relative to classical case of 0.3%, the financial savings is significant as seen in table 26 below.

TABLE 26: Illustration of estimated cost of failures with and without six sigma method

Equipment	Failure rates		Cost of failure	
	Normal	6Sigma	Normal	6Sigma
Master valve	0.15	0.3	10800	5400
Flow control valves	0.15	0.3	14400	7200
Small steam valves	0.15	0.3	180000	90000
Steam pipe spares	0.15	0.3	2100000	1050000
Steam traps	0.15	0.3	18000	9000
Level electrodes	0.15	0.3	360	180
Insulation spares	0.15	0.3	63000000	31500000
Gland packing material	0.15	0.3	741600	370800
Total annual cost of failure			66,065,160	33,032,580

As can be seen from the table, the potential savings for a reduced failure rate of the equipment can be very high. Similar savings can be illustrated when the method is used to address the other maintenance related problems.

5.4 RCM

The RCM method is suitable for determining and optimizing maintenance strategies for newly installed equipment, determining PM procedures for complex systems and for analysing and cutting down excessive maintenance costs. There are a number of maintenance cases in GPPs in which RCM is the most appropriate management tool. Examples include a case where new wells have been drilled and connected to the existing steam system but the new design is different from the existing so that new maintenance procedures must be developed for the new equipment. Another case in GPP where RCM is useful is when the plant has high down time. An RCM method can be used to analyse the maintenance needs for the new plant by doing FMEA analysis and develop maintenance procedures that will meet the requirements at the same time fitting into the existing maintenance programs.

To address the high downtime, RCM method will employ the root cause analysis, fault tree analysis and FMEA to identify the causes of the down time. By identifying and solving the root causes of downtime, down time costs will be greatly reduced. To illustrate the benefits of the method, consider a GSGS in which the annual forced outage of the equipment under normal maintenance is 2%. Assuming that an RCM method can reduce this cost to 0.1%, the potential cost savings can be substantial. The cost model for this scenario is shown in Table 27. Similar savings can be expected from other RCM initiatives.

TABLE 27: Estimated down time savings from application of RCM

Equipment	Product value	Product rate	Forced outage (%)		Outage cost (kr)		Savings
	(kr/kg/s)	(kg/s)	RCM	Normal	RCM	Normal	(kr)
Wellhead	0.158	100	0.1	2	498,744	9,974,883	9,476,139
Two-phase pipeline	0.158	100	0.1	2	498,744	9,974,883	9,476,139
Separator station	0.158	100	0.1	2	498,744	9,974,883	9,476,139
Main hotwater pipeline	0.059	46	0.1	2	185,644	3,712,873	3,527,229
Main Steam transmission	0.242	54	0.1	2	763,633	15,272,654	14,509,021

5.4.1 Lean

There are many maintenance problems in GPPs that can be addressed by lean method. They include waste of manpower when maintenance staff are used to do non-maintenance tasks, long delays of work due to lack of spare parts or waiting for people, maintenance tasks taking long because of delays of transport, spare parts, waiting for the equipment to be stopped and isolated or waiting for the people. Lean can be used identify man hours wasted because of unnecessary human movements of to pick tools or to stores and back.

As an example, consider a situation where lean is applied to address high manpower costs. The method is able to identify man-hours that don't add value to maintenance such as excess staff on a task, waiting time, movement etc. When these wasted man-hours are eliminated, manpower costs can be reduced significantly.

6. DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

6.1 Overview

Literature review has showed that most organizations view maintenance as a cost centre when it is actually an important economic activity to the organization. This view can change if maintenance activities are optimized so that only the right activities are done by the right personnel at the right time using the right tools, resources and procedures. The management methods are useful in optimizing maintenance through proper planning and execution of maintenance tasks. The growing interests in geothermal energy worldwide and the fact that geothermal plants are operated as baseload plants puts high demand on plant maintenance teams to ensure high availability, reliability and safety of the plants.

6.2 Maintenance and management methods

The emerging management methods such as six sigma, lean and RCM have been widely applied in the aviation industry, manufacturing industry and nuclear power plants with remarkable results. The benefits from these methods can be of great use to improving maintenance in GPPs. Interview with staff at RioTinto-Alcan Aluminium Company in Iceland showed that they use RCM principally and lean and six sigma for targeted improvement and waste elimination. The Svartsengi geothermal plant planned to implement RCM but the cost and demands of the RCM method high.

The maintenance methods of PM, CBM and CM have their strengths and weaknesses and suitability. CBM is presented by many authors as the most optimum maintenance method because the maintenance tasks are based on the measured need of the equipment. The cost of CBM tools is a high. PM is the most widely used method but is only suitable where failure is age related. Most failures are not age related. CM is most appropriate where failure has little consequences.

6.3 Maintenance in GPPs

The FMEA analysis showed that most of the maintenance problems in GPPs are related to the chemical and physical properties of the geothermal fluids. A survey of maintenance in some selected GPPs showed that the nature of fluid to significantly influence the design, operation and maintenance strategies in a GPP. Olkaria plants in Kenya have high manpower to MW ratio compared to the Icelandic plants. The per-hour rates and technological level is equally low at the Kenyan GPPs compared to the Icelandic ones. Reykjanes and Svartsengi have a higher staff ratio to Krafla and this can be related to the differing chemistry of the fluids at the two plants. The acidic fluids in svartsengi cause frequent puncture of steam pipes.

6.4 Comparison of management methods

The comparison was carried out to develop a tool that can be used to compare management methods for maintenance of power plants using a GSGS as a case study. The comparison was done using AHP and cost model using various assumptions and estimates of performance parameters for the comparison. Because the performance parameters are based on assumptions, they are not accurate but present a useful tool that can be used for comparison when actual performance data is available.

From the AHP, RCM gave the highest score followed by 6-sigma. The alternatives scored differently in delivery of maintenance objective, which shows that an optimum maintenance process is only possible from a combination of methods. RCM was seen the best alternative in matters related to reliability and safety. Six sigma scored well in cost cutting objectives while lean was best in matters of reducing wastes and organizational excellence. From the cost model, six sigma scored the highest followed by RCM.

6.5 Conclusions

Maintenance costs in GPPs contribute a significant part of the unit cost of geothermal energy and affect the profitability of the plants. It is necessary to minimize maintenance costs by optimizing maintenance processes to make the plants run economically. This is achieved by optimizing maintenance methods.

The research showed that the methods commonly applied in maintenance processes are PM, CBM and CM. Each of these methods have their individual strengths and weaknesses when applied to different maintenance scenarios. It was seen that careful blending of these methods is needed to achieve an optimum and cost effective maintenance strategies.

Interviews and observations in GPPs revealed that a number of concepts in the conventional management are already being practiced under the classical concepts. All that lacks is formalizing and documenting the processes as required in the conventional methods. Most GPPs find the classical approach as cost effective but selective application of the formal methods could yield better results.

The qualitative analysis of the management methods showed that the RCM method is the most preferred choice for GPPs. The generalized cost model showed that the six sigma method as the most cost effective followed by RCM method. The lean method ranked least in both analyses. Both the qualitative and quantitative analysis is based on estimates and intuitive judgements on the part of the author. Proper analysis will require inputs of real performance data from plants that are applying the management methods.

The high costs of implementing and maintaining modern management concepts has limited the application of the methods in GPPs. In addition, there is a general resistance among maintenance personnel in GPPs to experimenting and implementing the new concepts. The argument is that the existing maintenance serves them appropriately and do not see the need for new concepts.

6.6 Recommendations

Further works in this research is needed to test the cost model by applying real performance data from GPPs that apply the formal management methods. This will give an accurate comparison of the methods and will facilitate selection to the methods for executing specific maintenance tasks. The cost model can be further improved by adding penalties of downtime and using real values of products.

LIST OF SYMBOLS

AHP	Analytical hierarchy process
CBM	Condition based maintenance
CM	Condition monitoring
CMMS	Computerised maintenance management
CTQ	Critical to quality
DCS	Distributed control system
DMAIC	Define, measure, analyse, improve control
DMM	Data management maintenance
DPMO	Defects per million opportunities
FMEA	Failure mode and effect analysis
FMECA	Failure mode, effect and criticality analysis
FR	Failure rate
GPP	geothermal power plant
GSGS	geothermal steam gathering system
JIT	Just in time
KPI	Key performance indicators
MTBF	Mean time between failures
MTTR	Mean time to repair
MMS	Maintenance management subsytem
O&M	Operation and maintenance
PM	Preventive maintenance
RCFA	Root cause failure analysis
RCM	Reliability centered maintenance
SCADA	Supervisory control and data acquisition
Σ	Sigma, symbol for standard deviation

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APPENDIX 1: Failure mode cause and effects analysis for GPPs

Equipment	Potential failure or defect	Likely causes	Likely consequences	Possible maintenance management solutions
Master valves and service valves	Silica scaling Wear of valve disc Leakage through glands Corrosion of metal	High silica fluid Improper operating press Worn/loose packing Exposed metal	Stuck valve, Uncontrolled well Lost well Lost valve	Repair valve Monitor and inspect Redesign valve Protect metal
Two phase pipeline	Scaling Insulation damage Wear of pipe wall Corrosion Fracture, leaking, burst	High silica, calcite Improper pressure Environment damage Water hammer in 2 phase Excessive pressure	blocked pipe, restricted flow Changes in flow characteristics Design errors Weather issues	Replace pipe Repair insulation or support Use inhibitors Redesign the system to match flow condition Control flow properties Monitoring flow indicators
Separator vessel	Scaling on walls Erosion of vessel wall Water in steam, Steam in water Bursting Damage to supports	High silica fluid Oxygen ingression Particles in the fluid Incorrect design of vessel Excessive press surges Thinning vessel wall Water hammers	Blocked pipes Reduced efficiency Flooding of vessel Damage to vessel Wet steam, steam lost Safety problems	Overhaul the vessel Redesign the system Replace vessel with suitable design Remove well with excess silica Monitor parameters
Separator vessel pressure relieve	Fail to operate Operate at lower press than design Leakage of steam	-corrosion Wrong design Silica scale cement Gasket failure Wrong installation	Damage to wellhead equipment in even of overpressure Lose of steam under normal pressure	Replace with right rated Replace damaged Monitor and inspect Replace gasket
Separator level controls	Allows excess level Level too low Erratic controls No response of control valves	Out of calibration Valve leaking Valve stuck Equipment damage	Flooding of separator Possible damage to equipment Water into steam line Steam lost with water Damaged equipment	Monitor Redesign Calibrate Overhaul Regular inspection and maintenance
Hot water piping	Scaling Corrosion Insulation damage Pipe and supports damage Leakage	Silica calcite too high Improper operating pressure Weather damage Water hammers Fracture of pipe Thinning of pipe wall	Blocked, constricted flow Burst pipe Heat loss Pipe and supports damage Loss of water Lost production	Monitor flow parameters Inspection and repairs Redesign the system to eliminate defects Overhaul the system Isolate problem wells
Steam pipeline	Heat losses Pipe damage Thinning of pipe wall Scaling on pipe Burst pipe	Damaged or poor insulation Corrosion damage Improper design Blocked pipes Excessive pressure surge Wrong expansion constraints	Heat loss, condensate Thinning pipe wall, pipe damage Constrained flow Damaged expansion loops	Redesign insulation Replace repair insulation Monitor flow and use results to determine status Keep oxygen out Keep pressure regulator

Equipment	Potential failure or defect	Likely causes	Likely consequences	Possible maintenance management solutions
Steam pipe pressure controller	No response to pressure Opens at low pressure Leakage of steam Erratic control response	Loss of power Out of calibration Valve disc worn Control valve sticking due to scale Unstable steam pressure	Excess steam pressure Damage to plant equipment Loss of steam Production shut down Induced pressure surges in the entire system	Inspection and repairs Restore power Monitor control operation and use result to make correction Redesign the pressure controls to eliminate defects
Steam pipeline instrumentation	Wrong readings No readings Unstable readings Damaged instruments	Out of calibration No power Blocked tapping pipes Faulty instruments	Wrong management data No data for operation Wrong control signals Safety problem	Regular calibration Inspect and repair Monitor and take action from monitored results Redesign the instrument or pipeline
Steam wash section (to remove dissolved salts)	Blocked spray nozzles Excessive or Inadequate water	Scaling at nozzles Control device out of calibration	Salts in steam, scale in turbine Flooding of mist separators	Regular inspect and maintain Monitor parameters and take action Is steam wash needed Redesign to remove defects
Steam scrubber and mist eliminator	Too high water level Too low water level Moisture in steam Steam in separated water	Faulty level controllers Controllers out of calibration Excessive moisture in steam Excessive wash water	Flooding Wet steam Lost steam Safety issues Water hammers Production stoppage	Monitor and use the data to take correction Inspect and maintain Regular calibration Redesign overhaul

APPENDIX 2: Excel worksheets for cost analysis

		Distribution of tasks per category				
Fraction of time spend by each staff category per activity	**Units**	**TM**	**TL**	**TS**	**TC**	**SW**
Inspection, monitoring and collection of data	%	3	15	25	50	7
Evaluation and analysis of data, Identification of wastes	%	5	30	50	10	5
Interpretation of data and defect diagnosis	%	5	30	50	5	10
Study and analysis of defect, causes and solutions	%	5	20	50	10	15
Evaluation of maintenance options and how to eliminate wastes	%	10	30	30	20	10
Decision making, planning the tasks, provision of resources	%	30	30	20	15	5
Execution of maintenance activities and elimination of wastes	%	2	10	20	60	8
Weights of tasks for each method		**6-sigma**	**RCM**	**Lean**	**Classical**	
Inspection, monitoring and collection of data	%	15	5	15	5	
Evaluation and analysis of data, Identification of wastes	%	20	10	20	5	
Interpretation of data and defect diagnosis	%	20	15	10	5	
Study and analysis of defect, causes and solutions	%	15	40	10	5	
Evaluation of maintenance options and analysing wastes	%	10	15	15	20	
Decision making, planning the tasks, provision of resources	%	10	10	10	20	
Execution of maintenance activities and elimination of wastes	%	10	5	20	40	
Distribution of maintenance effort (time) per job category	Units	**6-sigma**	**RCM**	**Lean**	**Classical**	
Top managers (decision and planning) - TM	%	7.4	8	7.35	9.7	
Special trained team leader (trained champion) - TL	%	24.25	24.25	22.75	20.75	
Technical specialists (data gathering and analysis) - TS	%	38.25	41.25	34.25	26.75	
Craft level trained (execution of tasks) - TC	%	21.5	15.75	27.5	34.75	
Support workforce (software, clerical, analysts etc) - SW	%	8.6	10.75	8.15	8.05	
Annual work hours (5day week, 8hrs day, 52week year)	hrs	2080	2080	2080	2080	
Effective fraction of work hours spent on GSGS	%	30	35	40	20	
Work hours on GSGS		624	728	832	416	
Annual man-hour	Units	**6-Sigma**	**RCM**	**LEAN**	**Classical**	
Top managers (decision and planning) - TM	hrs/year	46.176	58.24	61.152	40.352	
Special trained team leader (trained champion) - TL	hrs/year	151.32	176.54	189.28	86.32	
Technical specialists (data gathering and analysis) - TS	hrs/year	238.68	300.3	284.96	111.28	
Craft level trained (execution of tasks) - TC	hrs/year	134.16	114.66	228.8	144.56	
Support workforce (software, clerical, analysts etc) - SW	hrs/year	53.664	78.26	67.808	33.488	
Annual man-hour costs per category		**6-Sigma**	**RCM**	**LEAN**	**Classical**	
Top managers (decision and planning)	kr	184,704	232,960	244,608	161,408	
Special trained team leader (trained champion)	kr	605,280	706,160	757,120	345,280	
Technical specialists (data gathering and analysis)	kr	954,720	1,201,200	1,139,840	445,120	
Craft trained (specialised tasks)	kr	536,640	458,640	915,200	578,240	
General workforce (general tasks)	kr	214,656	313,040	271,232	133,952	
Total annual manpower costs	**kr**	**2,496,000**	**2,912,000**	**3,328,000**	**1,664,000**	