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EVALUATION OF MAINTENANCE MANAGEMENT THROUGH BENCHMARKING IN GEOTHERMAL POWER PLANTS

MSc thesis
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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 1979-2009, 424 scientists and engineers from 44 countries have completed the six month courses. They have come from Asia (43%), Africa (28%), Central America (15%), and Central and Eastern Europe (14%). 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 who have only BSc degrees 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.

It is a pleasure to introduce the nineteenth UNU Fellow to complete the MSc studies at the University of Iceland under the co-operation agreement. Mr. Mulugeta Asaye Adale, BSc in Mechanical Engineering, from the Ethiopian Electric Power Corporation – EEPCo, completed the six month specialized training in Geothermal Utilization at the UNU Geothermal Training Programme in October 2004. His research report was entitled "Methods to evaluate flow and scaling in geothermal systems with reference to the case: Aluto Langano power plant, Ethiopia". After three years of geothermal research work in Ethiopia, he came back to Iceland for MSc studies at the Faculty of Engineering – Department of Mechanical and Industrial Engineering of the University of Iceland in September 2007. In May 2009, he defended his MSc thesis presented here, entitled "Evaluation of maintenance management through benchmarking in 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 him on his achievements and wish him all the best for the future. We thank the Faculty of Engineering of the University of Iceland for the co-operation, and his supervisors for the dedication.

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

With warmest wishes from Iceland,

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

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ABSTRACT

In today's competitive energy market, many power plants are increasing their competitiveness by adopting new operating and maintenance philosophies to reduce their Operation and Maintenance (O&M) costs. Comparing performance among geothermal plants is difficult, as each power plant works within a unique context of resource, physical plant settings, and organizational goals. However, benchmarking provides indicators that allow us to examine individual circumstances and performances within groups of similarly-sized power plants. As geothermal power plants are base-load stations, the role of maintenance management to improve equipment reliability and plant availability is very important. In recent practice, power plants have started using benchmarking to identify the best practices for enhancing their maintenance management. This research involved using benchmarking for maintenance management of geothermal power plants and developing a comprehensive model which can help to compare maintenance performance. The model helped in the search for optimum methods of maintenance management practices in order to improve the overall effectiveness of operation and maintenance. Appropriately, by adopting the best practices, benchmarking could help geothermal plants to become more cost-effective in maintenance.
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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

DMADV	Define, Measure, Analyze, Design, and Verify
DMM	Dynamic Maintenance Management
DPMO	Defects per million opportunities
EAM	Enterprise asset management
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
O&M	Operation and maintenance
PDCA	Plan-Do-Check-Act
PdM	Predictive maintenance
PM	Preventive maintenance
RCFA	Root cause failure analysis
RCM	Reliability centred maintenance
SCADA	Supervisory control and data acquisition
SIPOC	Supplier-Inputs-Outputs-Customer
TPM	Total productive maintenance
WIP	Work in progress

1. INTRODUCTION

Around 1976, the modern version of benchmarking began with competitive benchmarking. This process was used by Xerox, who compared itself with its competitors in order to determine how to maximize productivity and minimize costs. The results of their benchmarking found that several of their processes were inferior to that of their competitors in terms of product quality, rework, and speed of production. Benchmarking helped Xerox identify their weak points and make changes to improve their company. Then, many companies in the 1980's used process benchmarking to seek ideas for improved processes outside their usual competition or industry. Recently, benchmarking has crossed all industrial lines (Walker, 2005).

Benchmarking is the continuous search for and adaptation of significantly better practices that lead to superior performance by investigating the performance and practices of other organizations. Benchmarking makes it possible to gain a competitive advantage over the competition. To gain this advantage, companies use several types of benchmarking (Walker, 2005). They include strategic benchmarking, competitive benchmarking, process benchmarking, functional benchmarking, internal benchmarking, external benchmarking, and international benchmarking.

In a typical benchmarking study, the information contained in a benchmark or a comparative measure of processes or results performance is used to establish which organization is a candidate for "best practice" for a particular business process. Then the business process must be specified in detail to understand how the benchmark result was achieved and to determine which specific activities enabled the successful performance. Finally, learning must be customized to apply new knowledge to organizations that have not attained the level of best performer.

Benchmarking is not just a checklist or set of numbers that are used to make management feel better about their current performance. Benchmarking really should make management uncomfortable due to the identification of gaps in business performance. Benchmarking should challenge management due to the discovery of performance enablers that could help them to improve (Watson, 2008).

For geothermal power plants to stay competitive, they also implement similar strategies to optimize their resources. This thesis deals with the evaluation of maintenance management through benchmarking in geothermal power plants.

The objectives of this research are:

- To evaluate maintenance performance through benchmarking.
- To analyze the maintenance methods and types and to understand the applications in real maintenance day to day work.
- To develop a comprehensive benchmarking model, in which we can compare maintenance performance indicators and facilitate further analysis.
- Using the model and process-step approach in benchmarking to provide evidence about the benchmarked power plant's current position among other best performing plants and their maintenance processes
- Based on the model results to determine the best practice for each benchmarked item and to make an analysis
- Identify and quantify relevant approaches for improvement based on the best experience of selected power plants through benchmarking
- To learn from leading organizations and indicate the implementation approach

This thesis looks at the use of benchmarking approaches for evaluating maintenance management and comparing performance indicators. Maintenance planning and activities have grown dramatically in importance across many industries. This importance is manifested by both the significant material resources allocated to maintenance departments as well as by the substantial number of personnel involved in maintenance activities in companies. For example, in most geothermal power plants over a quarter of the total workforce in the process industry is said to deal with maintenance work. This situation, coupled with an increasingly competitive environment, creates economic pressures and a heightened need to ensure that these considerable maintenance resources are allocated and used appropriately, as they can be significant drivers of competitiveness.

The maintenance of a geothermal plant is also very dependent on local factors, namely, the geothermal system, location, weather, and climate (Thorolfsson, 2005a). These unique conditions pushed the maintenance community to think about how to choose the best maintenance methods. Most geothermal power plants follow combined types of maintenance methods and strategy. Different maintenance methods have their own advantages and disadvantages. This paper will discuss different types of maintenance management and approaches, and their application in geothermal power plants.

This thesis outlines a 'process-step approach' to maintenance benchmarking of geothermal power plants, which can help identify the key performance indicators and, based on that, to develop a maintenance performance benchmarking model. The benchmarking model is then examined and an analysis made using two Icelandic geothermal power plants, as a best performer and benchmarked power plant.

The thesis is structured into six chapters. Chapter 1 (introduction) discusses the history of benchmarking, the objective of this thesis and the advantages of benchmarking. In Chapter 2, the maintenance management approaches are presented and described. Chapter 3 presents detailed descriptions of maintenance management methods. Three management methods; six sigma, RCM and lean maintenance are discussed to understand the applications and indicate a set of tools which helps to apply each method. In Chapter 4, the theorethical background of benchmarking is discussed. as is the benchmarking process with special emphasis on maintenance management in power plants. In Chapter 5, the the application of different maintenance management in geothermal power plants is presented, along with a general description of the benchmarked power plant and the best performer power plant, detailed performance benchmarking calculations and results. Chapter 6 presents the main conclusions.

2. MAINTENANCE MANAGMENT APPROACHES

Maintenance is any activity carried out on an asset in order to ensure that the asset continues to perform its intended functions. According to Jerry D. Kahn (2006), maintenance management is the coordination, control, planning, execution and monitoring of the right equipment maintenance activities in manufacturing and facilities operations. In a maintenance improvement programme, the maintenance activities are analyzed to ensure that the correct blend of maintenance strategies is utilized.

Over the past twenty years, maintenance has changed, perhaps more so than any other management discipline. The changes are due to a huge increase in the number and variety of physical assets (plant, equipment and buildings) which must be maintained throughout the world, much more complex designs, new maintenance techniques and changing views on maintenance organization and responsibilities. Maintenance is also responding to changing expectations. These include a rapidly growing awareness of the extent to which equipment failure affects safety and the environment, a growing awareness of the connection between maintenance and product quality, and increasing pressure to achieve high plant availability and to contain costs (Moubray, 2001).

This importance is manifested by both the significant material resources allocated to maintenance departments as well as by the substantial number of personnel involved in maintenance activities in companies. The maintenance of a geothermal plant is very dependent on different factors, namely, the geothermal system, the nature of the geothermal fluids, technological complexity of the plant, the remoteness of location, weather, and so on. In the face of growing interest in geothermal energy and the fact that most geothermal power plants are operated as baseload stations, developing and maintaining optimum maintenance approaches remain a challenge to maintenance teams in order to ensure high availability and reliability and to ensure sustainability of geothermal resources and to meet growing expectations.

Maintenance methods have been presented by different authors in different perspectives. In this research, a 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. There are four basic maintenance strategies that can be applied (Kahn, 2006):

- Corrective run-to-failure or breakdown maintenance (unplanned)
- Preventive periodic and prescribed maintenance (time-based)
- Predictive maintenance based on equipment condition (condition-based)
- Proactive focus on mitigating the need for maintenance (root-cause finding)

Different organization also includes a project work approach for maintenance. Project work makes up an important part of a maintenance strategy.

Corrective strategy has the lowest investment, the highest operating cost and provides the lowest equipment availability. The predictive and proactive strategies generally require the largest investment, have the lowest operating costs, and yield the highest equipment availability. The best strategy is to utilize a different strategy for each piece of equipment based on equipment criticality, economic (payback) analysis and risk assessment. This optimized blend of maintenance strategies is termed the best practice maintenance model, depicted in Figure 1. A best practice blend of maintenance strategies is 10% corrective, 30% preventive, 50% predictive, and 10% proactive. Current practice, however, has much room for improvement, with corrective maintenance being over 40%. (Kahn, 2006)

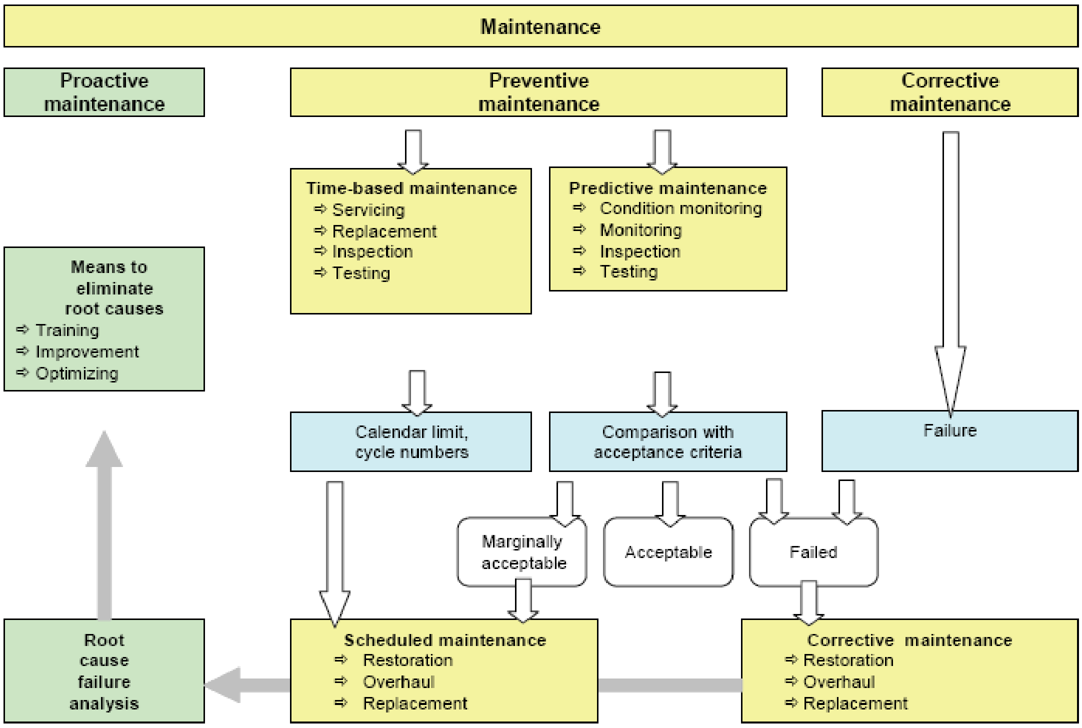

FIGURE 1: The best practice maintenance model

2.1 Corrective, run-to-failure or breakdown maintenance (unplanned)

This method, defined as no maintenance activity, is performed on machinery until it fails. At first impression this method seems the most cost effective because the manpower and their associated costs are minimal.

But closer examination shows that when the machinery fails, considerable expense is required to allocate manpower on an emergency basis, repair/replacement parts, and lost revenues due to non-production can mount rapidly depending upon the production process. Clearly, this method has the highest associated cost and maintenance is unpredictable at best. In addition, an unexpected failure can be dangerous to personnel and the facility.

The major downside of reactive maintenance is unexpected and unscheduled equipment downtime. If a piece of equipment fails and repair parts are not available, delays ensue while the parts are ordered and delivered (Chalifoux and Baird, 1999). If these parts are urgently required, a premium for expedited delivery must be paid. If the failed part is no longer manufactured or stocked, more drastic and expensive actions are required to restore equipment function. Cannibalization of similar or duplicate equipment or rapid prototyping technology may satisfy a temporary need but at substantial cost. Also, there is no ability to influence when failures occur because no (or minimal) action is taken to control or prevent them. When this is the sole type of maintenance practiced, both labor and materials are used inefficiently. Labor resources are thrown at whatever breakdown is most pressing. In the event that several breakdowns occur simultaneously, it is necessary to practice a kind of maintenance triage in an attempt to bring all the breakdowns under control. Maintenance labor is used to “stabilize” (but not necessarily fix) the most urgent repair situation, then it is moved on to the next most urgent situation, etc. Replacement parts must be constantly stocked at high levels, since their use cannot be anticipated. This incurs high carrying charges and is not an efficient way to run a storeroom.

Corrective maintenance is maintenance carried out after fault recognition and is intended to put the equipment into a state in which it can perform a required function. Corrective maintenance can be immediate or deferred (Márquez, 2007).

- Immediate maintenance. Maintenance which is carried out without delay after a fault has been detected to avoid unacceptable consequences;
- Deferred maintenance. Corrective maintenance which is not immediately carried out after a fault detection but is delayed according to given maintenance rules.

2.2 Preventive maintenance

Advancement on a breakdown maintenance programme is a preventive programme. Preventive maintenance (PM) is a schedule of planned maintenance actions aimed at the prevention of breakdowns and failures. The primary goal of PM is to prevent the failure of equipment before it actually occurs. It is designed to preserve and enhance equipment reliability by replacing worn components before they actually fail. PM activities include equipment checks, partial or complete overhauls at specified periods, oil changes, lubrication and so on. In addition, workers can record equipment deterioration so they know to replace or repair worn parts before they cause system failure. Recent technological advances in tools for inspection and diagnosis have enabled even more accurate and effective equipment maintenance. The ideal PM programme would prevent all equipment failure before it occurs.

There are multiple misconceptions about PM. One such misconception is that PM is unduly costly. This logic dictates that it would cost more for regularly scheduled downtime and maintenance than it would normally cost to operate equipment until repair is absolutely necessary. This may be true for some components; however, one should compare not only the costs but the long-term benefits and savings associated with PM. Without PM, for example, costs for lost production time from unscheduled equipment breakdown will be incurred. Also, PM will result in savings due to an increase of effective system service life. Preventive maintenance includes periodic and condition based (predictive) maintenance.

2.2.1 Time-based preventive maintenance

Periodic maintenance may be done at calendar intervals, after a specified number of operating cycles, or a certain number of operating hours. These intervals basically are established based on manufacturers' recommendations, and utility and industry operating experience. The equipment population covered by preventive maintenance was established during the plant startup stage and is refined as experience accumulates. Generally, the equipment population covered, the associated maintenance tasks, and their frequency of performance were initially established without a systematic evaluation of the related factors such as (IAEA, 2007):

- Importance of equipment failure to the overall plant function.
- Equipment duty cycles.
- Equipment redundancies.
- Effectiveness of the maintenance activities in preventing failures.
- Effectiveness of the maintenance activities in predicting failures.

The follow-up shows that there were too many maintenance tasks, high work backlogs, and equipment failures which led to reliability centered maintenance process.

Advantages of PM:

- Cost effective in many capital intensive processes.
- Flexibility allows for the adjustment of maintenance periodicity.

- Increased component life cycle.
- Energy savings.
- Reduced equipment or process failure.
- Decreased cost of replacement.
- Better spares inventory management.
- Decreased system downtime.
- Improved system reliability.

Disadvantages:

- Catastrophic failures still likely to occur.
- Labor intensive.
- Includes performance of unneeded maintenance.
- Potential for incidental damage to components in conducting unneeded maintenance.

Long-term effects and cost comparisons usually favor PM over performing maintenance actions only when the system fails.

PM is a logical choice with the following two conditions (ReliaSoft's System Analysis Reference, 2009):

- The component in question has an increasing failure rate. In other words, the failure rate of the component increases with time, thus implying wear-out. PM of a component that is assumed to have an exponential distribution (which implies a constant failure rate) does not make sense.
- The overall cost of the PM action must be less than the overall cost of a corrective action. (Note: In the overall cost for a corrective action, one should include ancillary tangible and/or intangible costs, such as downtime costs, loss of production costs, lawsuits over the failure of a safety-critical item, loss of goodwill, etc.)

The following techniques are recommended for setting initial periodicity (Chalifoux and Baird, 1999):

- Anticipating failure from experience. For some equipment, failure history and personal experience provides an intuitive feel for when to expect equipment failure. In these cases, failure is time related. Set monitoring so that there are at least three monitoring PM visits before the anticipated onset of failures. These three visits will give the maintenance technician enough of a "look" at the piece of equipment to become familiar with it. In most cases it is prudent to shorten the monitoring interval as the wear-out age is approached:
- Failure distribution statistics. In using statistics to determine the basis for selecting periodicities, the distribution and probability of failure should be known. Weibull (2009) distributions can provide information on the probability of equipment exceeding some life.
- Lack of information or "Conservative approach." The most common practice in the industry is to monitor the equipment biweekly or monthly due to lack of information and poor monitoring techniques. This often results in excessive monitoring. In these cases, significant increases in the monitoring interval may be made without adversely impacting equipment reliability.

2.2.2 Predictive maintenance based on equipment condition (condition-based)

Predictive maintenance (PdM) programmes measure equipment on a regular basis, track the measurements over time, and take corrective action when measurements are about to go outside the equipment operating limits. Repairing equipment as-needed requires fewer man-hours and parts than preventive maintenance. However, tracking the measurements requires new tools, training, and software to collect and analyze the data and predict repair cycles. As with the introduction of any new technology, proper application and training is of critical importance. This need is particularly true in the field of PdM technology that has become increasingly sophisticated and technology-driven. Most industry experts would agree (as well as most reputable equipment vendors) that this equipment should not be purchased for in-house use if there is not a serious commitment to proper implementation, operator training, and equipment monitoring and repair. If such a commitment cannot be made, a site is well advised to seek other methods of programme implementation—a preferable option may be to contract for these services with an outside vendor and rely on their equipment and expertise (Sullivan, 2004).

The goal of condition based maintenance is to optimize reliability and availability by determining the need for maintenance activities based on equipment condition. Using "predictive techniques", technologies, condition monitoring, and observations can be used to project forward in an effort to establish the most probable time of failure, enhancing the ability of the plant to plan and act in a proactive manner. PdM/CBM assumes that equipment has indicators that can be monitored and analyzed to determine the need for condition directed maintenance activities. Condition based maintenance allows the lowest cost and most effective maintenance programme by determining the correct activity at the correct time (IAEA, 2007).

Condition based maintenance is accomplished by integrating all available data to predict impending failure of equipment as well as to avoid costly maintenance. This process depends to a large extent on the ability to recognize undesirable operating conditions as measured by diagnostic monitoring systems. The process also allows equipment to continue operating in an undesirable condition while it is being monitored until maintenance can be scheduled.

The primary objectives of an optimized maintenance strategy programme that includes predictive and condition based maintenance are (IAEA, 2007):

- Improve availability
    - Reduced forced outages
    - Improve reliability
- Enhance equipment life
    - Reduce wear from frequent rebuilding
    - Minimize potential for problems in disassembly and reassembly
    - Detect problems as they occur
- Save maintenance costs
    - Reduce repair costs
    - Reduce overtime
    - Reduce parts inventory requirements

Condition based maintenance refers to a set of tasks performed to detect incipient failures of equipment, to determine the maintenance actions required, and to restore equipment to its operable condition after detection of an incipient failure condition. Condition monitoring may consist of continuous monitoring (for example, on-line diagnostics used in digital instrumentation systems or turbine generator thrust bearing wear monitoring) using permanently installed instrumentation or activities performed at specified intervals to monitor, diagnose, or trend the functional condition of equipment. The results from this activity support an assessment of the current and future functional capability of the equipment monitored and a determination of the nature and schedule for required maintenance (IAEA, 2007).

A variety of technologies can and should be used as part of a comprehensive condition based maintenance programme. Since mechanical systems or machines account for the majority of plant equipment, vibration monitoring is generally the key component of most condition based maintenance programmes. However, vibration monitoring cannot provide all of the information that will be required for a successful condition based maintenance programme. This technique is limited to monitoring the mechanical condition, not other critical parameters required for maintaining reliability and efficiency of the machinery. Therefore, a comprehensive condition based maintenance programme must include other monitoring and diagnostic techniques (IAEA, 2007). These techniques include:

- Vibration monitoring.
- Acoustic analysis.
- Motor analysis technique.
- Motor operated valve testing.
- Thermography.
- Tribology.
- Process parameter monitoring.
- Visual inspections.
- Other nondestructive testing techniques.

Additional advantages and some disadvantages of PdM are:

Advantages:

- Increased component operational life/availability.
- Decrease in equipment or unanticipated process downtime.
- Decrease in costs for parts and labour.
- Better product quality.
- Improved worker and environmental safety.
- Improved worker moral.
- Energy savings.
- Improved usage efficiency and reliability of equipment.
- Direct focus on the problem.

Disadvantages:

- Increased investment in diagnostic equipment.
- Increased investment in staff training.
- Savings potential not readily seen by management.

If PdM methods are superior to PM, why use PM at all? The answer is simple. The nature of your operation will determine which methods are most effective. In actual practice, some combination of PM/PdM is required to ensure maximum reliability. The degree of application of each will vary with the type of equipment and the percent of time these machines are operating. Pumps, fans, gear reducers, other rotating machines, and machines with large inventories of hydraulic and lubricating oils lend themselves to PdM surveillance methods. Assets which have critical timing adjustments, which tend to loosen and require precision adjustments, or have many cams and linkages which must be reset over time, lend themselves to PM activities.

The strategy for selecting the appropriate or predictive approach involves the following decision process (Peters, 2006):

- Consider the variety of problems (defects) that develop in your equipment.
- Use the predictive method if a predictive tool is adequate for detecting the variety of maintenance problems you normally experience. One or a combination of several PdM methods may be required.
- Use PM if it is apparent that PdM tools do not adequately apply. Inspection tasks must be developed that reveal the defects not adequately covered by preventive maintenance.
- After you have decided the combination of inspection methods, determine the frequency at which the particular inspection tasks must be applied. Some equipment will be satisfactorily monitored using only PdM. Other equipment will require PM. Ultimately, some combination of methods will provide the required coverage to ensure reliable performance. It is wise to apply a combination of methods to ensure that equipment defects do not go undetected.

2.3 Proactive focus on mitigating the need for maintenance (root-cause finding)

The proactive approach responds primarily to equipment assessment and predictive procedures. The overwhelming majority of corrective, preventive and modification work are generated internally in the maintenance function as a result of inspections and predictive procedures. The goals of this method are continuous equipment performance to established specifications, maintenance of productive capacity, and continuous improvement.

A proactively maintained system may still break, but it is more likely to have a fix available if the maintenance plan is well thought-out and well executed. A proactively maintained system is also less likely to need a major overhaul, as it never gets too far behind.

Proactive maintenance is characterized by the following attitudes (Chalifoux and Baird, 1999):

- Maintaining a feedback loop from maintenance technicians to building architects, engineers, and designers, in an attempt to ensure that design mistakes made in the past are not repeated in future designs.
- Viewing maintenance and supporting functions from a life-cycle perspective. This perspective will often show that cutting maintenance activities to save money in the short term often costs more money in the long term.
- Constantly re-evaluating established maintenance procedures in an effort to improve them and ensure that they are being applied in the proper mix.

Proactive maintenance uses the following basic techniques to extend machinery life (Chalifoux and Baird, 1999):

- Proper installation and precision rebuild;
- Failed-parts analysis;
- Root-cause failure analysis;
- Reliability engineering;
- Rebuild certification/verification;
- Age exploration;
- Recurrence control.

2.4 Project maintenance

Project work is intended to make the plant or involved equipment better, while normal maintenance aims to preserve the function of equipment by keeping equipment in its present condition. Project maintenance aims to preserve the function of equipment by improving equipment. In order to increase reliability, planners must consider projects at the corporate level. These projects will place new equipment and systems at the plant to upgrade the old system. In addition to corporate level projects, the plant also carries out project work at the plant level. Any work order that modifies equipment or restores equipment to perform at a superior level may be considered a project. The plant should continually be evaluating project ideas for making the plant more reliable.

3. DESCRIPTION OF MANAGEMENT METHODS

The management methods reviewed in this thesis are six-sigma, lean maintenance and reliability-centred maintenance (RCM). Many articles, publications and quite a number of books have been written to explain or promote specific methods to the industry. Competitive marketing of the methods often cause confusion and a procedure to compare and select the appropriate method is necessary.

3.1 Six-sigma method

According to Kahn (2006), the fundamental objective of the Six Sigma methodology is the implementation of a measurement-based strategy that focuses on process improvement and variation reduction through the application of Six Sigma improvement projects. The Six-Sigma, DMAIC process (Define, Measure, Analyze, Improve and Control) is an improvement system for existing processes falling below specification and looking for incremental improvement. Six-Sigma has two key methods: DMAIC and DMADV both inspired by Deming's Plan-Do-Check-Act Cycle. DMAIC is used to improve an existing business process; DMADV is used to create new product or process designs (Kahn, 2006). There are five basic steps in the application of Six Sigma tactics, seen in Figure 2.

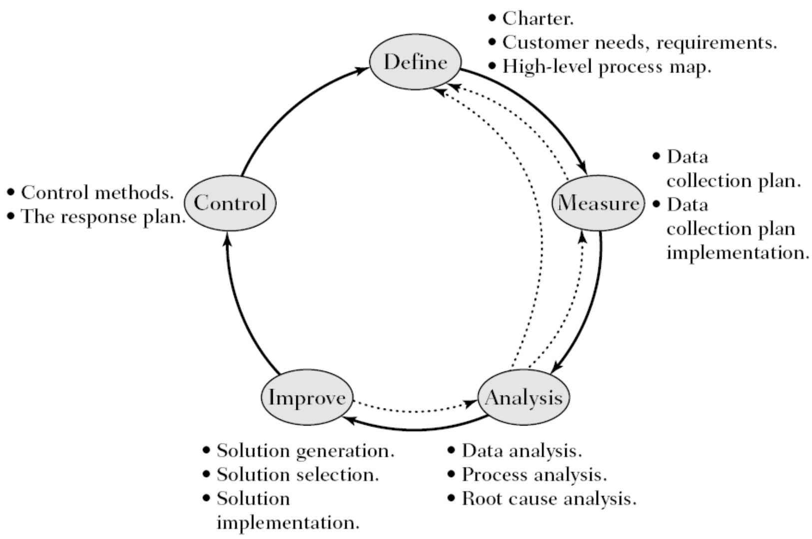

FIGURE 2: Basic DMAIC improvement methodology

The basic method consists of the following five steps:

- Define high-level project goals and the current process.
- Measure key aspects of the current process and collect relevant data.
- Analyze the data to verify cause-and-effect relationships. Determine what the relationships are, and attempt to ensure that all factors have been considered.
- Improve or optimize the process based upon data analysis using techniques such as designing experiments.
- Control to ensure that any deviations from the target are corrected before they result in defects. Set up pilot runs to establish process capability, move on to production, set up control mechanisms and continuously monitor the process.

The Six Sigma tools that can be applied during each step of the process are described in the following sections. (Kahn, 2006)

3.1.1 Define

The purpose of the Define step is to identify the major pains within the organization. These could include:

- Excessive outage rate
- Critical equipment down
- Repeat failure
- Maintenance staff constantly overloaded
- Lack of spare parts

- Excessive rework
- Dissatisfied customers (both external and internal).

It is important in the Design step to describe the process, and identify the key issues requiring resolution. Tools that can be applied include

- Critical to quality (CTQ) tree
- Affinity diagram
- Supplier-inputs-outputs-customer (SIPOC)
- Process mapping

3.1.2 Measure

The purpose of the Measure step is to gather information and data on the current situation. Data sources are identified, and methods of collecting the data are articulated. This includes the accumulation of existing procedures, equipment histories and baselines. Six Sigma tools that are applicable to the Measure step include:

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

3.1.3 Analyze

The goal of the Analyze step is to identify the causes of problems. The data collected in the Measure step is analyzed in detail, cause and effect relationships are explored, and failure causes and consequences are evaluated. Tools used to analyze the data include:

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

3.1.4 Improve

During the Improve step, possible solutions to problems are devised and developed so they can be proposed to management for approval and funding. Each solution must be both feasible (both in resources and time requirements) and cost effective. Six Sigma tools that can be utilized during the Improve step include:

- Brainstorming
- Benchmarking
- Decision matrix

3.1.5 Control

The purpose of the Control step is to ensure that the maintenance improvement projects are being effectively implemented, that the gains promised will be realized, and to continue to seek out additional improvement potential. This is done by

- Monitoring process trends and variations
- Monitoring key performance indicators (KPI), and

- Instilling continuous improvement programmes. The process parameters should be continually monitored using the control charts and run charts used in the Measure step.

3.2 Lean maintenance

Ricky Smith defines Lean maintenance as ‘a proactive maintenance operation employing planned and scheduled maintenance activities through total productive maintenance (TPM) practices using maintenance strategies developed through the application of Reliability Centered 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 (EAM) system. They are supported by a distributed, Lean maintenance/MRO (Maintenance, Repairs, Operations) storeroom that provides parts and materials on a just-in-time (JIT) basis, backed by a maintenance and reliability engineering group that performs root cause failure analysis (RCFA), failed part analysis, maintenance procedure effectiveness analysis, predictive maintenance (PdM) analysis, and trending and analysis of condition monitoring results’ (Smith, 2004). Based on the above definition, the key elements of a Lean maintenance method are:

- Proactive
- Planned and scheduled
- Total productive maintenance
- Empowered (self-directed) action teams
- 5S process
- Kaizen improvement events
- Autonomous maintenance
- Multi-skilled, maintenance technician
- Work order system
- Computer managed maintenance system
- Distributed, lean maintenance/MRO storeroom
- Parts and materials on a just-in-time basis
- Maintenance and reliability engineering group

Basic Lean concepts are:

- Waste reduction
- Integrated supply chain
- Enhanced customer value
- Value creating organization
- Committed management
- Winning employee commitment/empowering employees
- Optimized equipment reliability
- Measurement (lean performance) systems
- Plant-wide lines of communication
- Making and sustaining cultural change

Tools:

- 5-S Process
    - Sort (remove unnecessary items)
    - Straighten (organize)
    - Scrub (clean everything)
    - Standardize (standard routine to sort, straighten and scrub)
    - Spread (expand the process to other areas)

- Seven Deadly Wastes
  - Overproduction ahead of demand.
  - Waiting for the next processing step
  - Unnecessary transport of materials
  - Over processing of parts due to poor tool and product design
  - Inventories more than the absolute minimum
  - Unnecessary movement by employees during the course of their work (looking for parts, tools, prints, help, etc.)
  - Production of defective parts
- Standardized work flow (TAKT [cycle] time, work sequence and WIP [work in progress])
- Value stream mapping/process mapping (use of symbols to draw a map of the steps in a process-process mapping)
- Kanban (visual cues or signals)
- Jidoka (Perfection [Quality] at the source—quality built in, not inspected in)
- Poka yoke (mistake or error proofing)
- Use of JIT and Pull (Supplying items JIT [Just-in-Time] and pulling items only as you need them)

According to Cooper (2002), "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. Any maintenance engineer or manager can begin Lean Maintenance by protecting automation, electronics, hydraulics and computer-controlled equipment from the real causes of malfunctions, failures, and downtime-chronic stress discussed above. Circuit board failures, hydraulic system failures and other malfunctions are only symptoms, not the underlying cause of unscheduled equipment downtime. This means:

- Increased profits
- Near 100% uptime required for lean manufacturing,
- Greatly reduced maintenance overhead, and
- Reduced dependence on outside support.

Lean Maintenance is maximizing uptime, yield, productivity, and profitability (Cooper, 2002).

3.3 Reliability centered maintenance (RCM)

Reliability centered maintenance (RCM) is a process that determines what must be done to ensure that any plant asset continues to function in the desired manner within its present operating context. There are numerous variations and derivatives of the classic RCM process in use today, most of which are aimed at facilitating the failure modes and effects analysis (FMEA) and developing the appropriate plan of action.

Sullivan (2004) and other leading writers in this business indicate that, basically, RCM methodology deals with some key issues not dealt with by other maintenance programmes. It recognizes that all equipment in a facility is not of equal importance to either the process or facility safety. It recognizes that equipment design and operation differs and that different equipment will have a higher probability to undergo failures from different degradation mechanisms than others. It also approaches the structuring of a maintenance programme recognizing that a facility does not have unlimited financial and personnel resources and that the use of both need to be prioritized and optimized. In a nutshell, RCM is a systematic approach used to evaluate a facility's equipment and resources to best mate the two and result in a high degree of facility reliability and cost-effectiveness. RCM is highly reliant on predictive maintenance but also recognizes that maintenance activities on equipment that is inexpensive and unimportant to facility reliability may best be left to a reactive maintenance approach. The following maintenance programme breakdowns of continually top-performing facilities would echo the RCM approach to utilize all available maintenance approaches with the predominant methodology being predictive.

- <10% reactive
- 25% to 35% preventive
- 45% to 55% predictive.

Because RCM is so heavily weighted in the utilization of predictive maintenance technologies, its programme advantages and disadvantages mirror those of predictive maintenance. In addition to these advantages, RCM will allow a facility to more closely match resources to needs while improving reliability and decreasing cost (Sullivan, 2004).

The key elements of the RCM process include the following:

- Analysis and decision on what must be done to ensure that any physical asset, system, or process continues to do whatever its users want it to do. Includes essential information gathering.
- Define what users expect from their assets in terms of primary performance parameters such as output, throughput, speed, range, and carrying capacity.
- As applicable, the RCM 2 process defines what users want in terms of risks, process and operational safety, environmental integrity, quality of the output, control, comfort, economy of operation, customer service, and the like.
- Identify ways in which the system can fail to live up to these expressions (failed states) and failure consequences.
- Conduct failure modes and effects analysis (FMEA) to identify all the events which are reasonably likely to cause each failed state.
- Identify a suitable failure management policy for dealing with each failure mode in the light of its consequences and technical characteristics. Failure management policy options include:
- Predictive maintenance
- Preventive maintenance
- Failure-finding
- Change the design or configuration of the system
- Change the way the system is operated
- Run-to-failure (if preventive tasks are found)

RCM, like other managment methods, has its own advantages and disadvantages.

Advantages:

- Can be the most efficient maintenance programme.
- Lower costs by eliminating unnecessary maintenance or overhauls.
- Minimize frequency of overhauls.
- Reduced probability of sudden equipment failures.
- Able to focus maintenance activities on critical components.
- Increased component reliability.
- Incorporates root cause analysis.

Disadvantages:

- Can have significant startup cost, training, equipment, etc.
- Savings potential not readily seen by management.

RCM can improve the efficiency of the system undergoing maintenance, and all other products or processes that interact with that system. Developing an effective RCM programme will optimize the maintainability of the system - allowing you to anticipate the times when the system is down for maintenance, and scheduling other activities or processes accordingly.

4. BENCHMARKING

4.1 What is benchmarking?

There are numerous definitions of benchmarking, but it essentially involves learning, sharing information, and adopting best practices to bring about step changes in performance (Figure 3). At its simplest, benchmarking means "improving ourselves by learning from others." A more detailed definition of benchmarking is a continuous and systematic process of identifying, analyzing, and adapting industries' best practices that will lead an organization to superior performance (Spendolini, 1992). More recently, Harrington described benchmarking as "a systematic way to identify, understand, and creatively evolve superior products, services, designs, equipment, processes, and practices to improve your organization's real performance" (Harrington and James, 1996). Benchmarking will continue to help us:

- Improve our performance and organization
- Learn about industry leaders and competitors
- Determine what world-class performance is
- Accelerate and manage change
- Achieve breakthrough results and identify gaps in performance
- Improve customer satisfaction
- Become the best in the business

Benchmarks serve as indicators to:

- Understand our process and approach. Comparing overall performance results can indicate whether an approach (e.g., maintenance, training, management decision) was effective. Benchmarks can indicate possible directions for change.
- Pinpoint areas for effective change. Comparison of a power plant´s performance to others in the industry can indicate areas for improvement.

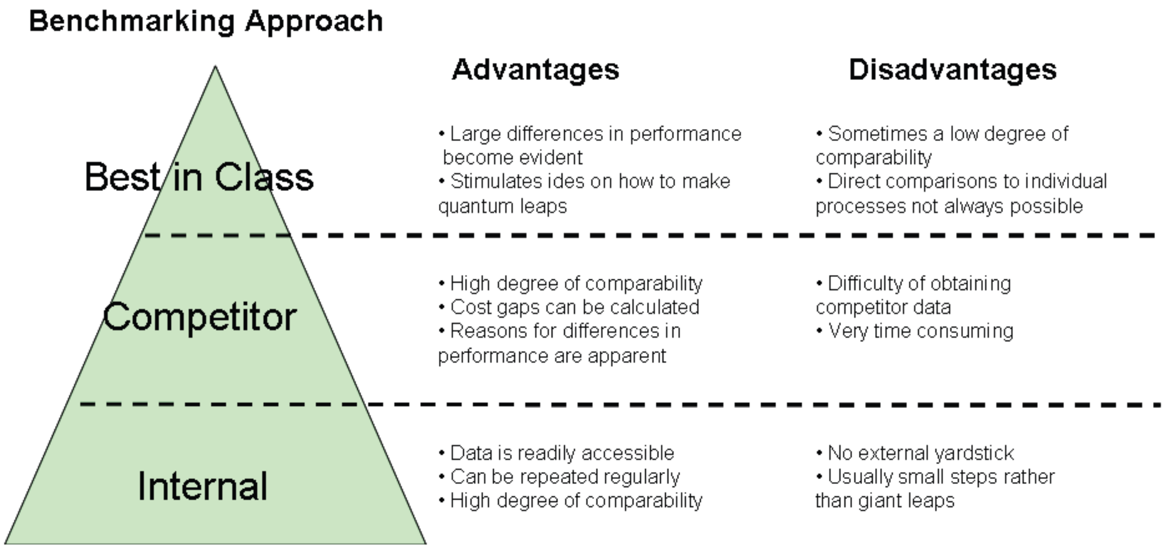

FIGURE 3: Approaches to benchmarking (Kahn, 2006)

Benchmarking is a structured approach for learning about process operations from other organizations and applying that knowledge gained to your own organization. It consists of dedicated work in measuring, comparing, and analyzing work processes among different organizations in order to identify causes for superior performance. Benchmarking is not complete with just the analysis, however. It must be adapted and implemented in order to have a complete cycle of learning. Benchmarking is not just a checklist or set of numbers that are used to make management feel better about their current performance. Benchmarking should make management uncomfortable due to the identification of gaps in business performance. Benchmarking should challenge management due to the discovery of performance enablers that could help them to improve. While differentiating benchmarking by describing what it is, and is not, is helpful, it would be even more useful to understand more fully the logic by which a benchmarking study is conducted (Watson, 2007). What is and is not is presented in Table 1.

TABLE 1: Benchmarking is - is not analysis

Benchmarking is:	Benchmarking is not:
A discovery process	A fixed, rigorous cookbook process
An improvement methodology	A panacea for developing all problem solutions
A source of breakthrough innovation	Supporting continuation of ‘‘business as usual‘‘
An opportunity to gain profound knowledge	A management fad or ‘‘tool of the day‘‘
An objective analysis of working proccesses	Based on a subjective ,‘‘gut feeling‘‘ or opinion
A process-based learning approach	Just a measurement of performance results
A way to generate ideas for creative imitation	Mearly a set of quantitative comparisons
A way to capture tacit process knowledge	Limited to within industry/competitor analysis

4.1.1 Types of benchmarking

Several types of benchmarking can be employed in conducting a benchmarking project. They include (Wireman, 2004 and 2005):

- Internal
- Competitive / similar industry
- Best practice

Internal benchmarking
Internal benchmarking typically involves different departments or processes within a plant. This type of benchmarking has some advantages in that data can be collected easily. It is also easier to compare data because many of the hidden factors (enablers) do not have to be closely checked. For example, the departments will have a similar culture, the organizational structure will likely be the same, and the skills of the personnel, labor relations, and management attitude will be similar. These similarities make data comparison quick and easy. The greatest disadvantage of internal benchmarking is that it is unlikely to result in any major breakthrough in improvements. Nevertheless, internal benchmarking will lead to small, incremental improvements and should provide adequate Return On Investment for any improvements that are implemented. The successes from internal benchmarking will very likely increase the desire for more extensive external benchmarking.

Competitive/ similar industry
Competitive or similar industry for benchmarking uses external partners in similar industries or processes. In many benchmarking projects, even competitors are used. This process may be difficult in some industries, but many companies are open to sharing information that is not proprietary. With similar industry/competitive benchmarking, the project tends to focus on organizational measures. In many cases, this type of benchmarking focuses on meeting a numerical standard, rather than improving any specific business process. In competitive benchmarking, small or incremental improvements are noted, but paradigms for competitive businesses are similar. Thus, the improvement process will be slow.

Best practices benchmarking
Best practice benchmarking focuses on finding the unarguable leader in the process being benchmarked. This search, which crosses industry sectors and geographical locations, provides the opportunity for developing breakthrough strategies for a particular industry. The organization studies business processes outside its industry, adapts or adopts superior business processes, and makes a quantum leap in performance compared to its competitors. Being the early adaptor or adopter will

give the organization an opportunity to lower costs or aggressively capture market shares. One of the keys to being successful with best practice benchmarking is to define a best practice. For example, does best mean:

- Most efficient?
- Most cost effective?
- Most customer service oriented?
- Most profitable?

When looking for Best practice companies, it must be understood that no single best practice company will be found. All companies have strengths and weaknesses. There are no perfect companies. Because the processes that are in need of improvement through benchmarking vary, the companies identified as the Best will also vary. A company that wants to insure it is benchmarking with the best needs systematic and thorough planning and data collection. Of the three types of benchmarking, Best Practice benchmarking is superior. It provides the opportunity to make the most significant improvement; the companies being benchmarked are the best in the particular process. Best practice benchmarking provides the greatest opportunity to achieve the maximum return on investment. Most important, best practice benchmarking provides the greatest potential for achieving breakthrough strategies, resulting in an increase in the company's competitive position (Wireman, 2005).

4.2 Benchmarking process

According to Gregory H. Watson (2008) the generic four-phases that these steps cover roughly follow a Plan-Do-Check-Act (PDCA) process that is called the Deming Cycle and which is generic in all process improvement models for process management and improvement. The PDCA approach to process benchmarking is shown in Figure 4.

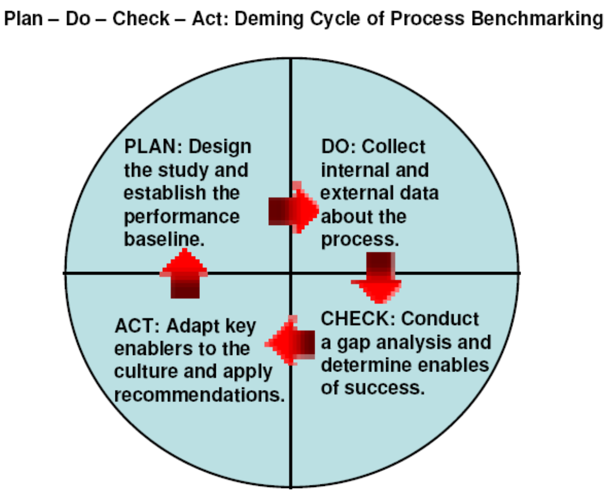

FIGURE 4: Deming cycle of process

There is a more detailed process for process benchmarking. However, the benchmarking process, with special emphasis on maintenance managment in the power plant, consisted of the following steps and the work that must be done in a benchmarking study will discussed in four-phase.

Seven steps process benchmarking: (Richard et al., 2000) A method for studying work process performance between two unique or distinct implementations of the same fundamental activity. Process benchmarking includes internal inspection of an organization's own performance as well as the external study of another organization that is recognized for achieving superior performance as evidenced by an objective standard of comparison (the benchmark). The objective of process benchmarking is not to calculate a quantitative performance gap, but to identify best practices that may be adapted for improvement of organizational performance.

1. Identify subject: Choose the key maintenance performance indicators (variables) that need to be benchmarked;
2. Plan study: Identify the power plant and plan your data collection;
3. Collect information: Actively collect the data and visit the power plants;
4. Analyse data: Analyze the data for performance trends and consistency over time;
5. Compare performance: Compare results to test differences for statistical significance;
6. Adapt applications: Prepare the lessons learned for transition to your own maintenance culture;

7. Improve performance: Implement projects to improve your processes.

Step 1: Choosing the benchmarking topic and planning the study
This step is the major step in the benchmarking process. Choose carefully key performance indicators to benchmark. These performance indicators can be used also to identify current performance gaps between current and desired performance and provides an indication of progress towards closing the gaps. The key maintenance performance indicators which have been identified are catagorized as follows:

- General information
  - labour data
  - training cost and hour
  - generating unit design data
  - generating unit operation data
- Maintenance performance management
  - work order management
  - outage management
  - spare parts management
- Maintenance processes:
  - maintenance work service
  - miscellaneous services
- Safety data
  - Lost time injury
  - Injury severity

Step 2: Identifying partners, collecting data, and answering questions
The following five tips will help organizations follow a structured process for partner selection that returns:

- Start the selection process with a clean slate.
- Establish well-defined criteria upfront for benchmarking partners.
- Define what "best practice" means at your organization, then who partners accordingly.
- Use secondary research to identify potential benchmarking partners.
- Weed out the best from the rest.

This step is extremely important. Identify “best-in-class” and potential partners to get the desired information and data. Discuss and decide the scope of the study and what type of information one is looking for in the process. Reliable, consistent, and accurate data collection will make the process easier along the way. Data collection is made easier by customizing forms to assure that the right data quickly ends up in the right place.

According to Robert Camp, face to face contact is necessary to search out benchmark data; that is not always the case. Much information you are seeking may be available publicly, in news, trade, or professional journals, annual reports, or online databases. If you are gathering new information personally, you may be able to collect it through mailed written surveys or telephone interviews. If you gather new information, it is critical that you agree at the start regarding the confidentiality of the information, and you may want to plan a way to share the information gathered with all of your benchmarking partners (Camp, 1989 and 2007).

In conducting a benchmark study, there are several different approaches to collecting data that can be pursued by a benchmarking team. Tables 2 and 3 illustrate several data collection schemes and identify when to use each approach as well as the advantages and disadvantages associated with each of the methods.

TABLE 2: Data collecting sheet 1

Method	Existing data review	Questionnaire/survey	Telephone survey
Definition	Analysis and interpretation of maintenance data that already exists in-house.	Written questions sent directly to benchmarking partner; can contain any type of question: multiple choice, open-ended, forced choice, or scaled answer.	A written script of questions used to solicit data or information over the telephone.
When to Use	Before conducting original research to establish what is the historical baseline.	When you need to gather information from a wide number of sources.	When information is needed quickly or to rapidly screen potential sources.
Advantage	A large number of sources of information is available.	Permits extensive data gathering over time, can be analyzed by computer, and data is easy to compile	Can cover a wide range of respondents quickly; people are more candid over the telephone.
Disadvantage	Gathering the appropriate information can be very time consuming.	Response rates are low: the interpretation of questions is sometimes subjective, creative ideas rarely surface, difficult to probe for how-to answers.	Locating the right person to answer your questions; no exchange of process information requires multiple calls.

TABLE 3: Data collecting sheet 2

Method	Existing data review	Questionnaire/survey	Telephone survey
Definition	A face-to-face meeting with a benchmarking partner using questions that are prepared and distributed in advance.	A panel discussion between benchmarking partners with a third party facilitator at a neutral location.	An on-premise meeting at a benchmarking partner facility that combines the interview with work process observation.
When to Use	When you need one-on-one interaction to probe and drive data collection to a specific objective or level of detail.	When you want to gather information from more than one source or perspective at the same time; when there are diverse opinions or ways to approach the objective.	When you need to observe specific work practices; (check font size) when interpersonal or faceto-face interaction is needed to evaluate human aspect of a process.
Advantage	Encourages interaction, in-depth discussion, and open-ended questions; a flexible style can provide unexpected information.	Direct sharing of information on best practice; brings the partners together to discuss a mutually established agenda.	Can observe actual practice and verify process, enablers, and measurement systems.
Disadvantage	Takes time; interviewees may be reluctant to talk about sensitive issues.	Logistics must be managed; result may be the lowest common denominator.	Requires careful planning and preparation; who asks what of whom?

One or many data collection techniques may be used. Typically, a team will decide for one (or multiple) data collection techniques while considering its overall appropriateness to the research, along with other practical factors, such as: expected quality of the collected data, estimated costs, predicted nonresponse rates, expected level of measure errors, and length of the data collection peiod. The most popular data collection techniques include: surveys, secondary data sources or archival data, objective measures or tests, and interviews, some of which are shown in Figure 5 (Lyberg and Kasprzyk, 1991).

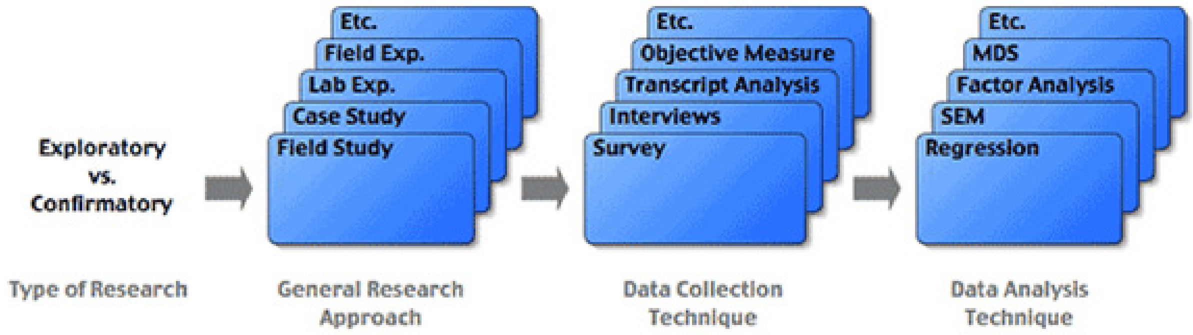

FIGURE 5: Type of research, general research approaches, data collection techniques, and data analysis techniques

Step 3: Analyzing performance and comparing processes
The step can be done by:

- Writing an outline of the information,
- Put information in comparing matrix of each company,
- Analyze matrix and the collected information in phases, and
- Summarize all data.

After the information has been collected and summarized, the next step is data analysis. The steps toward information analysis are:

- Check for misinformation,
- Identify the patterns of the data,
- Identify omissions or displacement,
- Check for data that do not fit, and
- Draw conclusions.

Convert the data into "useful data" or information that people can quickly use to determine root cause and corrective action to improve performance. Useful data shows the current performance compared to a historical trend. Charting the data in an easy-to-read format contributes to its usefulness. Annotating root causes for deviations from the goal makes the data very useful for making corrective actions and preventing recurrences.

Step 4: Implementing recommended changes to improve the process
Plan for change: as a result of what you have learnt from your partners, identify which ideas you can adopt or adapt to improve your process, and how to implement them.

After the normalization of the maintenance management data, the positive and negative gaps of maintenance performance in the power plant would be clearly identified against the leading organizations in the world. The causes of negative gaps can be easly analyzed by understanding how the other leading organization achieved their outstanding results.

In this step, all actions that are required to change the process that the plant chose to benchmark are implemented. These actions may include making recommendations, conducting a report or preparing a presentation to apply to the process.

- Producing a benchmarking report: This is one of the major tasks of the benchmarking process. The report will serve several purposes including: a report to be delivered to the benchmarking customers, a summary of data that were collected and analyzed, a record of the organization benchmarked and key project contacts, and a communications product for other internal employees and functions.

- Presenting findings to benchmarking management: This step might be provided upon management request. This step offers an opportunity to expand the audience for the benchmarked findings and stimulate action for changes.
- Identifying possible product and process improvements: This step implements the action which the company has planned.

4.3 Maintenance performance benchmark model and performance indicators used for the benchmarking

The model is designed to make performance benchmarking of one power plant with one or more other plants. The model includes outages, power de-rating information, unit generation Performance data and unit time information. Different equations were used to calculate different performance indicators. The model also facilitates using more data and equations to calculate additional performance indicators. Excel worksheet was used for the model development. Most terminologies in the model were adapted from the North American Electric Reliability Corporation data reporting instruction and from the paper prepared by the International Geothermal Association (2001) for the World Energy Council Working Group on «Performance of Renewable Energy Plants». A list of minimum data for the model is listed and attached as Appendix II. The complete model is attached as Appendix I.

Some performance indicators in the model are discussed as follows:

4.3.1 Productivity level

Based on different researches the maintenance productivity level of equipment is measured in terms of the total maintenance costs of labour, material and tools etc. spent in maintenance activities divided by the generated electricity in MW.

$$AEMC = \frac{\sum_{N=1}^{5}(TPMC - TPCC - TTSC - TCDR)}{number\ of\ years} \qquad (1)$$

Where,

AEMC - average equipment maintenance cost for five years
TPMC - total plant maintenance cost per year
TPCC - total pollution control cost per year
TTSC - total technical support cost per year
TCDR - total cost for disaster and rehabilitation per year
N - number of years (N = 1, 2, 3, 4 and 5)

The maintenance productivity, which is measured by dividing the average equipment maintenance cost by the installed capacity, found using Formula 2 and the result is illustrated in Table 7.

$$x = \frac{AEMC}{Installed\ capacity} \qquad (2)$$

4.3.2 Power plant reliability

Equipment failures and maintenance mean that power plants are not always available for operation. When assessing capacity, forced outages are the most critical ones since they are often unplanned. The main indicators of power plant reliability are the forced outage rate (FOR), the equivalent forced outage rate (EFOR), and the equivaalent forced outage rate demand (EFORd). Reliability is then the main indicator of power plants in operation. FOR and EFOR are reasonable indicators for base load or near base load types of generating units.

Forced outage rate (FOR): The percentage of time that a given point in the supply chain is nonfunctional due to forced outages. Forced outage rates are used when calculating the overall reliability of an energy delivery system, calculated by Equation 3:

$$FOR = \frac{FOH}{(FOH+SH)} \times 100\% \qquad (3)$$

where FOH - Forced outage hours
SH - Service hour

EFOR differs only in that EFOR considers the "equivalent" impact that forced de-ratings have in addition to the full forced outages that FOR considers and is calculated by Equation 4.

$$EFOR = \frac{(FOH+EFDH)}{FOH+SH+\text{EFDH})} \times 100\% \qquad (4)$$

where FOH - Forced outage hours
SH - Service hour
EFDH - Equivalent forced de-rating hours

The average equivalent forced outage rate (AEFOR) is calculated by Equation 5.

$$AEFOR = \frac{\sum_{N=1}^{5} EFOR \times SH}{\sum_{N=1}^{5} SH} \qquad (5)$$

Availability factor (AF) of a power plant is the amount of time that it is able to produce electricity over a certain period, divided by the amount of time in that period. Occasions where only partial capacity is available may or may not be deducted and calculated by Equation 6.

$$AF = \frac{AH}{PH} \times 100\% \qquad (6)$$

where AH - Available hours or the sum of all hours the unit is connected to the transmission system and is available as a reserve.
PH - period hours or the number of hours the unit is in an active state.

In addition, different maintenance related costs and equipment reliability performance indicators were used in the model.

4.4 Benchmark benefits and pitfalls

Benchmarking is a business change process that encourages managed change by making an external and objective assessment of its own performance (Watson, 2008). It is the discovery of the performance gap that provides a wake-up call that causes alarm in an organization and develops a state of urgency and dissatisfaction with the way things have been done. (See Figure 6)

The benefit of benchmarking comes from three specific actions:

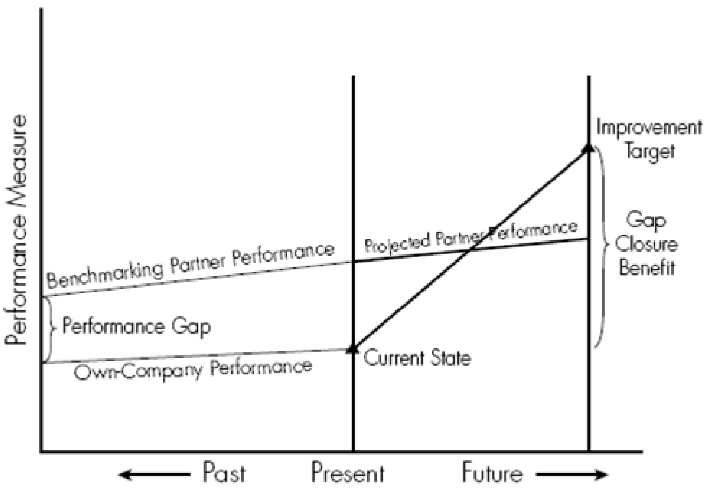

FIGURE 6: Performance gap illustration

- The gap between internal and external practices creates the need for change.
- Understanding the benchmarked best practices identifies what must change.
- Externally benchmarked practices provide a picture of the potential result from change.

When benchmarking is used properly, it can make a major contribution to the continuous improvement process. However, it can also be completely devastating to a company's competitive position when used improperly.

Some of the improper uses of benchmarking include (Wireman, 2005):

- Using benchmarking data as a performance goal**.** When companies benchmark their core competencies, they can easily fall into the trap of thinking a benchmark should be a performance indicator. For example, they focus all of their efforts on cutting costs to reach a certain financial indicator, losing focus on the real goal. A company receives greater benefits when the tools and techniques used by a partner to achieve a level of performance are understood. This understanding allows the company not only to reach a certain number, but also to develop a vision of how to achieve an even more advanced goal. By focusing on reaching a certain number, some companies may have changed their organizations negatively (e.g., by downsizing or cutting expenses). However, they may have also removed the infrastructure (people or information systems) and soon find they are not able to sustain or improve the benchmark. In such cases, benchmarking becomes a curse.

- Premature benchmarking**.** When a company attempts to benchmark before the organization is ready, it may not have the data to compare with its partners. Therefore, someone makes a "guesstimate" that does the company no good. The process of collecting data gives an organization an understanding of its core competencies and how it currently functions. Premature benchmarking will lead back to the first trap--just wanting to reach a number. Companies that step into this trap become "industrial tourists." They go to plants and see interesting things, but don't have enough of an understanding to apply what they see to their own businesses. The end results, then, are reports that sit on shelves and never contribute to improved business processes.

- Copycat benchmarking**.** Imitation benchmarking occurs when a company visits its partners and, rather than learning how the partners changed their businesses, concentrates on how to copy the partners' current activities. This practice may be detrimental to a company because it may not have the same business drivers as its benchmarking partners. Also, there may be major constraints to implementing the partner's processes. Such constraints might include incompatible operations, different skill levels of the work force, different union agreements, different organizational structures, and different market conditions.

- Unethical benchmarking**.** Sometimes a company will agree to benchmark with a competitor and then try to uncover proprietary information while on the site visit or by use of the questionnaire. Clearly, this kind of behaviour will lead to problems between the companies and virtually ruin any chance of conducting a successful benchmarking exercise at a later date. A second type of unethical benchmarking entails referring to or using the benchmarking partners' names or data in public without receiving prior permission. This, too, will damage any chance for ongoing benchmarking between the companies. Even worse, the bad experience may prevent management from ever commissioning further benchmarking exercises with other partners.

5. MAINTENANCE BENCHMARK APPLICATIONS IN GEOTHERMAL POWER PLANTS

5.1 Benchmarking case

In this thesis, two Icelandic geothermal power plants were used for maintenance benchmarking: Svartsengi and Reykjanes as benchmarked power plants and Nesjavellir as the best performer power plant.

5.1.1 Svartsengi and Reykjanes power plants

Both geothermal power plants are owned and operated by the Sudurnes Regional Heating Corporation (Sudurnes) which supplies geothermal heat and electricity to the Reykjanes Peninsula in SW-Iceland.

Svartsengi power plant
The cogeneration power plant exploits geothermal brine at 240°C with a salinity of about two thirds seawater. Geothermal heat is transferred to freshwater in several heat exchangers. After improvements and expansion in late 1999, the total installed capacity of the Svartsengi power plant increased to 200 MWt for hot water production and 75 MWe for electrical generation. Of that, 8.4 MWe came from Ormat binary units using low-pressure waste steam. The total electrical generation of the Svartsengi power plant in 2005 was 368 GWh. The effluent brine spillover from Svartsengi is disposed into a surface pond called the Blue Lagoon (Commerce, April 2006). Figure 7 shows a schematic flow diagram for the electricity generation and thermal production process of the Svartsengi power plant.

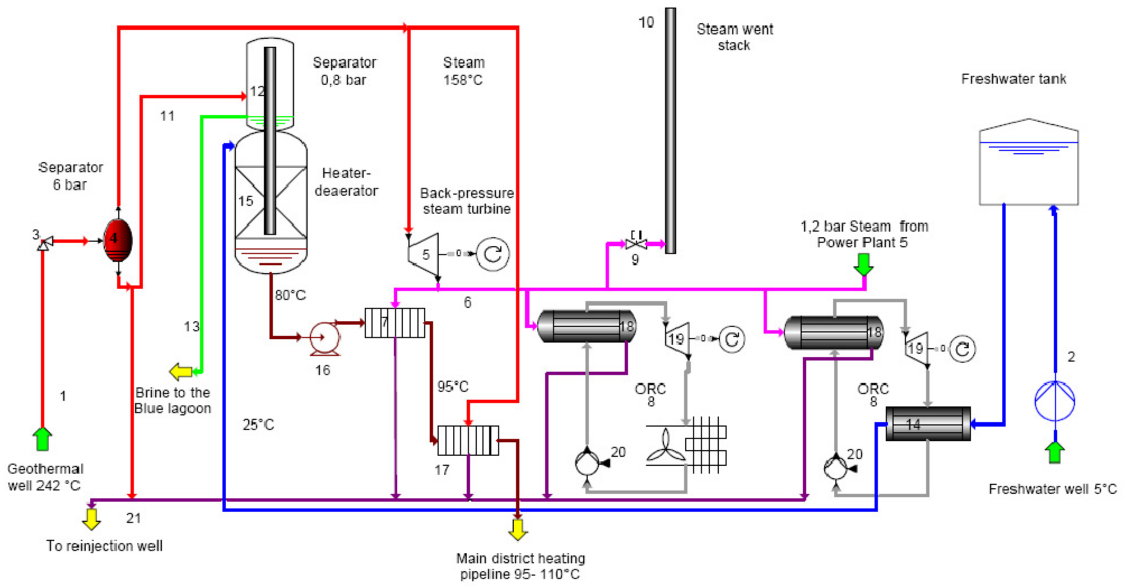

FIGURE 7: Flow diagram of Svartsengi power plant (Thorolfsson, 2005b)

According to Geir Thorolfsson, currently, the Svartsengi power plant consists of:

- Power Plant 1: Commissioned in 1977/78: The installed heat exchange capacity was 150 L/s for the district heating system, corresponding to 50 MJ/s (MWt). Additionally, two 1-MWe AEG back-pressure steam turbine generators were installed. In the year 2000, half of the heat exchange system was decommissioned.
- Power Plant 2: Commissioned in 1981: The installed heat exchange capacity is 225 L/s for the district heating, corresponding to 75 MJ/s (MWt).
- Power Plant 3: A 6-MWe Fuji Electric back-pressure turbine, started commercial production on January 1, 1981.
- Power Plant 4: Commissioned in September 1989, with three 1.2-MWe ORMAT ORC units. On these units, water-cooled condensers are utilized. The second part was commissioned in 1993 by adding four 1.2- MWe ORMAT units with air-cooled condensers.

- Power Plant 5: A 30-MWe Fuji Electric extraction condensing steam turbine, was commissioned in November 1999, and in April 2000, a district heating part of 75-MJ/s (MWt) thermal power was commissioned. (Thorolfsson, 2005b).

From the power plant combination we can assume the neccessity of high class maintenance planning and comprehnsive maintenance skills to keep the plant running with high availability and reliability. The complexity of the plant created various problems.

Reykjanes power plant
The Reykjanes geothermal power plant in Iceland produces 100 MWe from two 50 MWe turbines. The plant uses steam from a reservoir at 290-320°C – the first time that geothermal steam of such high temperature has been used to generate electricity on a large scale. The new plant is located on the Reykjanes peninsula, in the southwest corner of Iceland. The Reykjanes plant uses steam and geothermal brine extracted from twelve 2,700 m-deep wells. After extraction, the brine is piped into a steam separator. From there, the separated steam passes under 19 bars of pressure to a steam dryer and into the two 50 MW turbines.

The plant is situated close to the ocean front, so seawater (4,000 l/s) at 8°C can be pumped through a condenser for cooling and condensing the steam.

5.1.2 Nesjavellir power plant

The plant has been the largest geothermal power plant in Iceland. It is located 177 m above sea level in the southwest part of the country, near Þingvellir and the Hengill volcano. Plans for utilizing the Nesjavellir area for geothermal power and water heating began in 1947. Some boreholes were drilled to evaluate the area's potential for power generation. Research continued from 1965 to 1986. In 1987, the construction of the plant began, and the cornerstone was laid in May, 1990. The station produces approximately 120 MW of electrical power, and delivers around 1800 l/s of hot water, servicing the Reykjavík area's hot water needs. Nesjavellir power plant is owned and operated by Reykjavik Energy Co. (2003).

In 1991, the production of electricity commenced with the installation of two 30-MWe turbines. In 2001, the third turbine was installed, increasing the capacity to 90 MWe. In 2003, the hot water production was increased to 290 MWt, and the fourth electricity turbine was installed in 2005, bringing the capacity to 120 MWe. The stepwise increases in production are summarized in Table 4. A simplified flow diagram for electric and thermal production of Nesjavellir power plant is shown in Figure 8.

TABLE 4: Co-generation of electricity and hot water at Nesjavellir (Lund, 2005)

Year	Hot water		Electricity co-generation
	l/s	MWt	MWe
1990	560	100	
1991	840	150	
1998	1,120	200	60
2001			90
2003	1,640	290	
2005			120

5.2 The maintenance management methods applied in geothermal power plants

Each management method should not be considered the only method, but should integrate with other programmes and methods as part of an overall business strategy. Each method should not replace other methods, but instead offer a tactical methodology to determine the best approach for a given situation/process. Each method supports the other. For example, Lean has integrated extremely well with different Six Sigma project work. In most cases, the Lean techniques can be used in different phases of the Six Sigma projects to lock in major improvements. Likewise, a number of Lean activities have identified Six Sigma projects which have subsequently liberated high values. In other cases, Six Sigma methodology has assisted more complex Lean implementations. Both power plants are using a combination of all management methods and some of these applications are discussed below.

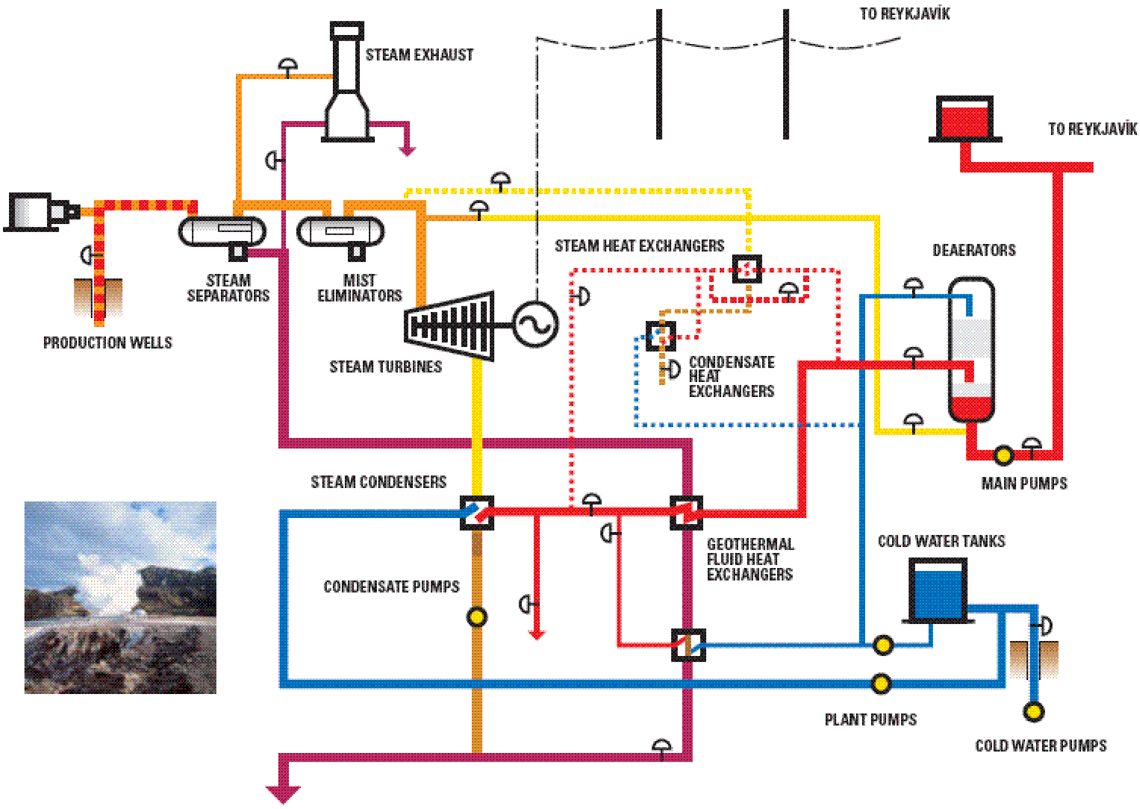

FIGURE 8: A Flow diagram of Nesjavellir geothermal power plant (Reykjavik Energy, 2003)

5.2.1 Six-sigma

For example, both power plants are using Lean and Six-Sigma methods to identify opportunities for improving their organizations by optimizing the flow of information through the organization. These methods can allow plant managers to quantify the complicated interactions associated with tasks and personnel in an organization, and determine how best to align personnel with tasks in order to accomplish their mission. There are many maintenance problems in power plants to which the six sigma method can be applied (Bore, 2008). Examples of cases where a six sigma method could 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 effects of the method will be to reduce the cost of spare parts because few parts will fail.

5.2.2 Lean

Few, if any, companies or plants fully implement the entire Lean manufacturing process. Instead, selected components, such as five-S or seven wastes, are implemented as quick-fix tools in one or more areas of production. While these are good and needed methodologies, they won't provide the benefit that most plants need for survival. There are many maintenance problems in GPPs that can be addressed by the Lean method. They include the 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 too long because of delays in transport, spare parts, waiting for the equipment to be stopped and isolated or waiting for the people and work place organization. Lean can be used to identify man hours wasted because of unnecessary human movements to pick tools or go 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 manhours that don't add value to maintenance such as excess staff on a task, waiting time, movement etc. When these wasted manhours are eliminated, manpower costs can be reduced significantly. Another example is work place organization. 'Five S' is the first step in improving the workplace in power plants. This applies to the shop floor, maintenance cribs, inventory storage areas and other locations over which the maintenance department claims dominion.

5.2.3 RCM

Where our primary objective is to solve several maintenance problems, we have the opportunity to decide, in a very systematic way, just what priority we wish to assign in allocating budgets and resources. In other words, all functions are not created equal and therefore all functional failures and their related components and failure modes are not created equal. Thus, we want to prioritize the importance of the failure modes. This can be done using RCM tools and by passing each failure mode through a simple three-tier decision tree which will place each mode in one of four catagories that can then be used to develop a priority assignment rational.

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 a FMEA analysis and developing maintenance procedures that will meet the requirements while simultaneously meshing with the existing maintenance programmes. To address the high downtime, RCM method will employ the root cause analysis, fault tree analysis and FMEA to identify the causes of the downtime. By identifying and solving the root causes of downtime, downtime costs will be greatly reduced (Bore, 2008).

5.3 Data collection

This section discusses the data collection and processing activities conducted for the benchmarking study. It should be noted that the data reviewed for this project is only for the 2004-2008 time period. The database includes only that for maintenance. Considering the sensitivity of the data collected during the project, and adhering to a generally accepted code of conduct for benchmarking, some data in the report used rounded numbers and some assumptions were used for missing data.

The data collection tool is comprised of questions and interviews of power plant personnel involved in operation, maintenance and administration. Both power plants using the DMM software for the day to day maintenance management and owned a large amount of data. Power plants have a lot of compiled data but use only a fraction of the data for their performance audit. To determine the ultimate performance measures or key performance indicators (KPIs) for critical functional areas, geothermal power plants must acquire a qualitative and quantitative data. Power plants must try not to get confused by considering every bit of data as a key performance indicator and should avoid data overload. Manual data collection will always be painful, and may increase the likelihood of error. The best collection approach must surely be one that is automatic that occurs throughout the complete lifecycle of a project, progressing virtually unnoticed. Some project management tools collect data as part of the natural planning and management process, from initial estimation through to maintenance and support. Such a system removes the pain of collection and increases the integrity of the data.

For data verification, mainly Excel was used. The data process was designed to accept sets of raw data from the plants, normalize them, and then provide comparative tables and graphs. Some information was published in company annual reports. In order to accommodate the numerous types of analyses that are possible, the project work sheet accepts much normalization which is necessary to provide meaningful data comparisons and to reconcile the differences among the plants by providing a common basis for comparison and further benchmarking. Turning data into useful information is the key to making critical equipment reliable.

Different power plants collect and own different data. In order to make successful comparisons and benchmarks, power plants should collect basic data which can give a complete picture about maintenance performance. The minimum data that power plants must acquire for maintenance performance benchmarking are listed and attached as Appendix II.

Both power plants have a well-developed documentation/procedure system. Such systems as well as an IT platform are important tools for information management. Information and data should be collected thoroughly. And the plant database must be established and maintained in a well-organized manner.

Inevitably there would be questions relating to the quality of the data (in terms of their accuracy, reliability or consistency etc.). In the absence of some data and information, estimated values based on the previous data were used.

5.4 Maintenance cost analysis

In order to successfully compete in the electrical generating industry today, plant availability and reliability must be maintained at desired levels while operating and maintaining costs must be kept as low as is reasonably achievable. Plant operating costs consist of operating and maintenance (O&M) costs, which are mainly labour to run and maintain the plant, and capital expenditures incurred after the plant entered commercial operation (capital additions). Capital additions are expenditures for major repairs and replacements of equipment, or plant modifications.

In this section, only maintenance costs, which comprise a major part of the operating costs of the plant, will be discussed. To get the total equipment maintenance cost, some costs like pollution control, disaster and rehabilitation costs and technical support costs were deducted. The maintenance cost data of the benchmarked (Svartsengi and Reykjanes) and the best performing (Nesjavellir) power plants are presented in Tables 5 and 6, respectively.

TABLE 5: Maintenance and other costs of benchmarked power plant

Description	Years				
	2004	2005	2006	2007	2008
	Svartsengi	Svartsengi	Svartsengi and Reykjanes	Svartsengi and Reykjanes	Svartsengi and Reykjanes
Total maintenance cost	268,000	220,000	242,000	391,000	547,000
Total pollution control cost	7,000	1,000	3,000	7,000	15,000
Total technical support cost	51,000	27,000	35,000	60,000	80,000
Total disaster and rehabilitation cost	–	–	–	–	–
Total equipment maintenance cost	208,000	170,000	167,000	269,000	401,000

TABLE 6: Maintenance cost of best performing power plant

Description	Years				
	2004	2005	2006	2007	2008
Total plant maintenance cost (x 1000 ISK)	146,000	146,000	149,000	166,500	339,000
Total pollution control cost (x 1000 ISK)	–	–	–	–	–
Total technical support cost (x 1000 ISK)	–	–	–	–	–
Total disaster and rehabilitation cost (x 1000 ISK)	–	–	–	–	–
Total equipment maintenance cost (x 1000 ISK)	146,000	146,000	149,000	166,500	339,000

Based on the information in Tables 5 and 6, the equipment maintenance costs for both power plants were compared. The results of the comparison show that the average equipment maintenance costs per MW in the benchmarked power plant, 1.39 million ISK, were relatively lower than that of the Nesjavellir power plant, 1.58 million ISK. The benchmarked power plant is a bit older and complicated. However, even though the benchmarked power plant maintained a low equipment maintenance cost, it still needs to take different measures to reduce it. It should be noted that low cost doesn't always correlate to high efficiency. Costs can be driven by other applicable factors, such as power plant age, site constraints, policy decisions, and regulatory requirements.

5.5 Maintenance productivity level

In order to average out the five years' total equipment maintenance costs from Tables 5 and 6, other costs like costs for pollution control, technical support, disaster and rehabilitation in the plant were excluded. To calculate the average annual equipment maintenance costs, Formula 1 was used. The maintenance productivity level of the equipment was measured in terms of the total maintenance costs of labour, material and tools etc. The cost in maintenance activities was divided by the generated electricity in MW, using Equation 2. The results are listed in Table 7.

TABLE 7: Productivity level comparisons

Description	Benchmarked power plant Svartsengi and Reykjanes	Best performer (Nesjavellir)
Forced outage rate, FOR (%)	3.51	0.68
Equivalent forced outage rate, EFOR (%)	4.42	0.68
Average equivalent forced outage rate, AEFOR (%)	4.3	0.9
Availability factor, AF (%)	91.58	92.8

The maintenance productivity level of both plants is reasonable even though the benchmarked power plant had better productivity. However, the benchmarked power plant needs to take measures to reduce the total maintenance cost by applying different types of maintenance management.

5.6 Power plant reliability

The forced outage rate (FOR), the equivalent forced outage rate (EFOR), and availability factor (AF) are the main indicators of power plant reliability. To calculate the five years forced outage rate (FOR), Equivalent forced outage rate (EFOR), average Equivalent forced outage rate (AEFOR) for the benchmarked power plant, Equations 3, 4, 5 and 6 were used. The results are listed in Table 8.

TABLE 8: Outage data comparisons

	Benchmarked power plant	Best performer (Nesjavellir PP)
Maintenanace productivity level	1,389	1,578

From Table 8 we can see that both power plants have good results, however the benchmarked power plant needs to work out an outage optimization strategy to lower the results to the level of the best performer.

The annual performance of the unit, which is based on the availability factor (AF), taking planned maintenance into account, is also presented. Both power plants have a high availability factor 91, 58% and 92, 8%, respectively.

5.7 Analysis of maintenance management practices

Most computerized maintenance management users do not adequately differentiate between preventive, predictive, corrective, or reactive work. This was observed during data collection in both power plants. However, both plants used a combination of all types of maintenance management systems. From Table 9, it is clearly seen that the benchmarked power plant mainly focused on predictive, constant monitoring and condition-based maintenance. The five years' average maintenance types used by the benchmarked power plant are shown in Figure 9.

The analysis of maintenance management practices performed by the benchmarked power plant and the best performing power plant is presented in Table 10.

TABLE 9: Maintenance types used by the benchmarked power plant

Types of maintenance (occurrence in %)	Years									
	2004		2005		2006		2007		2008	
	Svart.	Reyk.	Svart.	Reyk.	Svart.	Reyk.	Svart.	Reyk.	Svart.	Reyk.
Emergency maintenance	10	-	10	-	10	30	10	15	15	10
Preventive maintenance	35	-	30	-	30	10	25	15	27	25
Predictive maintenance	40	-	40	-	45	15	40	55	40	50
Planned corrective maintenance	15	-	20	-	15	45	25	15	18	15

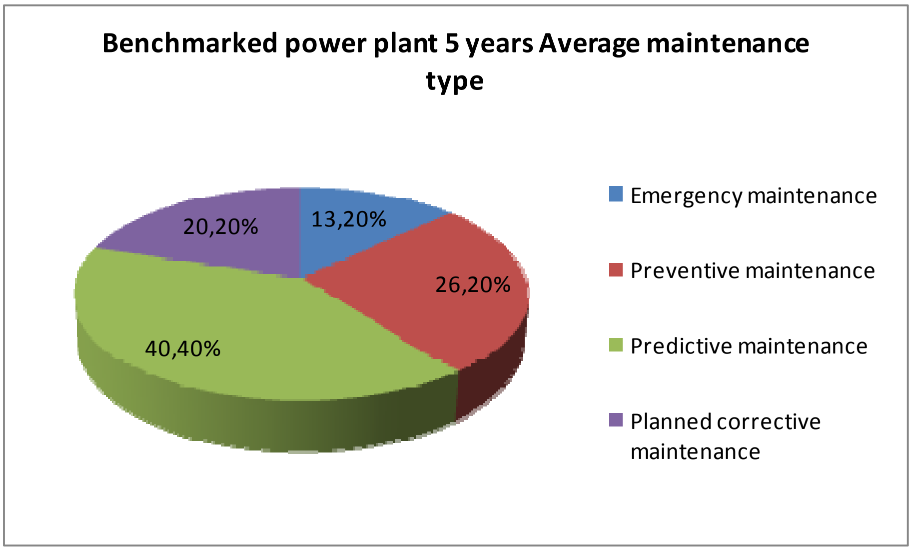

FIGURE 9: Five years' average maintenance types used by the benchmarked power plant

TABLE 10: Maintenance type used by the two power plants

Types of maintenance	Best performer	Benchmarked power plant
Emergency maintenance, EM	14	13
Preventive maintenance, PM	13	26
Predictive maintenance, PdM	71	41
Planned corrective maintenance,	2	20

From the five years' average results, we see that preventive and predictive maintenance approaches have been widely adopted in both power plants. Both power plants have mainly utilized the Reliability Centred Maintenance (RCM) approach to work out the content and the mix of its preventive and predictive maintenance activities. The benchmarked power plant is using a combination of different maintenance managements. The reason is connected with the age, working condition and the complexity of the power plant. Based on the costs and the history of the equipment, the benchmarked plant needs to focus on predictive maintenance. 22% preventive maintenance in the benchmarked plant is high. Also, emergency maintenance seems to be high in both power plants. In order to reduce the excessive preventive works, the benchmarked power plant needs to rely more on planned corrective maintenance without affecting the reliability of the system. With better condition-based fault diagnosis and better prediction of the deterioration of equipment, more planned corrective maintenance could be achieved.

Clearer information on the maintenance cost distribution based on the implemented percentage of a combination maintenance system is presented in Table 11. In both plants, predictive is the preferred system in delivering a flexible, dynamic and proactive maintenance procedure, achieving high reliability, safety and system security and ensuring high availability, minimum down time and repair time. By reducing the percentage of emergency and time based preventive maintenance and maximizing the predictive and planned corrective maintenance, both power plants might achieve more maintenance cost savings byutilizing precision maintenance technologies such as vibration analysis, thermal imaging, laser alignment, and dynamic balancing to improve equipment reliability and efficiency.The total maintenance cost distribution of the benchmarked power plant, by type of maintenance, is illustrated in Figure 10.

TABLE 11: Distribution of maintenance cost according to the average percentage of the maintenance system

Types of maintenance	**Maintenance cost based on the average percentage of maintenance system (ISK x1000)**	
	Svartsengi and Reykjanes	**Nesjavellir**
Emergency maintenance	32,076	26,502
Preventive maintenance	63,666	24,609
Predictive maintenance	98,172	134,403
Planned corrective maintenance	49,086	3,786

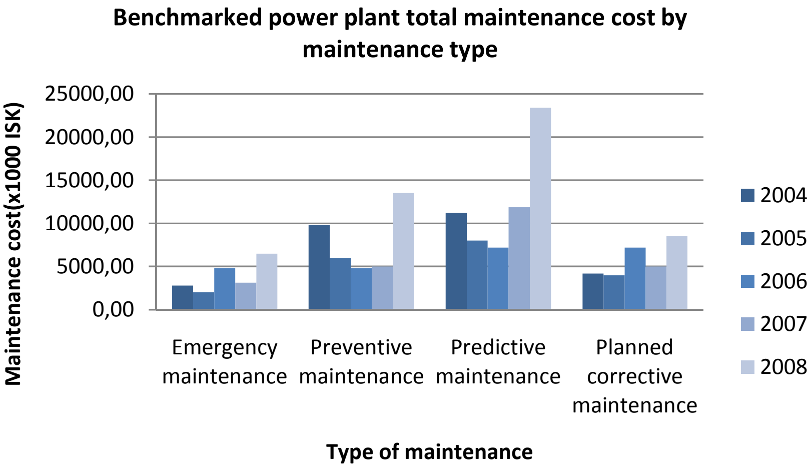

FIGURE 10: Maintenance cost distribution of the benchmarked power plant by maintenance type

A principal advantage of PdM is the capability it offers the plant to perform inspections while the equipment is operating. In particular, in order to reflect routine operating conditions, the technique requires that measurements be taken when the equipment is normally loaded in its production environ-ment. Since the machine does not need to be removed from the operating cycle, there is no shutdown penalty or additional cost. Another advantage of PdM is that the cost of surveillance labour can be much less than the cost of PM activities. Although the technical knowledge required for PdM inspections is usually higher than those for PM, the inspection time required per asset is much less. With PdM, assets do not have to be disassembled for inspection. For example, with vibration analysis, 50 to 60 assets may be inspected in a single day using modern computer data collectors. When comparing cost advantages of PdM over PM, we need to consider customer downtime costs, maintenance labour costs, maintenance materials costs, and the cost of holding spare parts in inventory.

5.8 Outage management

The competitive environment for electricity generation has significant implications for geothermal power plant operations, including among others the need for efficient use of resources, and effective management of plant activities such as on-line maintenance and outages. Plant outages are shutdowns in which activities are carried out between disconnection and connection of the unit to the electrical grid. Highly effective outage performance is an essential element in maximizing plant availability and reliability and for improving overall generation system performance. The outage period should be considered as part of plant operation, therefore the operability of needed systems and functions should be assured and planned. The plant outage strategy has to be carefully implemented to enable the development of a comprehensive and effective work programme, and to minimize outage duration in connection with improvements in costs, quality and safety. Planning and preparation are important phases in the optimization of the outage duration which should ensure safe, timely and successful execution of all activities in the outage. The post outage review will provide important feedback for the optimization of the next outage planning, preparation and execution.

The equivalent forced outage rate for the five years of the benchmarked power plant is higher than for the best performing power plant. EFOR comparison of the two power plants is illustrated in Figure 11. Due to a steam shortage, the benchmarked power plant had a bit higher EFOR. From year 2007 the de-rating values due to steam shortage increased and we can see the EFOR value also increased.

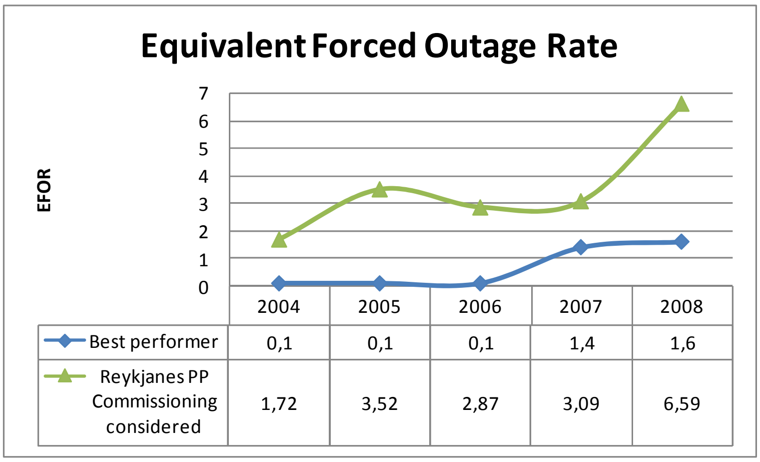

FIGURE 11: Equivalent Forced Outage Rate comparison

The forced outage rate, aside from de-ratings due to steam shortage, in the benchmarked power plant is presented in Figure 12.

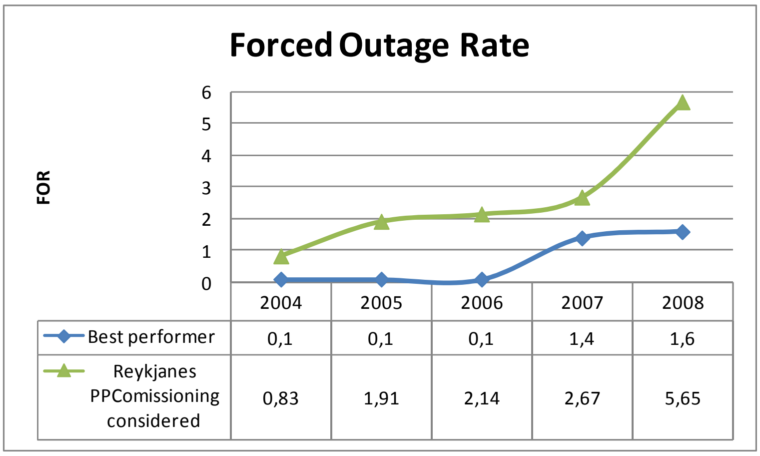

FIGURE 12: Forced outage hours comparison

In the benchmarked power plant, outage planning begins at least one year prior to outage start with the development of pre-outage milestones which provide a logical progression of scope, schedule, and budget from general to the level of detail required to implement the planned work within schedule and budget limits.

Both power plants have very effective outage optimization strategy and had comparatively minimum forced and planned outages. For planned outages, the plant manager conducts final review and approves the outage schedule prior to review by senior management. The schedule contains comprehensive analysis and identified schedule risk areas and necessary mitigating actions. The outage manager is responsible for preparing an integrated outage plan.

Table 12 shows the 1997-2001 operational reliability performance data for five central station technologies. Data from the Distributed Generation Operational Reliability and Availability Database were used for comparison (Energy and Environmental Analysis, Inc., 2004).

TABLE 12: Summary of 5 years' average operational reliability performance for different types of power plants and the results of the benchmarked geothermal power plant

OR Measure	Fossil (Boiler)	Nuclear	Gas Turbine	Combined cycle	Hydro	Geothermal (the benchmarked power plant)
Availability factor, %	86.66	82.87	90.31	85.85	90.62	91.6
Forced outage Rate, %	5.16	7.83	41.4	3.24	4.68	3.51
Scheduled Outage factor, %	9.59	10.09	6.36	7.64	6.53	8.0
Service factor, %	68.98	82.85	4.72	61.36	57.95	92

In order to minimize the plant outage the plant management, in general, should establish clear and long term goals and programmes for all main plant activities. The key issues for outage optimisation strategy are as follows:

- Continuous improvement management policy,
- Optimisation of maintenance and inspection programmes,
- Personnel policy of the plant supporting effective performance,
- Maintenance safety supported by a good safety culture,
- Outage experience feedback system,
- Continuous upgrading training.

5.9 Maintenance management organization and structure

We can see a similarity in plant organization, maintenance and plant leadership in the two plants (Figures 13 and 14). The effectiveness of an existing maintenance management structure of the two power plants was evaluated. In this regard, important issues in a maintenance effective management organization for an operating plant assure stable and continuous operation, help to bring cost reductions in operation and maintenance (O&M), and improved facility reliability.

The goals and objectives of the maintenance organization determine the type of maintenance organization that is established. If the goals and objectives are progressive and the maintenance organization is recognized as a contributor to the corporate bottom line, variations on some of the more conventional organizational structures can be used.

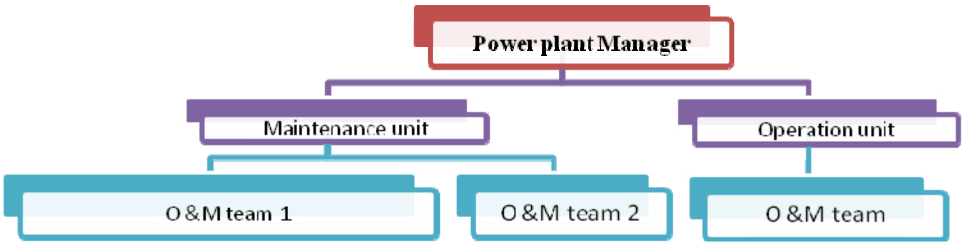

FIGURE 13: Organization structure at Svartsengi and Reykjanes power plants

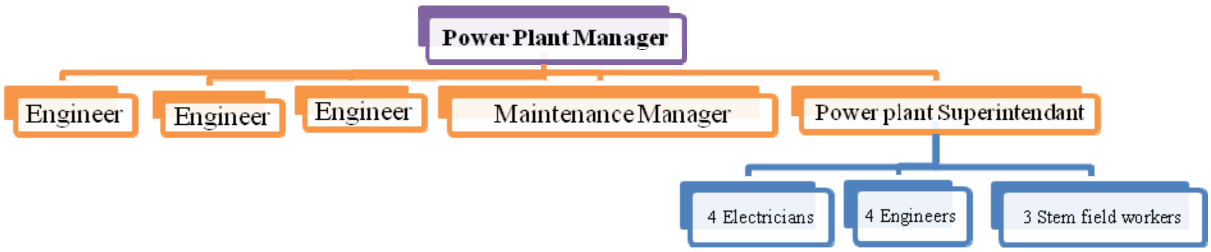

FIGURE 14: Organizational structure of Nesjavellir power plant

Such a flattened structure facilitates both power plants in reducing the number of approvals needed for maintenance action, allowing front-line workers to exercise more control over results and thereby improve their productivity. The existing management layer consists of one or more supervisors of the same level or rank and facilitates a smooth communication.

Span of control refers to the number of employees or subordinates that report directly to a supervisor or manager. This figure generally is rendered as a ratio. Average span of control ratio in both power plants is 1:4. In both power plants, the competitive advantage of the Lean management systems was observed.

Complex organizational structures should be avoided in order to facilitate decision making processes. Self assessment processes at the plant level as well as at an individual level should be encouraged and a questioning attitude fostered to make the organization sensitive to deviations from planned activities and to avoid outage extensions. Cross-functional expertise is necessary to take responsibility for equipment as well as for maintenance, control, scheduling and engineering that have a direct influence on plant performance.

This flattened operating organization in the benchmarked power plant creates a good teamwork spirit and stresses values such as integrity, respect for the individual, accountability, innovation and continuous improvement in their day to day plant operation activities.

In analyzing their organizational design, power plants may consider some of the following principles:

- Design the organization based on the company's vision.
- Organize work functions to enhance interfaces among work groups.
- Increase spans of control and minimize layers of management.
- Minimize the number and size of staff (support) organizations.
- Design the organization to be flexible.
- Change the organization design only when needed to meet objectives.

5.10 Human resource management

Maintenance activities vary in scope, skills, and time required accomplishing the tasks. Planned or scheduled maintenance typically requires trade skilled operators and/or substantial process shutdown time. Operations maintenance is typically performed by operations personnel and may include activities such as rearranging equipment, walk around verification, and part changes. Optimally, equipment monitoring is performed to detect abnormal conditions or adverse trends, so that appropriate maintenance action can be taken before equipment malfunction occurs. Additionally, documentation is needed to provide a record or log of actions taken. These logs can be used for review and/or the transfer of experience and skill to others.

In the benchmarked power plant, maintenance and operation staff consists of 22 men who regularly attend to 12 turbines, specifically 5 steam turbines and 7 Organic Rankine Cycle (ORC) units. In addition, they look after 36 cooling fans, 17 geothermal wells and wellheads, 70 control valves, 100 pumps, 20 kilometre pipelines, and thousands of valves that require maintenance (Thorolfsson, 2005a). This flexible, co-operative and shared responsibility approach among production and maintenance personnel helps to keep a few skilled and creative operators and maintenance staff. The power plants provide continuous on the job training to introduce new technology to personnel. A job rotation programme within the operating and maintenance personnel should be considered to widen individual experiences and competences. Comprehensive knowledge of the overall plant facilitates understanding and communication, essential for plant performance.

On the job training of employees gives them the opportunity to earn more pay while increasing their skills and experience and helps the organization and its employees remain competitive in the industry. By broadening employees' skills, many handoffs that can cause delays and interruptions in work processes are reduced. The multi-skilled programme has advantages for both employees and the company. Employees develop new skills while making the most of current ones, and the organization will move into the future with a workforce that is more flexible, more efficient and more competitive.

5.10.1 Training

Training is the key to greater knowledge and improved performance. Training of personnel is an extremely important component of the managed maintenance programme. Training can be used in a variety of ways, including:

- Orienting and informing employees,
- Developing desired skills,
- Preventing accidents through safety training,
- Supplying professional and technical education, and

- Providing supervisory training and executive education (Cherrington, 1995).

Each of the training methods mentioned has benefits to the individual as well as to the organization. Some of the benefits are reducing the learning time for new hires, teaching employees how to use new or updated technology, decreasing the number and cost of accidents because employees know how to operate a machine properly, providing better customer service, improving the quality and quantity of productivity, and obtaining management involvement in the training process.

Training should be focused on improving knowledge, skill, abilities and overall job performance of the plant. The success of the training programme is in large part dependent on the support of management. The productivity of the maintenance programme is directly related to the organization's willingness to invest in its' human resources. The benchmarked power plant has a comprehensive training programme while the best performer trains only the newcomers to the plant. Continuous training helps to maintain a high-performance, more knowledgeable and proficient team.

Asides from the training system and information management mentioned above, factors contributing to human resource management include almost all other technical and managerial aspects related to the safety and quality of power plants. Initial and continuing training programmes should be in place to ensure that both plant and contractor personnel have the competency needed for their assigned tasks during outages. Plant maintenance is optimized by developing a highly motivated, qualified and skilled workforce, and a safe work environment. This is accomplished by providing an effective training and qualification programme, and by implementing a human performance initiative that stresses positive behaviour and values.

5.11 Work order planning and control

A work order system is often used to record maintenance history and to control maintenance costs. It is a useful tool for optimizing the utilization of direct or indirect resources like manpower, cost, equipment, materials, tools, facilities and information in maintenance. It also provides prompt and precise communications among participants in a maintenance job.

In both power plants all work orders, inspection routines, preventive, predictive and other types of maintenance routines are handled by DMM. DMM is a software solution which embodies dynamic maintenance management system, quality control system and facility management system. Knowledge of processes and procedures is stored within DMM regardless of staff changes. The software controls the issue and documentation of planned and unplanned maintenance work.

The work order allows the assignment of labor, parts, tools, and inspections to each work. Labor time and all costs are also tracked with work orders and are used in many standard reports. Therefore, the system must be used comprehensively to record all maintenance activities. Unless the work is tracked from request through completion, the data is fragmented and useless. If all of the maintenance activities are tracked through the work order system, it gives a good backup to the planners. The overall work order system in the benchmarked and the best performing plants is presented in Table 13.

In both power plants, after a work order is written requesting the services of the maintenance department, planning goes into action. A maintenance planner takes the work order and does preparatory planning for the crew supervisor and craftsmen who will ultimately execute the work. The planner considers the proper scope of work for the job, for example, the work requester may have identified a noisy valve. The planner determines whether the valve should be patched or replaced and identifies the materials needed for the specified job and their availability. If the material is not on hand, the planner, working with the maintenance supervisor, determines how quickly it is needed. When the stores personnel advise the planner that the part has been received, the job may be scheduled. In addition, the planner specifies the appropriate craft skills for the job. Having these determinations made before the crew supervisor assigns a job for execution helps avoid problems such as delays caused by having assigned a person with insufficient craft skills or from not having all the required materials.

TABLE 13: Work order system

Work order system	Svartsengi and Reykjanes plants	Nesjavellir power plant
Approval steps of work order	2	2
Number of hand off	2	2
Cycle time of minor corrective job (hours)	8	7

Having time estimates also allows crew supervisors to judge how much work to assign and thus better control the work in the sense that supervisors have expected completion times and can work to resolve any problems that might interfere with the schedule. The planners help the stores and purchasing personnel ensure that there is proper inventory control. Planners can advise which stock parts should be checked for turnover on a regular basis. Then minimum and reorder quantities may be kept up for functional use without having unnecessarily high inventories.

Consequently, maintenance planning brings together or coordinates the efforts of many maintenance activities, including craft skills and knowledge, labour and equipment availability, materials, tooling, and equipment data and history.

5.12 Inventory and stores

The timely availability of parts, materials, and services is a key element of a strong and effective maintenance programme. Correct parts and materials in good condition are necessary to maintain design configuration and maintenance requirements for activities during normal operating periods and to support both planned and forced outages. Special services are needed periodically to provide unique or supplementary maintenance support.

In the benchmarked power plant, inventory management is supported by the DMM. The total number of parts, in addition to the stores' policies, purchasing policies and overall inventory management practices are supported by this software and contribute to the overall maintenance materials costs. It includes selecting spair stock items, determining quantity requirements, establishing stock levels, reordering quantities, and initiating procurement and replenishment actions.

Correct parts and materials in good condition should be available for maintenance activities to support both planned and forced outages. Procurement of services and materials for outages must performed in time to ensure that materials will be available without impact to the schedule. Storage of parts and materials provides for maintaining quality and the shelf life of parts and materials.

Good inventory control enables plants to lower the value of the inventory and continue to maintain a high maintenance service level. This enables the maintenance department to be responsive to the operations group, while increasing the maintenance department's own personal productivity. Successful computerized maintenance management system users have less material costs.

Minimizing inventory on hand helps maintenance organizations eliminate waste. Approximately 50 percent of a maintenance budget is spent on spare parts and material consumption. In organizations that are reactive, up to 20% of spare parts cost may be waste. As organizations become more planned and controlled, this waste is eliminated (Wireman, 2005).

6. CONCLUSIONS

Benchmarking is, by its very nature, a diagnostic tool for managing an organization's resources. While it provides insights and perspectives on the performance of an individual power plant compared with other similar or best performing plants, it does not provide specific answers for the best way to improve performance at a specific facility. On the other hand, power plants that properly implement benchmarking can stay innovative and competitive with their respective partners. Geothermal power plants must use benchmarking in an ethical way so that competitors are willing to share information freely. If the information is shared, power plants can benefit from their benchmark studies. With this perspective in mind, this thesis has reached the following conclusions:

- Benchmarking is a very useful tool. Properly applied, you can gain great insight into the processes that yield the results you wish to achieve. However, a properly executed benchmark project is not simple or quick. It requires careful preparation, analysis, and execution.
- Systematic maintenance data collection, analysis and a continued reliability study can provide valuable information about plant performance. The results greatly depend on the quality of the data. Data collection and analysis is an extremely important phase of the entire benchmarking project.
- Such a model can assist power plant management to understand the current performance of the plant, helps to take actions for reaching and surpassing identified business standards, can improve performance, set specific goals, take appropriate actions, and measure results against the benchmarks.
- The model also gives a basic idea and information for further improvement to minimize the performance gap between their own and best performers.
- Benchmarks are not the end-all. A benchmark performance does not remain a standard for long. Continuous improvement must be the goal.
- Benchmarking is the practice of being open enough to admit that someone else is better at something, and being wise enough to learn to be as good as/or even better than them.
- Benchmarking can drive performance to the next level by setting goals and surpassing them through a learning process from the best practice.

The model was structured for a maintenance performance benchmark study of power plants. However, future improvement is needed to make a better benchmark and comparison of different performance indicators. Updating the maintenance benchmark model on a regular basis will ensure continued usefulness and increase the confidence to implement the benchmarked results.

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APPENDIX 1: Maintenance performance benchmarking model

Maintenance benchmarking model

Data descripition	5 years data of the benchmarked power plant, BPP year 1	year 2	year 3	year 4	year 5	5 years Avarage	5 years average results from Best Performer Power
Maintenance service data							
SH, Service hours							
Total outage energy loss, MWh							
Forced outage energy loss, MWh							
Maintenance outage energy loss, MWH							
FOH, Unplanned (Forced) Outage hours							
MOH, Maintenance outage hours							
Number of forced outages							
Number of maintenance outages							
Operation man hour							
Maintenance man hour							
Operation and maintenance man hour							
Steam field man hour							
Capacity and Energy							
Unit sevice or auxiliaries consumption (total), GWh							
GMC, Gross Maximum Capacity							
GDC, Gross Dependable Capacity							
GAG, Gross Actual Generation(GWh)							
NMC, Net Maximum Capacity							
NDC, Net Dependable Capacity							
NAG, Net Actual Generation, (GWh)							
Outages and derating data							
Total maintenance outage energy loss, MWh							
Unplanned (Forced) outage MWh							
PO, Planned outage hour							
Planned energy loss due to derating, MWh							
PD, Planned derating, Hours							
Forced (unplanned) derating, MWh							
FD,Forced (unplanned) derating Hours							
Size of reduction							
Summary of various time and energy factors used by indexes							
AH, Available hour							
EPDH, Eq. Planned Derating Hours							
EUDH, Eq. Unplanned Derating Hours							
ESDH, Eq. Scheduled Derating Hours							
PH, Period hours							
FOH, Forced Outage Hours							
EFDH, Eq. Forced Derated Hours							
CF (%), Capacity Factor							

Unweighted (time-based) performance index							
FOR (%), Forced Outage Rate							
EFOR (%), Equ. Forced Outage Rate							
EAF(%), Eq. availability Factor							
AF (%), Availability Factor							
MOH, maintenance outage Hours							
EMOF, Equivalent Main. Outage Factor							
POF, Planned Outage Factor							
SF, Service factor							

Maintenance cost

Data descripition	5 years data of the benchmarked power plant, BPP					5 years Avarage	5 years average results from Best Performer Power
	year 1	year 2	year 3	year 4	year 5		
Total maintenance cost							
Total pollution control cost							
Total technical support cost							
Total disaster and rehabilitation cost							
Total equipment maintenance cost							

Other maintenance costs

Data descripition	5 years data of the benchmarked power plant, BPP					5 years Avarage	5 years average results from Best Performer Power
	year 1	year 2	year 3	year 4	year 5		
Spare parts and consumables cost							
Down time cost							
special tools and software							
man power cost							
Different taxes							

Maintenanae Productivity level	Results
Avarage eq. maintenance cost, AEMC	
Maintenance productivity, x	
Maintenanae service level	
Avarage eq. Forced outage rate, %	

Type of maintenance for the benchemarked power plant

Data descripition	5 years data of the benchmarked power plant, BPP					5 years Avarage	5 years average results from Best Performer Power
	year 1	year 2	year 3	year 4	year 5		
Emergency maintenance							
Preventive maintenance							
Predictive maintenance							
Planned corrective maintenance							

Total maintenance cost by maintenance type

Data descripition	5 years data of the benchmarked power plant, BPP					5 years Avarage	5 years average results from Best Performer Power
	year 1	year 2	year 3	year 4	year 5		
Emergency maintenance							
Preventive maintenance							
Predictive maintenance							
Planned corrective maintenance							

Maintenance and operation man hour

Data descripition	5 years data of the benchmarked power plant, BPP					5 years Avarage	5 years average results from Best Performer Power
	year 1	year 2	year 3	year 4	year 5		
Total O&M man hour							
Operation man hour for both plants							
Maintenance man hour for both plants							
Operation man hour							
Maintenance man hour							

Safety and prodctivity

Data descripition	5 years data of the benchmarked power plant, BPP					5 years Avarage	5 years average results from Best Performer Power
	year 1	year 2	year 3	year 4	year 5		
No of accident in the plant and steam field							
Operation and maintenance man hour							
Number of days lost							
Safety							
Lost Time Injury , LTI							
Injury Severity Rate ,ISR							
Man power Productivity							
Number of employee at site							
Net electricity generated a year							
Labour productivity							
Capital productivity							

APPENDIX 2: Minimum list of data required to conduct maintenance performance benchmarking

Outages
PO - Planned Outage
MO - Maintenance Outage
ME - Maintenance Outage Extension
PE - Planned Outage Extension
SE - Scheduled Outage Extension
SF - Startup Failure
U1 - Unplanned (Forced) Outage - Immediate
U2 - Unplanned (Forced) Outage - Delayed
U3 - Unplanned (Forced) Outage – Postponed

De-ratings
PD - Planned De-rating
D4 - Maintenance De-rating
DM - Maintenance De-rating Extension
DP - Planned De-rating Extension
DE - De-rating Extension
D1 - Unplanned (Forced) De-rating - Immediate
D2 - Unplanned (Forced) De-rating - Delayed
D3 - Unplanned (Forced) Derating – Postponed

Unit Generation Performance
Gross Maximum Capacity (GMC)
Gross Dependable Capacity (GDC)
Gross Actual Generation (GAG)
Net Maximum Capacity (NMC)
Net Dependable Capacity (NDC)
Net Actual Generation (NAG)

Unit Time Information
Unit Service Hours
Reserve Shutdown Hours
Available Hours
Planned Outage Hours
Unplanned (Forced) Outage Hours and Start-up Failure Hours
Maintenance Outage Hours
Extensions of Scheduled Outages
Unavailable Hours
Period Hours

Cost related data
Total maintenance cost
Total pollution control cost
Total technical support cost
Total disaster and rehabilitation cost
Total equipment maintenance cost
Spare parts and consumables cost
Down time cost
Special tools and software
Man power cost

Other data
Steam supply
Brine supply
Steam production shortfall
Brine supply shortfall

APPENDIX 3: Summary of time, energy factors and other equations used in the calculation

Definitions and equations used in the model are adapted from North American Electric Reliability Corporation Generating Availability Data System data reporting instructions (NERC, 2008) and from a Paper prepared by the International Geothermal Association for the World Energy Council Working Group on «Performance of Renewable Energy Plants» in March 2001(IGA, 2001).

Operation and Outage States

Available

State in which a unit is capable of providing service, whether or not it is actually in service, regardless of the capacity level that can be provided.

Forced De-rating (D1, D2, D3)

An unplanned component failure (immediate, delayed, and postponed) or other condition that requires the load on the unit be reduced during the period.

Forced Outage (U1, U2, U3, SF)

An unplanned component failure (immediate, delayed, postponed, startup failure) or other condition that requires the unit be removed from service during the period.

Maintenance De-rating (D4)

The removal of a component for scheduled repairs that can be deferred beyond the end of the next weekend, but requires a reduction of capacity before the next planned outage.

Maintenance Outage (MO)

The removal of a unit from service to perform work on specific components that can be deferred beyond the end of the period, but requires the unit be removed from service before the next planned outage. Typically, a MO may occur anytime during the year, have flexible start dates, and may or may not have a predetermined duration.

Planned De-rating (PD)

The removal of a component for repairs that is scheduled well in advance and has a predetermined duration.

Planned Outage (PO)

The removal of a unit from service to perform work on specific components that is scheduled well in advance and has a predetermined duration (e.g., annual overhaul, inspections, testing).

Scheduled De-ratings (D4, PD)

Scheduled de-ratings are a combination of maintenance and planned de-ratings.

Scheduled De-rating Extension (DE)

The extension of a maintenance or planned de-rating.

Scheduled Outages (MO, PO)

Scheduled outages are a combination of maintenance and planned outages.

Scheduled Outage Extension (SE)

The extension of a maintenance or planned outage.

Time

Available Hours (AH)

a. Sum of all Service Hours (SH), Reserve Shutdown Hours (RSH), Pumping Hours, and Synchronous Condensing Hours, or;

b. Period Hours (PH) less Planned Outage Hours (POH), Forced Outage Hours (FOH), and Maintenance Outage Hours (MOH).

Equivalent Forced De-rated Hours (EFDH)

The product of the Forced De-rated Hours (FDH) and the Size of Reduction, divided by the Net Maximum Capacity (NMC).

Equivalent Planned De-rated Hours (EPDH)

The product of the Planned De-rated Hours (PDH) and the *Size of Reduction, divided by the Net Maximum Capacity (NMC).

Equivalent Scheduled De-rated Hours (ESDH)

The product of the Scheduled De-rated Hours (SDH) and the *Size of Reduction, divided by the Net Maximum Capacity (NMC).

Equivalent Unplanned De-rated Hours (EUDH)

The product of the Unplanned De-rated Hours (UDH) and the *Size of Reduction, divided by the Net Maximum Capacity (NMC).

Forced De-rated Hours (FDH)
Sum of all hours experienced during Forced De-ratings (D1, D2, D3).

Forced Outage Hours (FOH)
Sum of all hours experienced during Forced Outages (U1, U2, U3, SF).

Maintenance De-rated Hours (MDH)
Sum of all hours experienced during Maintenance De-ratings (D4) and Scheduled De-rating Extensions (DE) of any Maintenance De-ratings (D4).

Maintenance Outage Hours (MOH)
Sum of all hours experienced during Maintenance Outages (MO) and Scheduled Outage Extensions (SE) of any Maintenance Outages (MO).

Period Hours (PH)
Number of hours a unit was in the active state.

Planned De-rated Hours (PDH)
Sum of all hours experienced during Planned De-ratings (PD) and Scheduled De-rating Extensions (DE) of any Planned De-ratings (PD).

Planned Outage Hours (POH)
Sum of all hours experienced during Planned Outages (PO) and Scheduled Outage Extensions (SE) of any Planned Outages (PO).

Scheduled De-rated Hours (SDH)
Sum of all hours experienced during Planned De-ratings (PD), Maintenance De-ratings (D4) and Scheduled De-rating Extensions (DE) of any Maintenance De-ratings (D4) and Planned De-ratings (PD).

Scheduled Outage Hours (SOH)
Sum of all hours experienced during Planned Outages (PO), Maintenance Outages (MO), and Scheduled Outage Extensions (SE) of any Maintenance Outages (MO) and Planned Outages (PO).

Service Hours (SH)
Total number of hours a unit was electrically connected to the system.

Unplanned De-rated Hours (UDH)
Sum of all hours experienced during Forced De-ratings (D1, D2, D3), Maintenance De-ratings (D4), and Scheduled De-rating Extensions (DE) of any Maintenance De-ratings (D4).

Unplanned Outage Hours (UOH)
Sum of all hours experienced during Forced Outages (U1, U2, U3, SF), Maintenance Outages (MO), and Scheduled Outage Extensions (SE) of any Maintenance Outages (MO).

<u>Capacity and Energy</u>

Gross Maximum Capacity (GMC)
Maximum capacity a unit can sustain over a specified period of time when not restricted by seasonal, or other de-ratings.

Gross Dependable Capacity (GDC)
GMC modified for seasonal limitations over a specified period of time. The GDC and MDC (Maximum Dependable Capacity) previously used as the same in intent and purpose.

Gross Available Capacity (GAC)
Greatest capacity at which a unit can operate with a reduction imposed by deratings.

Gross Actual Generation (MWh) (GAG)
Actual number of electrical megawatt hours generated by the unit during the period being considered.

Net Maximum Capacity (NMC)
GMC less the unit capacity utilized for that unit's station service or auxiliaries.

Net Dependable Capacity (NDC)
GDC less the unit capacity utilized for that unit's station service or auxiliaries.

Net Availability Capacity (NAC)
GAC less the unit capacity utilized for that unit's station service or auxiliaries.

Net Actual Generation (MWh) (NAG)
Actual number of electrical megawatt hours generated by the unit during the period being considered less any generation (MWh) utilized for that unit's station service or auxiliaries.

Notes:

* Size of reduction is determined by subtracting the Net Available Capacity (NAC) from the Net Dependable Capacity (NDC). In cases of multiple de-ratings, the Size of Reduction of each de-rating is the difference in the Net Available Capacity of the unit prior to the initiation of the de-rating and the reported Net Available Capacity as a result of the de-rating.

<u>**Equations**</u>

Availability Factor (AF)
[AH/PH] x 100 (%)
Equivalent Availability Factor (EAF)
[(AH - (EUDH + EPDH + ESEDH))/PH] x 100 (%)
Equivalent Forced Outage Rate (EFOR)
[(FOH + EFDH)/(FOH + SH + EFDHRS)] x 100 (%)
Equivalent Maintenance Outage Factor -- EMOF
EMOF = (MOH + EMDH)/PH x 100%
Forced Outage Factor (FOF)
[FOH/PH] x 100 (%)
Forced Outage Rate (FOR)
[FOH/(FOH + SH)] x 100 (%)
Planned Outage Factor (POF)
POF = POH/PH x 100%
Service Factor (SF)
[SH/PH] x 100 (%)
Capacity factor (%) = (Total MWh generated in the period x100)/ (Installed Capacity (MWe) x period (hours))
Load factor (%) = (Total MWh generated in the period x 100)/ (Maximum Load (MWe) x period (hours))
Availability factor (%) = (Total hours of plant in operation during the period x 100)/ (Total length of period (hours))

APPENDIX 4: Detailed maintenance performance benchmark of the benchmarked (Svartsengi and Reykjanes) power plants

Benchmarked power plant maintenance performance (Svartsengi and Reykjanes)

	Years						Results from
	2004	2005	2006	2007	2008	5 years	Best
Data description	Svart.	Svart.	Svart. & Rey	Svart. & Rey	Svart. & Rey	Average	Performer
Maintenance service data							
SH, Service hours	8547	8249	8365	8129	6824	8022,8	
Total outage energy loss MWh,	21113	27837	42195	45564	33995	34140,8	
Forced outage energy loss, MWh	8566	16150	27231	32314	31496	23151,4	
Maintenance outage energy loss, MWH	12547	11687	14964	13250	2499	10989,4	
FOH, Unplanned (Forced) Outage hours	71	161	183	223,2	408,3	209,22	
MOH, Maintenance outage hours	166	375	426	520,8	952,7	487,98	
Number of forced outages	26	48	91	89	131	77	
Number of maintenance outages	23	82	85	90	30	62	
Operation man hour	23758,25	23256,43	25780,59	23005,46	24966,53	24153,45	
Maintenance man hour	23998,56	23020,74	27754,23	36018,92	40048,03	30168,1	
Operation and maintenance man hour	47756,81	46277,17	53534,82	59024,38	65014,56	54321,55	
Steam field man hour	2781,89	2243,63	2835,17	4883,44	6532,43	3855,312	
* In May,2006 Reykjanes power plant came to online							
Capacity and Energy							
Unit service or auxiliaries consumption (total), GWh	40	40	42,4	42,4	42,4	41,44	
GMC, Gross Maximum Capacity	407,6	367,8	880,7	1213,1	1430,9	860,0234	
GDC, Gross Dependable Capacity	373,5	329,7	479,0	1133,4	1329,8	729,0927	
GAG, Gross Actual Generation(GWh)	373,5	367,8	880,7	1213,1	1430,9	853,217	
NMC, Net Maximum Capacity	367,6	327,8	838,3	1170,7	1388,5	818,5834	
NDC, Net Dependable Capacity	333,5	289,7	436,6	1091,0	1301,4	690,446	
NAG, Net Actual Generation, (GWh)	333,5	327,8	838,3	1170,7	1388,5	811,777	
Outages and derating data							
Total maintenance outage energy loss, MWh	21113	27837	42195	45564	33995	34140,8	
Unplanned (Forced) outage MWh	8566	16150	27231	32314	31496	23151,4	
PO, Planned outage hour	12547	11687	14964	13250	2499	10989,4	
Planned energy loss due to derating, MWh	27,9	31,2	329,4	65,4	82,8	107,3631	
PD, Planned derating, Hours	3840,9	8057,3	5308,7	2429,7	4566,6	4840,624	
Forced (unplanned) derating, MWh	6,1	6,9	72,3	14,4	18,2	23,56752	
FD,Forced (unplanned) derating Hours	843	1769	1165,32	533,34	1002,42	1062,576	
Size of reduction	34,0	26,0	46,0	79,7	101,0	57,36341	
Summary of various time and Factors used by indexes							
AH, Available hour	8547	8249	8365	8129	6824	8022,8	
EPDH, Eq. Planned Derating Hours	477,92	881,87	682,13	216,59	432,35	538,1719	
EUDH, Eq. Unplanned Derating Hours	433,67	779,35	355,24	201,84	405,24	435,0681	
ESDH, Eq. Scheduled Derating Hours	433,67	779,35	355,24	201,84	405,24	435,0681	
PH, Period hours	8784	8760	8760	8760	8760	8764,8	
FOH, Forced Outage Hours	71	161	183	223	408	209,22	
EFDH, Eq. Forced Derated Hours	78	140	64	36	73	78,31	
CF (%), Capacity Factor	2%	2%	6%	8%	9%	5,56%	

Unweighted (time-based) performance index							
FOR (%), Forced Outage Rate	0,83	1,91	2,14	2,67	5,65	2,64	
EFOR (%), Equ. Forced Outage Rate	1,72	3,52	2,87	3,09	6,59	3,56	
AEFOR(%) Average Equ. Forced Outage Rate						3,4	
EAF(%), Eq. availability Factor	82,0	66,3	79,6	85,7	63,7	75,46	
AF (%), Availability Factor	97,6	94,2	95,5	92,8	77,9	91,58	
MOH, maintenance outage Hours	166	375	426	521	953	487,98	
EMOF, Equivalent Main. Outage Factor	7	14	13	8	16	11,71	
POF, Planned Outage Factor	1,89%	4,28%	4,86%	5,95%	10,88%	5,57%	
SF, Service factor	97%	94%	95%	93%	78%	0,92	

Maintenance cost for both plants (x1000)

	Years						Results from
	2004	2005	2006	2007	2008	5 years	Best
Cost description	Svart.	Svart.	Svart. & Re	Svart. & Re	Svart. & Re	Average	Performer
Total maintenance cost	268.000	220.000	242.000	391.000	547.000	333600	
Total pollution control cost	7.000	1.000	3.000	7.000	15.000	6600	
Total technical support cost	51000	27000	35000	60000	80000	50600	
Total disaster and rehabilitation cost	_	_	_	_	_	_	
Total equipment maintenance cost	208.000	170.000	167.000	269.000	401.000	243000	

Maintenance costs (x 1000 ISK)

	Years						Best
	2004	2005	2006	2007	2008	5 years	Performer
Additional cost descripition	Svart.	Svart.	Svart. & Re	Svart. & Re	Svart. & Re	Average	Power Plant
Spare parts and consumables cost	28000	20000	24000	25000	52000	29800	
Down time cost	_	_	_	_	_	_	
special tools and software	_	_	_	_	_	_	
man power cost	108000	115000	138000	178000	206000	149000	
Different taxes	14497,816	14745,051	15482,749	24080,009	35953,866	20951,9	

Maintenance Productivity level	
Average eq. maintenance cost, AEMC	243000
Maintenance productivity, x	1389
Maintenance service level	
Average eq. Forced outage rate, %	

Type of maintenance for both plants

	Years						Results from
	2004	2005	2006	2007	2008	5 years	Best
Type of maintenance in %	Svart.	Svart.	Svart. & Re	Svart. & Re	Svart. & Re	Average	Performer
Emergency maintenance	10%	10%	20%	13%	13%	13,20%	
Preventive maintenance	35%	30%	20%	20%	26%	26,20%	
Predictive maintenance	40%	40%	30%	42%	45%	40,40%	
Planned corrective maintenance	15%	20%	30%	20%	16%	20,20%	

Total maintenance cost by maintenance type

Type of Maintenance	Years 2004 Svart.	2005 Svart.	2006 Svart. & Re	2007 Svart. & Re	2008 Svart. & Re	5 years Average	Results from Best Performer
Emergency maintenance	2800,00	2000,00	4800,00	3125,00	6500,00	3845,00	
Preventive maintenance	9800,00	6000,00	4800,00	5000,00	13520,00	7824,00	
Predictive maintenance	11200,00	8000,00	7200,00	11875,00	23400,00	12335,00	
Planned corrective maintenance	4200,00	4000,00	7200,00	5000,00	8580,00	5796,00	

Man hour

Description of man hour	Years 2004 Svart.	2005 Svart.	2006 Svart. & Re	2007 Svart. & Re	2008 Svart. & Re	5 years Average	Results from Best Performer
Total O&M man hour	47756,81	46277,17	53534,82	59024,38	65014,56	54321,55	
Operation man hour for both plants	23758,25	23256,43	25780,59	23005,46	24966,53	24153,45	
Maintenance man hour for both plants	23998,56	23020,74	27754,23	36018,92	40048,03	30168,1	
Operation man hour	23758,25	23256,43	25780,59	23005,46	24966,53	24153,45	
Maintenance man hour	23998,56	23020,74	27754,23	36018,92	40048,03	30168,1	

Resource Part

Description of man hour	Years 2004 Svart.	2005 Svart.	2006 Svart. & Re	2007 Svart. & Re	2008 Svart. & Re	5 years Average	Results from Best Performer
Steam supply(x 1,000,000)							
Brine supply (x 1,000,000)							
Steam production shortfall							
Brine production shortfall							
No of production wells							

APPENDIX 5: Detailed maintenance performance benchmark of the best performer (Nesjavellir) power plant

Best Performer Power Plant (Nesjavellir Power Plant)

Data description	Years 2004 Nesjavellir	2005 Nesjavellir	2006 Nesjavellir	2007 Nesjavellir	2008 Nesjavellir	5 years Average	Results from Best Performer Power Plant
Maintenance service data							
SH, Service hours	8092	6448	8572	8548	8313	7994,53	
Total outage energy loss MWh,	13000	7000	10000	10000	9000	9800,00	
Forced outage energy loss, MWh	206	298	426	5754	2618	1860,40	
Maintenance outage energy loss, MWH	12794	6702	9574	4246	6382	7939,60	
FOH, Unplanned (Forced) Outage hours	11	8	8	124	137	57,49	
MOH, Maintenance outage hours	681	672	180	92	334	391,70	
Number of forced outages							
Number of maintenance outages							
Operation man hour							
Maintenance man hour							
Operation and maintenance man hour							
Steam field man hour							
Capacity and Energy							
Unit service or auxiliaries consumption (total), GWh	73000	79000	91000	90000	91000	84800,00	
GMC, Gross Maximum Capacity	673000	780000	1030000	1027000	976000	897200,00	
GDC, Gross Dependable Capacity	673000	780000	1030000	1027000	976000	897200,00	
GAG, Gross Actual Generation(GWh)	746614	859991	1121878	198190	967000	778734,60	
NMC, Net Maximum Capacity	600000	701000	939000	937000	885000	812400,00	
NDC, Net Dependable Capacity	600000	701000	939000	937000	885000	812400,00	
NAG, Net Actual Generation, (GWh)	586000	693000	937000	928000	876000	804000,00	
Outages and derating data							
Total maintenance outage energy loss, MW	13000	7000	10000	10000	9000	9800,00	
Unplanned (Forced) outage MWh	206	298	426	306	377	322,60	
PO, Planned outage hour	12794	6702	9574	9694	8623	9477,40	
Planned energy loss due to derating, MWh	_	_	_	_	_		
PD, Planned derating, Hours	_	_	_	_	_		
Forced (unplanned) derating, MWh	_	_	_	_	_		
FD,Forced (unplanned) derating Hours	_	_	_	_	_		
Size of reduction	_	_	_	_	_		
Summary of various time and Factors							
AH, Available hour	8092	6448	8572	8548	8313	7994,53	
EPDH, Eq. Planned Derating Hours	_	_	_	_	_		
EUDH, Eq. Unplanned Derating Hours	_	_	_	_	_		
ESDH, Eq. Scheduled Derating Hours	_	_	_	_	_		
PH, Period hours	8784	8760	8760	8760	8760	8764,80	
FOH, Forced Outage Hours	11	8	8	124	137	57,49	
EFDH, Eq. Forced Derated Hours	_	_	_	_	_		
CF (%), Capacity Factor	70,83	81,81	106,72	18,85	91,99	74,04	

Unweighted (time-based) performance index							
FOR (%), Forced Outage Rate	0,1	0,1	0,1	1,4	1,6	0,68	
EFOR (%), Equ. Forced Outage Rate	0,1	0,1	0,1	1,4	1,6	0,68	
AEFOR(%) Average Equ. Forced Outage Rate						0,9	
EAF(%), Eq. availability Factor	92,12	73,61	97,85	97,58	94,90	91,21	
AF (%), Availability Factor	92,12	73,61	97,85	97,58	94,90	91,21	
MOH, maintenance outage Hours	681	672	180	92	334	391,70	
EMOF, Equivalent Main. Outage Factor	7,75	7,67	2,05	1,04	3,81	4,47	
POF, Planned Outage Factor	7,75%	7,67%	2,05%	1,04%	3,81%	0,04	
SF, Service factor	92%	74%	98%	98%	95%	0,91	

Maintenance costs (x1000 ISK)

	Years						Results from
	2004	2005	2006	2007	2008	5 years	Best Performer
Data description	Nesjavellir	Nesjavellir	Nesjavellir	Nesjavellir	Nesjavellir	Average	Power Plant
Spare parts and consumables cost	30000	30000	30000	40000	210000	68000	
Down time cost							
special tools and software	2000	2000	2000	2500	3000	2300	
man power cost	114000	114000	117000	124000	126000	119000	

Other maintenance and different costs (x 1000 ISK)

	Years						Results from
	2004	2005	2006	2007	2008	5 years	Best Performer
Data description	Nesjavellir	Nesjavellir	Nesjavellir	Nesjavellir	Nesjavellir	Average	Power Plant
Total maintenance cost	146000	146000	149000	166500	339000	189300	
Total pollution control cost	0	0	0	0	0		
Total technical support cost	0	0	0	0	0		
Total disaster and rehabilitation cost	0	0	0	0	0		
Total equipment maintenance cost	146000	146000	149000	166500	339000	189300	
Total training cost	_	_	_	_	_		
Total training hour	_	_	_	_	_		
Total man hours worked							
Total man power cost(only for the plant)	114000	114000	117000	124000	126000	119000	
Maintenance Productivity level							
Average eq. maintenance cost, AEMC	189300						
Maintenance productivity, x	1578						
Maintenance service level							
Average eq. Forced outage rate, %	0,71						

Type of maintenance

	Years						Results from
	2004	2005	2006	2007	2008	5 years	Best Performer
Data description	Nesjavellir	Nesjavellir	Nesjavellir	Nesjavellir	Nesjavellir	Average	Power Plant
Emergency maintenance	8%	12%	15%	19%	18%	14%	
Preventive maintenance	10%	18%	11%	16%	8%	13%	
Predictive maintenance	81%	68%	70%	64%	72%	71%	
Planned corrective maintenance	1%	2%	4%	1%	2%	2%	

Total maintenance cost by maintenance type

Data description	Years					5 years Average	Results from Best Performer Power Plant
	2004	2005	2006	2007	2008		
	Nesjavellir	Nesjavellir	Nesjavellir	Nesjavellir	Nesjavellir		
Emergency maintenance	11680,00	17520,00	22350,00	31635,00	61020,00	26502,00	
Preventive maintenance	14600,00	26280,00	16390,00	26640,00	27120,00	24609,00	
Predictive maintenance	118260,00	99280,00	104300,00	106560,00	244080,00	134403,00	
Planned corrective maintenance	1460,00	2920,00	5960,00	1665,00	6780,00	3786,00	

Man hour

Data description	Years					5 years Average	Results from Best Performer Power Plant
	2004	2005	2006	2007	2008		
	Nesjavellir	Nesjavellir	Nesjavellir	Nesjavellir	Nesjavellir		
Total O&M man hour							
Operation man hour for both plants							
Maintenance man hour for both plants							
Operation man hour							
Maintenance man hour							

Resource Part

Data descripition	Years					5 years Avarage	Results from Best Performer Power Plant
	2004	2005	2006	2007	2008		
	Nesjavellir	Nesjavellir	Nesjavellir	Nesjavellir	Nesjavellir		
Steam supply(x 1,000,000)	7884	7884	7884	7884	7884	7884	
Brine supply (x 1,000,000)	8515	8515	8515	8515	8515	8515	
Steam production shortfall	_	_	_	_	_	_	
Brine production shortfall	_	_	_	_	_	_	
No of production wells	15	15	15	15	15	15	