Performance Indicators for Maintenance in Geothermal Power Plants

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30 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Industrial Engineering

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Abstract

Reliability is important when operating a geothermal power plant. Maintenance is mainly carried out according to preventive maintenance in order to ensure delivery reliability and durability of expensive assets in the production. Preventive maintenance on the other hand is expensive, and maintenance of geothermal power plants is one of the most costly factors in the operation. In order to reach the available opportunities for optimization in the field, measurements have to be made. Performance indicators can be used to track maintenance performance and manage maintenance activities. They provide managers with the right tools for detecting underperformance in the planning or execution process of maintenance activities. When implemented thoroughly, maintenance performances indicators should as well allow for a means of improving on the shown figures. This Master's thesis was carried out in cooperation with all the operators of geothermal power plants in Iceland and an assessment was made of the current maintenance performance measurement system. Finally an ideal maintenance performance measurement system is presented and a comparison made between the organizations' current procedures and the ideal model.

Keywords: Geothermal Power Plant, Maintenance, Performance Indicators, Reliability, Management

Útdráttur

Viðhald jarðvarmavirkjana er einn umfangsmesti einstaki þáttur í rekstri þeirra, en til þess að tryggja afhendingaröryggi og endingu á dýrum tækjabúnaði er viðhaldi að miklu leiti sinnt með fyrirbyggjandi aðferðum. Skilvirk stjórnun og framkvæmd viðhaldsaðgerða getur því haft mikil rekstrarleg áhrif hjá fyrirtækjunum, en möguleika til úrbóta á því sviði má finna með því að fylgjast með og greina skilvirkni viðhaldsaðgerðanna. Til þess þarf að notast við svokallaða árangursvísa (e. performance indicators) en þeir geta gefið stjórnendum og öðrum sem koma að viðhaldsmálum skýra mynd af stöðu mála hverju sinni. Þannig fá þeir í hendur upplýsingar sem nýta má til þess að bregðast við þegar afköst falla undir væntingamörk. Verkefnið var unnið í samvinnu við rekstraraðila allra jarðvarmavera á Íslandi og mat lagt á núverandi stöðu þeirra við notkun árangursvísa í viðhaldsstjórnun. Sett var fram tillaga að því hvaða árangursvísa æskilegast væri að nota til þess að fylgjast með skilvirkni í viðhaldi og þeir bornir saman við þá vísa sem orkufyrirtækin styðjast við í dag.

Efnisorð: Jarðvarmaver, Viðhald, Árangursvísar, Áreiðanleiki, Stjórnun

This thesis is dedicated to my wonderful son, Hilmar Nóel

Preface

"…when you can measure what you are speaking about and express it in numbers you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind."

Baron William Thomson Kelvin [1]

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Abbreviations

CM	*Corrective maintenance*	
CMMS	*Computerized maintenance management system*	
DMM	*Dynamic maintenance management system*	
CEN	*European Committee for Standardization*	
EAM	*Enterprise asset management system*	
GPP	*Geothermal power plant*	
JIT	*Just in time*	
KKS	*Kraftwerk-Kennzeichensystem*	
KPI	*Key performance indicator*	
LCC	*Life cycle cost*	
MPM	*Maintenance performance measurements*	
MRO	*Maintenance, repair and operating materials*	
MTBF	*Mean time between failures*	
MTBR	*Mean time between repairs*	
MTTR	*Mean time to repair*	
MWe	*Megawatt electric*	[MW]
MWt	*Megawatt thermal*	[MW]
NPP	*Nuclear power plant*	
O&M	*Operation and maintenance*	
PdM	*Predictive maintenance*	
PI	*Performance indicator*	
PM	*Preventive maintenance*	
RAV	*Replacement asset value*	
SENUF	*Safety of Eastern European Type Nuclear Facilities*	

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1 Introduction

When Michael Faraday discovered the principles behind electricity generation in 1820’s he opened a door to a world of endless opportunities. Electricity is nowadays one of the foundations of modern communities and demand has been constantly rising during the last decades [2]. Projections estimate that the electric energy consumption will continue to rise throughout the next decades [3]. Over 80% of the world’s primary electricity supply comes from fossil fuels, which in addition to being non-renewable make severe environmental impact [2]. The focus on renewable energy sources, such as hydro, geothermal, solar and wind power, has been increasing for these reasons. Geothermal resources accounted for only 0.05 percent of the total world electrical production in the year 2010 [2, 4]. Renewable energy is estimated to be the one of the fastest growing source of energy in the world from 2010-2030, with an average yearly increase of 3 percent compared to an average increase of 1.6 percent for total world energy consumption [5].

Geothermal energy is now harnessed for electricity production in 24 countries, with a total installed capacity of 10,715 MWe [4]. Estimations indicate that with current technology the world’s installed geothermal electricity production capacity can be increased to 70 GW, and up to 140 GW with more advanced technology [6].

Geothermal systems are mainly classified into four types; hydrothermal, geopressure, magma energy, and hot dry rock. Hydrothermal resources are to date the only geothermal systems that have been developed commercially for electric power production. In hydrothermal system water acts, in a liquid or vapor phase, as a carrier to transfer heat from earth’s crust to the surface [7].

Capital cost for a typical geothermal power plant can be considered on par with other sources, i.e. does not stand out as being either significantly high or low [5]. However fixed operational and maintenance cost is significantly higher than for non-renewable sources. Maintenance usually offers the largest controllable cost in production-companies and this adheres as well to geothermal power plants [8]. Therefore, it raises the pressure on geothermal power plant operators to focus on performing their maintenance activities in the most cost effective way possible to stay competitive in today’s economically driven markets.

Delivery reliability is an important aspect for electricity buyers and power plant operators have to make sure they can deliver on their promises and guarantees. A reliable plant can defined as: "…available when needed, capable of performing to designed requirements economically and safely for a specified lifespan" [9]. Effective maintenance management plays a major role in sustaining the plant's reliability, which in turn supports stable means of production. In order to provide the optimal reliability, maintenance of most geothermal power plants is mostly carried out according to preventive maintenance. The maintenance process of geothermal power plants is complex, with the power plant comprised of a magnitude of components. Scaling, corrosion and erosion are problems resulted from corrosive chemicals and particles in the working fluid. As a result specific and regular maintenance procedures are required [10].

To maximize profitability organizations have to minimize operational and maintenance cost. A cost-effective maintenance program is both based on effectiveness by performing the right operations at the right time, and on efficiency by utilizing the available maintenance resources in the most efficient manner. It can however, be hard to notice when optimality in these areas is reached. The key to keep track of maintenance performance and progress is to register and monitor the results for maintenance activities. Maintenance performance measurement, which is an approach in quantifying results of maintenance activities, can achieve this. By quantifying the effectiveness or efficiency of activities within the maintenance function, an assessment can be made of how cost effectively resources are utilized. This analysis can be made to form a 'ground level' performance, or current performance, for each area of the maintenance function. This ground level should then be used as a frame of reference when compared to so-called benchmarks. Benchmarking is an ongoing systematic course of action where organizations compare their processes performance to goals, which have been chosen for each given process. In order to close the gap between the ground level and the benchmark, performance measurements are made to quantify the path to reach the benchmark level of performance and carry out improvements in the maintenance function. In addition to providing the aid of quantifying the path of improvement, maintenance performance measurements can also be used to detect underperformance or when abnormal values appear and then provide a means to intervene and make correct adjustments. Better resource utilization and organization of the maintenance activities should in turn improve on the reliability of the plant, given that more cost-effective maintenance activities will not result in budget reduction within the organization.

The effort of implementing and utilizing a maintenance performance measurement system requires a system for data registration and clear processes supported by all employees. A clearer vision of maintenance operation can be obtained by utilizing performance indicators (PI) and areas for improvements can be discovered more easily. To take advantage of these possibilities companies must strive for continuous improvements, and in return they can get closer to reaching maintenance optimality. Icelandic power plants have been considered as the model of geothermal development and the power plants are operated in a more cost-effective way than many others [11]. To maintain this world leading position, Icelandic geothermal power plants must keep on developing the industry in terms of techniques and work procedures guided by the use of maintenance performance measurements.

1.1 Motivation and Objectives

The intention of this research is to contribute towards the ongoing development of the Icelandic geothermal industry. An effort will be made to answer the following questions regarding the use of maintenance performance measurements:

1. Which possibilities are available for geothermal power plants to monitor maintenance performance?
2. How are the Icelandic power companies applying these possibilities for monitoring the results of their maintenance efforts?
3. How can the maintenance performance measurement system be improved at the Icelandic geothermal power plants? Which factors or parameters should be taken into account and how should they be used?

In order to answer these questions, the thesis is built on documentation review; such as books, reports, journal articles and researches. Interviews were conducted with maintenance managers and other specialists in the field in order to assess the current status of the Icelandic geothermal industry both qualitatively and quantitatively. Additionally relevant standards in the field of maintenance were taken into consideration, and they form the basis for a proposed maintenance performance indicator system. The scope is confined with maintenance and maintenance related activities in geothermal power plants, and their respective performance indicators.

1.2 Structure of the thesis

This thesis is structured in the following way. Chapter 2 provides a background of the research area and begins with the historical development of maintenance. Maintenance methods are defined and common maintenance procedures in geothermal power plants are described. Maintenance management and the role of managers in the process of monitoring maintenance performance are then described. An overview of performance indicators is provided where important aspects regarding maintenance performance measurements are presented. The chapter also provides a description of computerized maintenance management systems. Chapter 3 describes the organizations considered in this thesis and their current status with regard to maintenance performance measurements. In Chapter 4 a proposed maintenance performance measurement system for geothermal power plants is presented. Discussion and comparison of the current status and the ideal model is then provided in Chapter 5.

1.3 Contribution

This research discusses and defines various concepts regarding maintenance performance measurements (MPM) and it’s application in geothermal power plants. The current MPM practices of three Icelandic geothermal power plants were studied in terms of the literature. Based on the literature, the current practices of the Icelandic geothermal power plants, and international standards, a holistic maintenance performance measurement framework aimed at the specific needs of geothermal power plants, is presented. Finally the current practices of the organizations are compared against the framework developed in this research and an assessment made of their current status.

2 Background

This chapter is concerned with the background of this study. First the historical development of maintenance is reviewed and maintenance methods presented along with maintenance procedures in geothermal power plants. The concept of maintenance management is defined, i.e. goals of maintenance, maintenance policy. Continuous improvement is then defined and the role managers play in sustaining it. Performance indicators (PIs) are defined in terms of how they should be monitored; how to manage with PIs, and recommendations for implementation. Finally computerized maintenance management systems are described.

2.1 Historical development of Maintenance

Ever since human beings started using tools, maintenance has been a necessary part of it. Initially, maintenance was in the form of being reactive, where measures were taken only when the equipment was no longer able to serve it’s purpose. The history of preventive maintenance can be traced as far back as 5000 years when the great pyramids were built [12]. However, during the last century maintenance approaches have developed substantially. Several factors contribute to this advancement, which was partially reliant on an increased research focus in the field of maintenance. The development in the 20th century was driven by fast changing customer demands along with a huge increse in amount of physical assets necessary for production [13]. This has entailed a stakeholders demand on increased efficiency, reduced costs and higher product quality within compananies in order to stay competitive [14]. At the same time, technical advancements have resulted in a more complex equipment along with the development of computerized maintenance management systems (CMMS).

The evolution of maintenance since the 1930’s can be classified into three generations according to John Moubray, as is shown in Figure 1 [13]. The first generation spans the time up to the Second World War when mechanization was not high in the industry and equipment was often over-designed. At that time maintenance was viewed as ‘necessary evil’ and little effort was made in downtime prevention [15]. Systematic maintenance was mainly in the form of simple operations such as lubrication and cleaning.

The inevitable changes following the Second World War initiated the second generation of maintenance. Demand for various goods rose with the war, as at the same time availability of manpower dropped. As a result, mechanization progressed and by the 1950’s complexity of machines had increased considerably, and the industry became dependent on it. This led to an increased focus on downtime and the idea emerged that failures of equipment could and should be prevented. The concept of preventive maintenance, which was at first mainly based on overhauls carried out at a fixed interval, emerged from these changes. With this method, which is commonly named time based maintenance, the operational security increased but the cost of maintenance and the tied up capital increased as well. As a response, manufacturers tried to prolong their assets lifetime and maintenance planning and control systems were enhanced.

The third generation started around the 1970’s when manufacturers began leaning towards just-in-time (JIT) systems in an effort towards reducing downtime [13]. One of the cornerstones of JIT is the reduction of stocks from work-in-progress and therefore a small failure can severely affect the whole operation of the plant. Automation and complexity of systems has grown considerably resulting in time-based maintenance methods becoming outdated. Regulations and standards have also become prerequisite in many industries forcing organizations to rethink their operations. A new perception of maintenance was established as an important business function with maintenance considered as a 'profit contributor' and the first maintenance management system (MMS) were introduced in the 1980's [16]. This resulted in a new maintenance approach known as reliability centered maintenance [13].

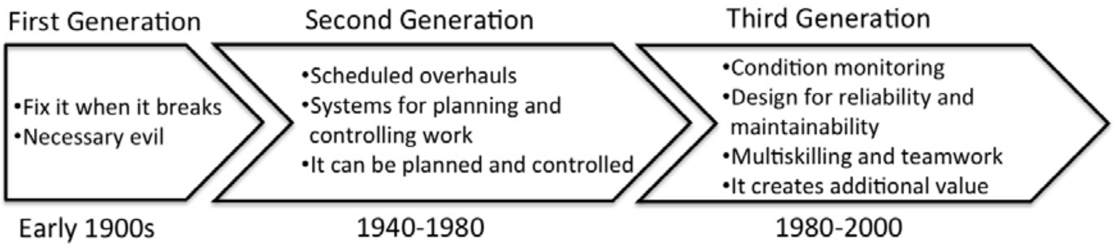

Figure 1 Historical development of maintenance techniques [13].

Following the changes in maintenance management led by the third generation, maintenance performance measurements (MPM) has gained a widespread recognition among researchers [17]. A renowned quotation to Peter Drucker 'you can't manage what you don't measure' is still appropriate and surely applies for maintenance. Without any measurements it is hard to know whether the performance is improving or getting worse and improvements become harder to accomplish. In order for any organization to function effectively is an effective performance measurement system (PMS) indispensable, wherein whatever gets measured has a higher likelihood of completion [16]. The essence of performance measurement can be described as the process of quantifying action, with measurement being the process of quantification and the resulting action leading to performance [18]. A performance measure is where metrics are used to quantify the effectiveness and/or efficiency of an action. The terms of efficiency and effectiveness should be stated, since they are an important attribute of performance measurements. Efficiency is a measure of how economically resources of the organization are utilized in achieving acceptable results, i.e. doing the right things. Effectiveness is the extent to which planned activities are performed and the intended results accomplished, or doing the things right [19]. The term productivity can be used to combine these two terms, since a productive organization is both effective and efficient [20].

An important prerequisite for performance measurements is analytical ability [21]. But for the measurements to be of any advantage for the organization it also demands that the right measures are made in the proper manner [17]. When using performance indicators to monitor activities it can be helpful to have some measure on how good the performance actually is. This can be done by relating measures to historical data gathered within the organization or by comparison with industry standards. This is the so-called benchmarking, which is a numerical expression of goal or objective to achieve [22]. Benchmarking has been popular in industry during the last decades to characterize the organizations' goals and objectives. Various benchmarking methods have been developed and no single benchmarking has been universally adopted [22]. Each organization has to decide the benchmarks they aim at, whether it is internally set standards, industry specific benchmarking or task specific.

The huge increase in both performance indicators and benchmarking being applied in all sort of industries during the last decades has raised the question whether it can be some kind of a fad. The truth is that many organizations jump on board and adopt these new measures without even knowing how to apply them [23]. This results in amounts of unsatisfied organizations, which fail to take advantage of the capabilities available through these methods. They may even abandon the change initiative and spread the word of how damaging these methods were for their organization. When implementing performance measurements into organizations, many aspects have to be taken into account to ensure success. Therefore, management must consider the implementation process wisely and how they intend to manage through the information acquired in the process. However, when implemented and utilized in the right ways it provides the organization a firm ground for keeping track of their performance and a guideline for improvements to ensure long-term profitability of the organization.

2.2 Maintenance methods

Many different approaches have been set forth in defining the concept of maintenance. Ricky Smith and Keith Mobley define maintenance as being either reactive or proactive, whereas Dhananjay Kumar and Ulf Westberg consider it as being either scheduled or unplanned [8, 24]. The definition presented in this thesis is however based on the EN 13306 standard, where maintenance is classified as either being preventive maintenance or corrective maintenance [25]. It is evident that academics are not unanimous about defining maintenance approaches and has this led to the field as sometimes being cited the ‘maintenance theory jungle’, referring to the ‘management theory jungle’ presented by Harold Koontz in 1961 [26]. In addition some overall models have been developed for maintenance such as total productive maintenance (TPM), reliability-centered maintenance (RCM) and life cycle costing (LCC). These models provide several advantages as well as some specific shortcomings. The challenge is to choose the most suitable approach for the respective situation and the right answer is based on the context, with its interaction with technology, business and of course how reliability is defined within the organization [14]. Therefore it can be stated that no right answer exists on how the concept of maintenance should be applied, but moreover it has to be developed and structured according to each organization’s needs and policies.

The overall view presented here and shown in Figure 2 is based on the EN 13306 standard. Various maintenance definitions exist, but this one was chosen since it is a simple, but yet a descriptive definition. The model divides maintenance into two categories, either preventive maintenance or corrective maintenance. For each system or component in the production a choice must be made whether it should belong to corrective maintenance or preventive. The choice is context specific and equipment criticality assessment should be made to support the decision-making. The criteria should take into account the effects that a failure of the system or component would have in terms of safety, environment, customer service, operating cost, etc. [8]. Within each category the failure consequences are ranked based on the severity and an overall assessment is made for the component.

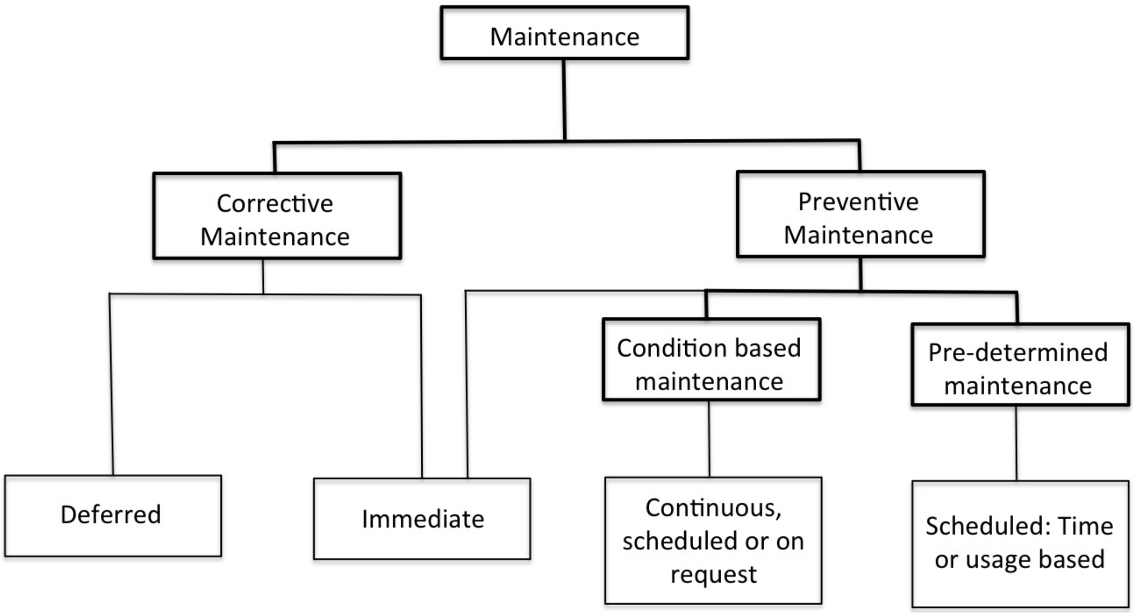

Figure 2 Overall view of maintenance as presented in the EN 13306:2010 standard with a minor change where preventive maintenance has been linked as well to immediate corrective maintenance.

2.2.1 Corrective Maintenance

Corrective maintenance is defined as maintenance carried out after a fault has occurred and intended to reestablish the item back to a state in which is can perform a required function [25]. Corrective maintenance can either be deferred or immediate, where deferred maintenance is not carried out immediately after a fault is recognized while immediate is executed as soon as a fault has been detected. The main difference between those two approaches lies in the fact that immediate corrective maintenance is performed when inaction can cause unacceptable consequences for the organization or environment, while deferred corrective maintenance can be applied on failures that are evaluated as not posing safety or financial impacts [25]. The advantage of deferred corrective maintenance over immediate lies in the fact that deferred allows for organizing necessary actions and carrying out the work in the most cost effective way. An effort is often made to prevent faults that can cause breakdowns since they may result in incremental production and maintenance costs, such as overtime, outsourcing and lost production [12]. However this does not always apply and can sometimes work as a very appropriate approach to allow equipment to wear out without intervention. This applies for instance to cheap equipment, where failure is easily detectable or if the failure does not have any effect on the production process or safety consequences [14]. No cost is incurred for keeping equipment sorted in the corrective maintenance group unless a failure occurs. This is due to the fact that the corrective maintenance method is about taking no action until a failure has occurred. Studies have though shown that when looked upon from the economical perspective deferred maintenance equipment does tend to deteriorate at a great rate compared to the interest rate of money saved on not repairing the equipment at first [12]. Therefore equipment should only be positioned in the corrective maintenance group if an equipment criticality assessment has deemed the consequences of failure as non-critical.

2.2.2 Preventive Maintenance

Preventive maintenance is a series of tasks performed at a predetermined frequency or according to prescribed criteria with the aim of either extending the life of an asset or to reduce the probability of a failure [25]. Preventive maintenance can be classified as either condition based maintenance or pre-determined maintenance, which both offer the lead time to efficiently carry out maintenance [12]. Pre-determined maintenance is carried out according to intervals based on either calendar time, or number of units of use based on the known characteristics of the equipment [25]. Studies have however shown that less than 20 percent of failures are age related, and as a consequence are over 80 percent of failures random [8]. By monitoring the equipment, it is often possible to detect early signs of random failure allowing for preventive measures to be taken before it no longer serves it function. Condition based maintenance includes a combination of nondestructive testing, monitoring and inspection performed on request or continuously to detect wear or fatigue that could lead to failure during some future period, and then take appropriate actions to avoid the consequences of failure. An output from condition based maintenance is predictive maintenance, which is carried out following forecast based on the ongoing measurements and known characteristics of the equipment [25]. If an asset, which is taken care of in accordance to preventive maintenance, experiences a functional failure it usually has to be responded to through immediate corrective maintenance. Expenses of preventive maintenance include for instance the cost of routine inspections and overhauls, and replacement of functional equipment. This is however the trade-off made to prevent the costs of running the equipment to failure, which could be even more costly for the organization in the long run.

2.3 Geothermal Power Plants and Maintenance

Operating a geothermal power plant is a continous process where equipment has to be maintained on a regular basis to keep the facility capable of providing the expected output. Most problems encountered in the production are related to the chemical composition of the geothermal fluid. Geothermal power plants can be divided into gathering system, turbine and cold ends [27]. Within the gathering system are wells, wellheads and separators. About 5-6 production wells are usually needed for a 30MW single-flash power plant [7]. The only moving part of a wellhead is the gate segment in valves and they are vulnerable against scaling, which builds up and can always be found there [10]. A drop in pressure or temperature increases the amount of scaling and any leak in the wellhead or pipelines will immediately cause scaling. Corrosion also affects the wellheads, and the worst type can be found on the outside of the wellhead. Both the amount of scaling and corrosion depend on the composition of the working fluid [10]. Maintenance of wellheads is an important part of the power plant operations and at Hellisheiði power plant the maintenance is classified into three categories; weekly, yearly and every fourth year maintenance [28]. The wellhead maintenance is for instance based on loosening up valves and lubricating them, removing scaling and checking temperature and pressure gauges. The role of the separators is to remove any fluid left in the steam to prevent scaling building up in other mechanism such as the turbines [7]. Maintenance of the separators is mainly in the form of inspection and cleaning carried out once a year apart from losening level control valves, which have a tendency to stick [10]. Turbines in geothermal power plants are for most parts traditional turbines that have been modified to suit the conditions faced in the geothermal fluid [10]. Scaling is the biggest problem faced in the operation of turbines apart from the regular maintenance necessary for conventional turbines [10]. In the Icelandic power plants, the turbines are shut down for a few days once a year to examine whether any damages have occurred. Every four to six years the turbine is overhauled, which is the most expensive maintenance operation in the power plant. The cold ends consist of condenser, cooling towers, gas removal system and re-injection wells [27]. Condenser serve the role of condensing the steam from the turbines and they can either be a surface-type or direct-contact [7]. Non-condensable gases are constantly removed during the condensation and it is important to keep the vacuum level high to prevent the generator output. Maintenance of condensers is mainly based on cleaning sulphur deposits and bacteria colonies at regular intervals [10].

Maintenance activities in geothermal power plants can broadly be divided into two categories; corrective maintenance and preventive maintenance. As can be seen from the description above, preventive maintenance is a big portion of the maintenance activities at geothermal power plants, and all equipment which has been considered critical for the production or in safety terms is cared for in a preventive manner. The procedures include a combination of condition based and pre-determined maintenance. Some equipment, such as the turbines, is monitored continuously in terms of vibration, temperature and pressure in order to detect any degradation. For most of the equipment, fixed intervals are used for the maintenance actions and inspections, and maintenance therefore carried out routinely. These intervals can range from weeks and up to several years, which can be based either on calendar time or usage. The big maintenance procedures, such as turbine overhauls, have to be accounted for in great advance because a notice must be given to Landsnet, the Icelandic transmission system operator, before a reduction is made for the distribution network. Corrective maintenance is kept at a minimum, with only non-critical equipment chosen to be in that group. Inspections regularly reveal failures on equipment, which appertains to preventive maintenance, and in these cases corrective measures must be taken.

Maintenance manager is usually responsible for planning, scheduling and managing all maintenance activities at the Icelandic geothermal power plants. The manager oversees the whole maintenance function and divides activities between employees. Scheduling of maintenance activities is usually done through a computerized maintenance management system (CMMS), where all work orders are registered and distributed. Big amount of data is registered daily in the database through the use of CMMSs and this data allows for information gathering, which can come of use for improving performance of the maintenance management.

Life cycle cost (LCC) is the total cost of establishing and operating a plant over its useful lifetime. It comprises of initial capital expenditures and the operation and maintenance costs (O&M). The objective of LCC is to select the most feasible approach from a group of possibilities with a long-term cost perspective. It is especially important for industrial plants that are operated for a long period of time, where maintenance cost stem for a big part of the LCC [14]. Capital cost of a typical 50 MWe geothermal steam power plant lies somewhere between 125 and 250 million USD and the annual O&M cost is estimated to be 1-4% of the capital cost [29]. From these figures it can be seen that efficient and effective maintenance strategies have a great potential in reducing O&M costs as well as reducing downtime and prolonging the lifetime of the power plant. In light of this it is worth noting that O&M costs of geothermal power has dropped significantly during the last two decades [30]. Despite of this, there is still a room for further improvements in the field, and organizations need to focus on developing its business operations to stay competitive.

2.4 Customer Demands in Geothermal Power Plants

About 79 percent of electrical power produced in Iceland is used in heavy industry, mostly aluminum smelters, and 18 percent are used by the public [31]. Sales contracts are made with customers in heavy industry and they can be bound for up to 40 years. In these contracts, prices are defined and the customer is bound to pay for the agreed amount of electricity, independent of whether he uses it or not [32]. Consequently efficient maintenance does not affect these customers in financial terms, but will directly affect the producer. However, delivery reliability is a big concern for aluminum smelters, since an unplanned outage can be very expensive for them and efficient maintenance directly affects the reliability of the power plant. Other external demands affecting the maintenance of power plants in Iceland are laws and regulations managed by the Consumer Agency of Iceland. They play the role of enforcing laws and regulations such as regulation no. 678/2009 which has to do with electrical installations, where safety and maintenance standards of power plants are defined.

Internal demands on maintenance in the power companies are affected by the external demands, but are custom made in each organization. They are stated in policy documents and every organization has its own maintenance philosophy [33]. These documents define for instance reliability, operational safety, and preventive maintenance procedures to maintain the assets of the company [33]. External demands or regulations do not make any pressure on the organizations to strive for continuous improvements, so such an effort must originate from within the organization itself. Figure 3 presents how these demands interconnect and shape the operation of power plants. First is the role of the power plant, which includes the inevitable risk factors of the operation. These risk factors in turn decide how the maintenance policy of the organization, which is shaped by the maintenance-attributes. The maintenance is intended to protect the reliability of the plant, which in turn ensures that the role of the plant is sustained.

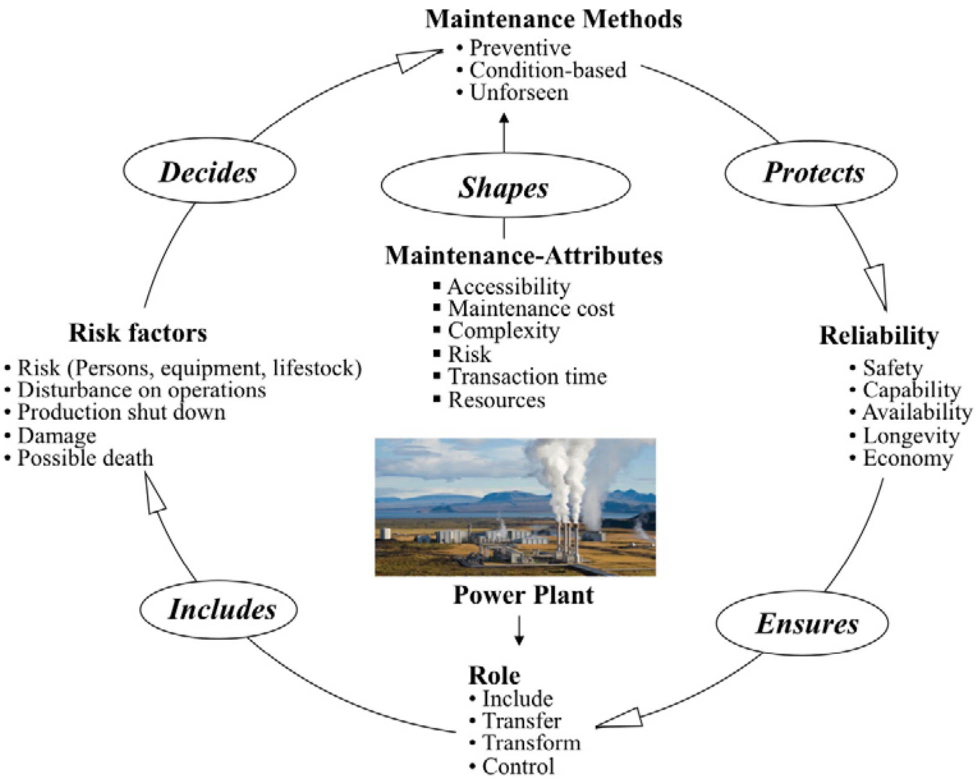

Figure 3 Interconnections of critical factors in maintenance [33].

2.5 Maintenance Management

Maintenance is defined by the European Standard as “a combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function” [25].

The ability of a system to perform its required function is determined by two factors according to Jezdimir Knezevic [34]. On one hand are the inherent characteristics of the system, which are determined at the early stages of the system design by designers and manufacturers. This covers the reliability and maintainability, which directly affect the failure frequency and how easily maintenance can be carried out. On the other hand are the operational characteristics of the system, which are determined by the user in terms of maintenance policies and logistic support.

Organizations usually aim at fulfilling one or more of the following objectives; minimizing costs, providing safe environment, maximizing profit, providing certain quality level for products or human resource development. All of these aspects are reliant upon the maintenance activities and consequently must the maintenance objectives be in line with the overall organizational objectives and strategies [35]. Cost of poor maintenance can arise through various reasons and affect all fields of the operations. One of the most easily detectable consequence of poor maintenance is inferior equipment performance, which can result in higher maintenance costs, increased equipment failure, asset availability problems and environmental impacts. Another aspect often neglected, is unnecessary preventive maintenance and when it is not carried out well enough [36].

According to PAS-55-1 a maintenance policy is “principles and mandated requirements derived from, and consistent with, the organizational strategic plan, providing a framework for the development and implementation of the asset management strategy and the setting of the asset management objectives" [19]. It describes how maintenance management and activities defined by the maintenance policy shall be carried out. Maintenance strategy is defined by the European Committee for Standardization (CEN) as "a management method used in order to achieve the maintenance objectives [25]. In PAS 55-1 is stated that the strategy shall be "long term optimized and sustainable direction for the management of the assets, to assist in delivery of the organizational strategic plan and apply the asset management policy" [19]. Maintenance plan is a "structured and documented set of tasks that include the activities, procedures, resources and the time scale required to carry out maintenance" [25]. The objectives of maintenance are defined by CEN as "targets assigned and accepted for the maintenance activities" [25]. They shall be specific and measurable outcomes required of assets and asset systems, and can be found on different levels of control, from strategic to operational level [19]. The interrelations of these terms are depicted in Figure 4. The continuous improvements indicate the iterative loop of maintenance management where the review leads to changes in work procedures or even policies.

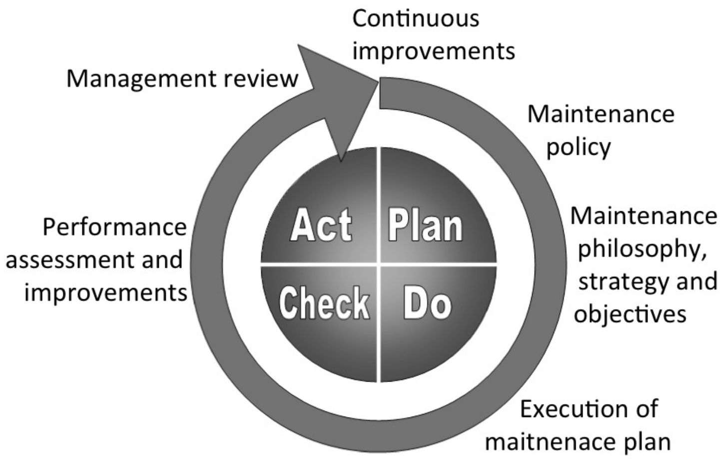

Figure 4 The interrelations of maintenance management terms depicted through the iterative cycle of plan, do, check, act.

The strategic goals of maintenance would be to perform cost-effectively at the same time as general production goals are met, such as reliability, availability and safety. Reliability can be defined in many terms such as "the ability of an item to perform a required function under a stated set of conditions for a stated period of time" [8]. However, reliability can be concerned with more segments of the operations, and such an approach will be used in this thesis. Lenahan set forth a definition of reliability based on five elements that can be abbreviated as 'SCALE' [9]. This stands for Safety, Capability, Availability, Longevity, and Economy. The elements are described in Table 2.1. Organizations operating in distinct industries where the goals of the production differ, can define their reliability in two wholly different ways, by placing emphasis on unlike elements. The approach taken in each company will therefore be aligned with their respective strategies, and emphasis on certain elements does not have to come down on the cost-effectiveness of the plant.

Table 2.1 Definition of the SCALE model [9].

Element	Description
Safety	A reliable plant operates without hazard to people, properties or the environment.
Capability	If the plant produces to the level of production capability then it is deemed as reliable.
Availability	In the maintenance strategy interruptions to the production, such as servicing of components or overhauls, should be used to calculate expected availability of the plant. If unavailability exceeds the defined period it is considered unreliable.
Longevity	All items of equipment have a life expectancy, and if an item of equipment fulfills this expectation or exceeds it, then it's reliable. Maintenance is firstly dedicated to sustaining the longevity of the plant as a whole, and secondly in sustaining the longevity of individual parts for as long as cost-effectively feasible.
Economy	If the plant operates within the calculated operation and maintenance cost, then it is considered a reliable plant.

Reliability is crucial for companies operating 24/7 all year round, where there is no space for unplanned shutdowns, which will in effect result in lost sales [8]. For companies to stay competitive in today's environment it is important that they strive for quality and cost-effectiveness. A good utilization of resources and cost-efficient operations is a way of meeting this demand [37]. Maintenance costs usually account for a large proportion of the operation and maintenance costs in heavy and capital-intensive industry, making efficient utilization of maintenance resources an important element in the economics of production. Nevertheless it is often regarded as a second rank, and ignored or neglected by those who influence production processes [38]. Studies have shown, that for profits in large companies, reductions of maintenance expenditure by $1 million can equal an increase in sales of $3 millions. In fact it is often easier for companies to reduce maintenance cost by $1 million than increasing sales by $3 millions [39].

Nowadays it is generally accepted that maintenance is a key function in providing long-term profitability for an organization [37]. However, no universal system exists on how maintenance should be designed or operated to reach optimal maintenance system, in terms of maintenance policies and hierarchy of authority [35]. It is dependent on many factors, such as technology advancement and age of equipment, scale of operations, organizational strategies, and culture etc.

The maintenance management function covers all maintenance related activities and consists of planning, organizing, executing and controlling maintenance activities [35]. Maintenance management is defined by EN as "all activities of the management that determine the maintenance objectives strategies, and responsibilities and implementing them by means such as maintenance planning, maintenance control and supervision, improvement of methods in the organization including economical aspects" [25]. The maintenance philosophy is put in effect through maintenance management. This can be seen in Figure 5, which depicts the leader's role in the maintenance process. The role of the leader is highlighted in the center, since this role can be seen as the cornerstone of efficient maintenance management. The organization must have a clear vision of their strategies in order to achieve performance objectives and targets regarding availability, quality or production, which are set in the planning process. In the organizing process the necessary resources are allocated to tasks and activities coordinated. Implementation process includes the execution of tasks determined in the organizing process. Finally is the process of control, which aims at monitoring and measuring performance of the maintained equipment and subsequently analyzing whether actions are needed to meet the objectives [37]. It is important to cover all those fields, because by neglecting some important parts of the maintenance function, it will never reach its full potential [40].

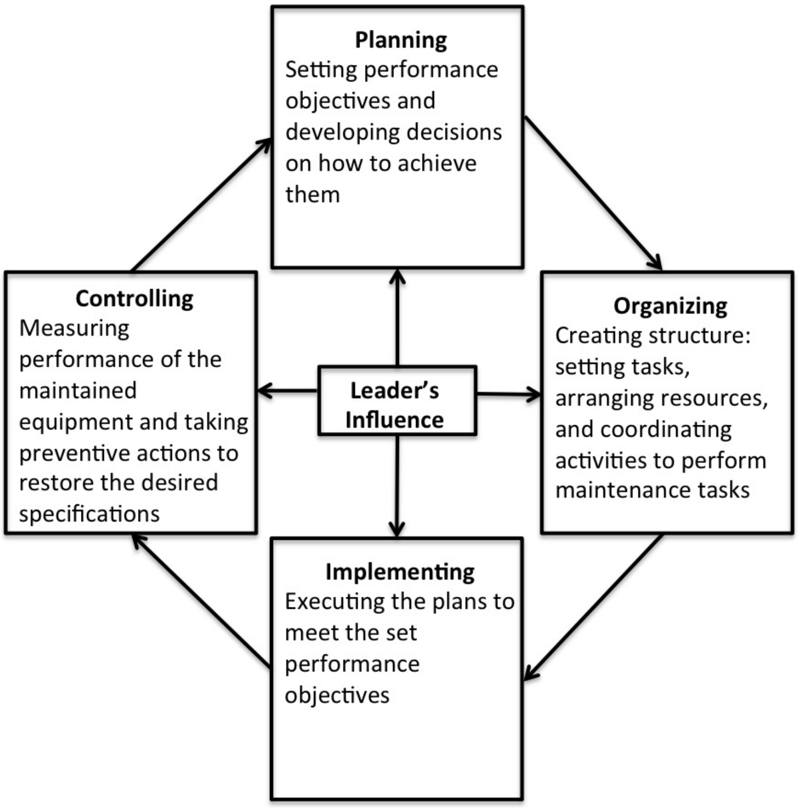

Figure 5 The leaders role in the maintenance process [35].

The maintenance department is responsible and accountable for how equipment works and looks and the costs necessary to provide the required performance level [8]. The level of maintenance is defined by specification, which is a detailed description of what is required for maintaining equipment and plant. In many companies these specifications are not detailed, but exist in the mind of the personnel accountable for maintaining the equipment. This type of specification is defined by and dependent upon personnel training, pressure of providing certain output or money, and time available [8]. However, formal specification should be held in the form of a design specification, a vendor specification or a specification developed within the organization itself. The specification is a requirement which has to be met and must provide a certain minimum accepted level of maintenance, stated in terms of attributes and capacity [8].

Furthermore several determinants will be stated here, which are crucial when designing the maintenance organization as presented by Ahmed Haroun and Salih Duffuaa [35]. These include for instance maintenance capacity, outsourcing or in-house maintenance and centralization or decentralization. Maintenance capacity planning is the art of determining the amount of needed resources in order to meet the objectives of the maintenance department. This includes the skilled staff for carrying out maintenance along with the tools, time and space needed. Usually the amount of workers is the main concern, but in capital and technically intensive industry, such as electricity production, the availability of appropriate tools becomes essential. Centralization vs. decentralization is concerned with whether maintenance is carried out at a single location or divided between units. In a centralized maintenance system all maintenance activities are carried out at a centrally administered location, while in a decentralized system each functional unit of the organization manages their own maintenance activities. However, centralized workshops are most often used in a decentralized system [41]. The main advantages of a centralized maintenance system is that it provides increased flexibility and better utilization of resources at the cost of transportation [35]. Haroun and Duffuaa state that in a decentralized system the range of skills of employees diminishes and utilization of manpower is worse than in a centralized system. In-house vs. outsourcing considers the sources needed for providing the maintenance capacity, and to which extent this capacity should be [35].

To conclude this chapter it is clear that in order to fulfill the reliability standard set within the organization it's necessary to specially design or develop maintenance procedures in accordance with the organization's needs. This is usually done with a combination of preventive, and corrective maintenance. It is important as well to have the needed foundations in place, and a special attention should be given to measurements and respective follow-up procedures. To emphasize this need a discussion about continuous improvements and the importance of managers for this field is given in chapter 2.6, since maintenance is closely interwoven with the culture of the organization.

2.6 The Managers Role in Performance Monitoring

Focus on short-term profitability for the cost of physical assets has for long been the Achilles heel of many organizations [42]. Organizations need to engage in a strategy for improvements that is aligned with their specific needs in order to benefit from these changing conditions. One of the primary areas such organizations have focused on is the maintenance management function. The maintenance management function serves as a crucial factor in sustaining competitive advantage on today's markets and the management needs to be the leading power behind improvement efforts in the field [42]. Behind every successful organizational change initiative there is a devoted team of managers. Changes often take a longer time than initially expected and management plays an important supporting role to sustain these efforts [43]. This is the case with measurement initiatives, which are often seen by employees as a managerial control device and only beneficial to the management [44]. Employees tend to respond with resistance towards change efforts and implementation becomes a process being forced through the organization. The reasons behind this resistance may be unclear to managers, but the cause can often be found in the organizational culture. Accordin to Edgar Schein organizational culture is one of the hardest parts to change in the organization [45]. He defines three levels of organizational culture as shown in Figure 6.

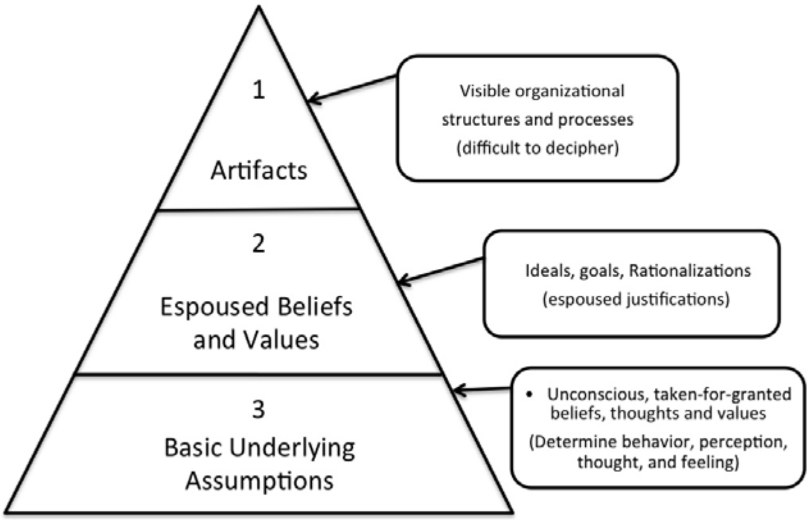

Figure 6 Levels of organizational culture [45].

The first level consists of artifacts that outsiders can see or perceive. Level two contains espoused values, which are the conscious elements of the organization's culture. This is for instance strategies and goals. The third level consists of basic underlying assumptions and they are intangible and can be difficult to detect in daily relations within the organization [45]. To overcome these often-invisible cultural barriers it is pivotal that employees understand the need behind the change initiative so they can embrace ideas and participate in the process. It is the responsibility of management to overcome these barriers by leading the way and preparing the staff for the necessary cultural change.

Michale Beer and Nitin Nohria suggest that all change initiatives can be categorized into two archetypes, theory E and theory O [46]. Theory E change is driven by economical value and seen as the 'hard' approach relying on layoffs, economic incentives and restructuring. Theory O change is on the other hand based on organizational capacity and considered as a 'soft' approach. The objective is to evolve human capability and corporate culture through learning the process of change, getting feedback and reflecting for further development. In practice it has turned out that organizations, which adopt theory O strategies, tend to have stronger and more commitment-based relationships with their employees [46].

Effective partnership of management with employees and other stakeholders is necessary to successfully achieve performance improvements. The performance measures have to be linked to the organization's strategic objectives, which should be set to achieve the organizational vision. Organizations that have taken the time to clearly define their vision and strategies become more successful in obtaining the collaboration of employees [44]. David Parmenter defines four foundation stones required to successfully implement and utilize key performance indicators, which are [44]:

- Partnership with the staff, unions, key suppliers, and key customers
- Transfer of power to the front line
- Integration of measurement, reporting, and improvement of performance
- Linkage of performance measures to strategy

The frontline, or shop floor workers, serve a big position in a successful implementation and therefore cooperative frontline is important. This can be directly linked to theory O by approaching the employees in the right way to ensure a long-term job satisfaction.

Terry Wireman describes the maintenance management function through a pyramid, referring to the necessary characteristics of a firm foundation before other tiers can be added [47]. Firstly the foundation must be laid by having a functional preventive maintenance (PM) system in place. Once the PM is fully functional, the next tier can be added. It includes stores and procurement, work flow system, computerized maintenance management system (CMMS), and training. The next tier is focused on equipment availability through predictive maintenance, operations involvement and reliability-centered maintenance. With sufficient data, the organization can move up to the next tier and focus on enforcing its asset strategy through total productive maintenance and financial optimization. In order to reach the final stage of continuous improvements, all of the foundations have to be in place and aligned to the corporate strategy. When performance objectives have been defined and represented in performance measures they should be followed by the continuous improvement loop of self evaluation and benchmarking, which can be seen as one of the most important factors in sustaining competitive advantage in today's markets [21]. Continuous improvements, also known by the Japanese name Kaizen, can be defined as 'the process of never accepting status quo of an organization' [42].

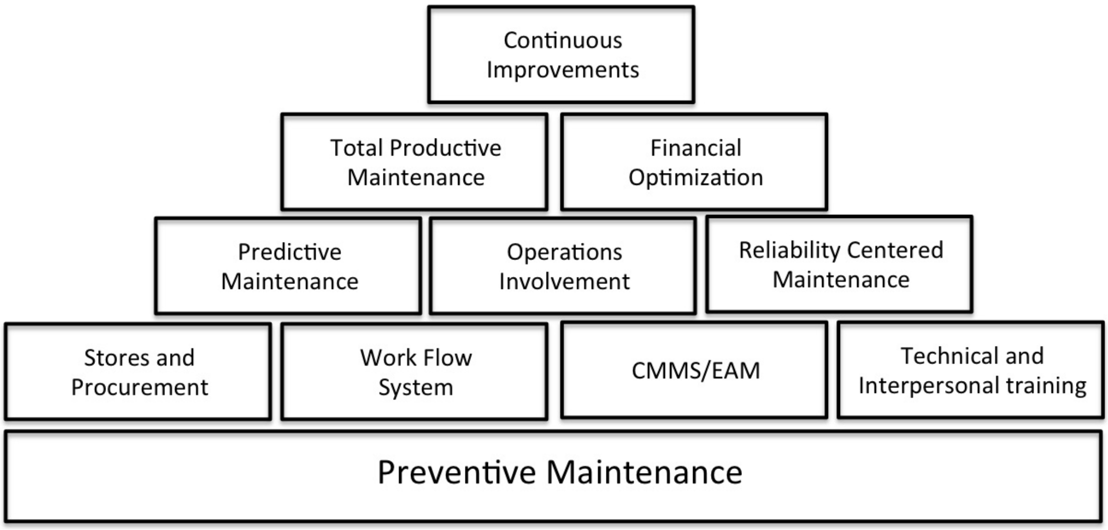

Figure 7 The maintenance management strategy pyramid [47]

The focus of productivity is to enhance the internal capacity and capabilities of the organization and it has to be built into all areas of the organization and made self-sustaining [21]. In certain 'soft' areas, as goes for productivity, there is a need to balance many different factors, although most of them is difficult to define or measure clearly [21]. However, productivity is central in every business and without productivity measurements, it's hard to keep it in control. There is a special need in such fields for management to sustain the focus on it in order to achieve continuous improvements [21]. Benchmarking is one of the best tools available for continuous improvements and a witty, but still clear look at benchmarking is:

"Benchmarking is having enough humility to recognize that someone is better at something we do in our company and wise enough to learn how to be better at it than they are…"[42]

2.7 Benchmarking

The current method of benchmarking can be traced back to the 1980's when Xerox started a benchmarking project with the intention of reducing cost and waste along with increasing quality. Robert Camp, who later published the first book on benchmarking, led the project [48]. A benchmark is a way of expressing a goal or objective by using metrics, and presented either as an absolute value or an interval [22]. The procedure of benchmarking can be described as an ongoing systematic process, where organizations compare their processes' performance to other organizations, which are considered to achieve 'best practices'. Best practices vary greatly with the business condition of each organization, but they can be defined as ones that enable organizations to become a leader in their respective field [47]. Through this procedure, knowledge is gained in order to improve current performance. Once the desired improvements are through, the process demands that another area for improvements should be identified and the process starts over again [42]. In addition to providing an overview of which fields need improvements, benchmarks will as well help in understanding the processes and the skills, which lead to superior performance [47].

Benchmarks can be utilized once the organization has identified certain fields, on which they want to improve their performance. Then they can study other companies, to identify the gap which has to be bridged in order to achieve acceptable results [42]. The benchmarks, or goals, can then derived from such a study or from the organizational goals [22]. In order to bridge this gap the distance left to reach the goal has to be quantified. Thats where performance indicators come into play to measure performance and reflect the improvements gained. They need to be identified and chosen appropriately for each functional process, which is the key to understanding the interrelationship between performance indicators and benchmarking [42]. Several different benchmarking approaches exist, and the most applicable in the maintenance management field are; one-to-one benchmarking, review benchmarking and database benchmarking [48]. One-to-one benchmarking is the most common method, where one participant visits another participant. Review benchmarking is usually carried out by visiting several companies and identifying their relative strengths and weaknesses. Database benchmarking is done through a comparison of the participants' data with known parameters from databases. Furthermore Wireman describes three types of benchmarking; internal benchmarking, similar industry benchmarking and best practices benchmarking [47]. The latter two are related to one-to-one/review benchmarking and database benchmarking respectively, but internal benchmarking brings a new aspect to the discussion. Internal benchmarking involves different departments or processes within the organization [47]. The main advantages of such an approach include ease of data collection and comparison but on the downside does it not provide the foundation needed for great improvements.

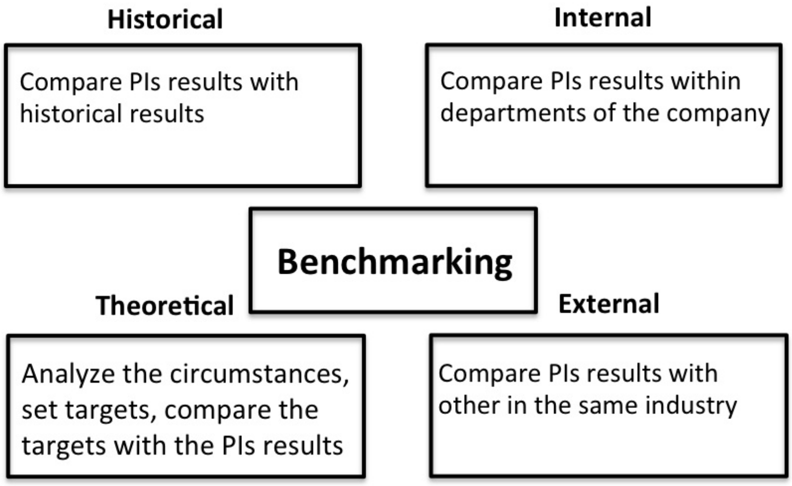

Figure 8 Different types of benchmarking.

The process of benchmarking is described by Wireman in the following ten steps [42]:

1. Conduct an internal audit of a process or processes.
2. Highlight potential areas for improvement.
3. Do research to find three or four companies with superior processes in the areas identified for improvement.
4. Contact those companies and obtain their cooperation for benchmarking.
5. Develop a "pre-visit" questionnaire highlighting the identified areas for improvement.
6. Perform the site visits to chosen partners.
7. Perform a "gap analysis," comparing the data gathered to your company's current performance.
8. Develop a plan for implementing the improvements.
9. Facilitate the improvement plan.
10. Start the benchmarking process over again.

Wireman emphasizes the need of communicating with other companies, which can be considered as best in class, in order to obtain valuable information on how improvements can be realized. These procedures reflect the twelve-stage methodology developed by Robert Camp as represented in the RCM guide of NASA [22]. Other sources, such as Abdul Raouf and Parmenter, rather stress the use of global best practices, or database benchmarking, which can be found globally without the connection to single companies [14, 44]. Such listings of maintenance benchmarks have for instance been published by Wireman, Mitchell and Smith & Mobley as well as being available through the service of consultants, which many of whom have built up their own databases [8, 47, 49]. Even though the thought of hiring consultants to do the job may be intriguing, caution must be kept, since they can provide a solution which tracks only so-called lagging indicators. This will not help with managing the maintenance since it will just quantify the already known problem [8].

Many organizations are keen on the thinking 'not invented here' and unwilling to look outside the company to admit the fact that somewhere in the world there can be found companies, which are performing better in certain fields [47]. It is necessary for management to be able to acknowledge this fact and not intend the benchmarks as some cairn showing how well they are performing. Companies that fail to develop such a global perspective will give in to other companies which are willing to think outside the box by viewing their business from external perspectives [47]. Benchmarks should therefore not be comfortable, but rather challenge the management to view their business critically in order to discover potentials for performance improvements.

Benchmarking can provide a competitive advantage to organizations through finding opportunities for improvements. This is, however, not achieved until the needed actions have been taken and improvements realized [42]. In order to achieve the desired results the allocation must be made to provide the necessary time and money [42]. The most necessary preliminary requirement before organizations start the benchmarking process is that they know their own processes explicitly. With deep knowledge and understanding of the processes it is easier to pinpoint areas with a potential for improvements [42]. Once the destination has been set, the need for performance indicators rises to chart the part between the current levels of performance to the desired benchmark level.

2.8 Performance indicators

A good way for clearly identifying the need of performance indicators is by stating the following about maintenance:

- Maintenance strategy is doing the right things
- Maintenance execution is doing the things right
- Maintenance control is making sure that the right things are done right

The essential question is how do you know you are doing the right things right? Selecting appropriate metrics and tracking performance indicators can accomplish this. Organizations have been progressing from the primeval approach of managing by opinion or feelings towards management by fact, supported by performance measurements [50]. The goal of performance measurements should be to provide management with the right performance-related information at the right time [50].

A metric is the product of measurements, made to quantify either a process or a result by assign numbers to the their respective properties or characteristics [51]. Performance indicators are formed by combining several metrics and when applied to the field of maintenance they are called maintenance performance indicators [52]. Aditya Parida defines maintenance performance measurements (MPM) as “The multi-disciplinary process of measuring and justifying the value created by maintenance investment, and taking care of the organization’s stockholder’s requirements viewed strategically from the overall business perspective” [53]. The main purpose of utilizing performance indicators is to compare actual conditions with specified requirements and thus measuring the distance between set goal and the current situation [52]. Key Performance Indicators (KPI) are formed to make an assessment of fields or processes, which are considered as key figures, and can be formed by combining several performance indicators [54]. Confusion with these indicator’s definitions are common, where people tend to mix the usage and meaning of those mentioned above, and this is for instance evident in how the European and American standard organizations differ in their use of the terms metrics and key performance indicators. However should it be stated that no matter what the measurement outcomes are named, when properly utilized they should provide objective evidence to emphasize areas with improvements opportunities [42].

The productivity of maintenance systems heavily influences their respective production systems by keeping them safe and ensuring that they can provide their expected output. One way of enhancing the productivity of maintenance is through an efficient utilization of maintenance resources [37]. To ensure efficient resource utilization and locate possible areas for improvements, performance measurements must be conducted. Maintenance performance measurements allow the organization to measure, monitor, control, and take timely and appropriate decisions [20].

Maintenance performance measurement system can provide substantial advantages when applied properly, such as for: [20, 50]

- Assessing the value created by the maintenance
- Determining current performance level, i.e. initial baseline, of the organization
- Establishing performance goals based on the initial baseline
- Identifying the gap between current performance level and the desired goal
- Revising resources in order to reach the performance goal
- Track the performance trends and the progress of bridging the gap between baseline and desired performance goal
- Identifying soft spot areas in the organization and take appropriate actions
- Setting benchmarks and compare performance to other organizations
- Form a basis for continuous improvements in maintenance management

2.8.1 The process of establishing maintenance performance measurement system

Bjørn Andersen and Tom Fagerhart present eight steps necessary for a maintenance performance measurement system [55].

1. Understand and map business structures and processes
2. Develop business performance priorities
3. Understand the current performance measurement system
4. Develop performance indicators
5. Decide how to collect the required data
6. Design reporting and performance data presentation formats
7. Test and adjust the performance measurement system
8. Implement the performance measurement system

The first three steps include the preparation needed before performance indicators can be developed. This draws the focus to the purpose of the operation in light of the overall organization’s strategy in order to pinpoint priorities in the business processes. All organizations have some sort of measurement system in place, and therefore they can either refurbish the older one or replace it with a totally new one. Introducing a new system can pose problems to the implementation process, since it can be hard to persuade employees to overturn their current work procedures. The fourth step is the centroid of the process, by developing a set of appropriate number of precise and relevant PIs. For the system to be of any use, the data collected must be measurable, accurate and accessible. The performance measurement system can either be manual or electronic and the choice between these alternatives should be made in context with how the PIs will be collected and expressed. In this step, the data collection frequency should be determined. Step six decides how the information extracted from the data should be presented to the end user, whether the information is to be used for management, monitoring or improvements. The final two steps take on how the system is adjusted to the organization and finally implemented when it is considered to be useable.

2.8.2 Choosing the right performance indicators

Before any measurements are conducted the following five questions should be asked within the organization [56]:

- What is the decision this measurement is supposed to support?
- What is to be measured?
- Why does this measurement matter to the decision it is supposed to support?
- What is currently known about this measurement?
- What does further measurement of it provide?

When these questions have been answered, it has to be considered how the measurement reflects the company's organizational strategy and the objectives of maintenance [52]. To avoid a mismatch between the organizational strategy and performance measurements they should follow a hierarchy classification to align with the hierarchical levels of the organization [57]. Properly formulated indicators are implemented from the top down, not bottom up, since they need to measure what is important to the management team in order to satisfy the needs of shareholders and other stakeholders [42]. On the other hand, the reporting structure of the performance indicators should follow a bottom-up perspective, where the upper tier indicators can for instance be made from aggregated indicators from lower levels [58]. In the EN 15341 standard are the indicators below level one a detailed description of indicators at a higher level [59].

Performance measurements need to be viewed along three dimensions according to Andersen and Fagerhaug [55]. These are effectiveness to ensure fulfillment of customer demands, efficiency to ensure optimal and economic use of organizational resources, and changeability to handle changes. This should cascade to the performance indicators established on all levels. Setting a performance indicator hierarchy for the maintenance function begins with focusing on the strategic level of the organization. This level is mainly subjective as it is linked to the long-term goals of the organization [20]. Examples of strategic level indicators include return on net assets, return on capital employed and economic value added [49]. Parmenter names these indicators, key result indicators, since they are the results of many actions and give a clear image of how well the organization is performing. However, they do not provide any information on how to improve the results [44]. While corporate indicators set the direction, the subsequent indicators must focus on supporting that direction [42]. The reason is that performance indicators which are not aligned with the strategies may become counterproductive and lead performance improvements in the wrong direction [49]. Below the strategic level should be indicators corresponding to the tactical or managerial level, including both financial and non-financial aspects [20]. These are the key performance indicators, and they should be directed towards effectiveness and efficiency. The bottom level should represent the operational or functional level, where work process efficiency is determined. These indicators can simply be called performance indicators, and they should be objective [20]. Figure 9 illustrates this hierarchy structure of maintenance performance indicators viewed along the hierarchical structure of the organization. As can be seen from the figure, the hierarchy is twofold with the organizational view on one side and the management view on the other side. The indicators can present either side or both, but it's dependent on the indicator and the context for each occasion. Subjectivity is dominant at the top of the hierarchy, where changes take a long time to realize as is in line with the organizational strategy, which is long viewed. At the bottom of the hierarchy is the objectivity prevailing, which can in fact be quickly changed as goes with the reaction of the employees. The objective indicators, which are aimed at the operators, should therefore connect the performance indicators value with the employees' actual performance. The example used here to represent the hierarchy of performance indicators is based on a typical production company, where the hierarchy is composed of organization, department and component levels [20].

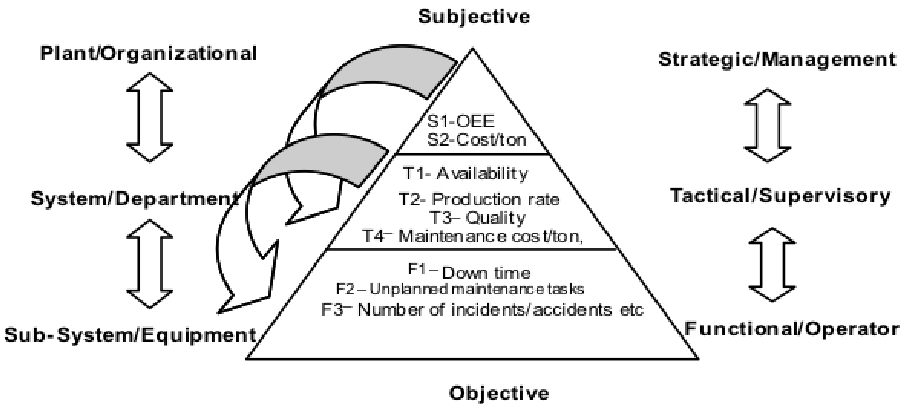

Figure 9 Hierarchy of maintenance performance indicators as presented by Parida [20].

When choosing appropriate performance indicators, the SMART test can be used to determine the quality of the indicators [47]. This test can for instance make sure that the operators and shop floor workers can understand the indicators and relate them to their day-to-day activities. SMART stands for:

- **S**pecific: clear and focused to avoid misinterpretation. Should include measure assumptions and definitions and be easily interpreted.
- **M**easurable: quantifiable and can be compared to other data. It should allow meaningful statistical analysis.
- **A**ttainable: achievable, reasonable, and credible under the conditions expected.
- **R**ealistic: fits into the organization's constraints and is cost-effective.
- **T**imely: obtainable within the time frame given.

The parameters chosen should as well be transparent and provide a means of accountability for all hierarchical levels. Furthermore, in order to collect valuable measurements the measurement system should be user friendly from the technological point of view [20].

2.8.3 Categorization of maintenance performance measurements

Several approaches exist for categorizing maintenance performance measurements. In the ÍST EN 15341:2007 standard, indicators are categorized into three groups; financial-, technical-, and organizational indicators [59]. The indicators then follow a three-level hierarchical classification within each group, representing the previously described hierarchy. The Society of Maintenance and Reliability Professionals (SMRP) categorize their indicators in accordance with the five pillars of the SMRP body of knowledge. The pillars are:

1.0 Business and Management
2.0 Manufacturing Process Reliability
3.0 Equipment Reliability
4.0 Organization and Leadership
5.0 Work Management

Parida presents in his doctoral thesis a multi-criteria hierarchical framework for maintenance performance measurements [53]. His work includes three hierarchical levels; strategic/top management, tactical/middle management, and functional/operational. Then he identifies seven groups within his multi-criteria:

- Equipment/Process related
- Cost/Finance related
- Maintenance task related
- Learning, growth and innovation related
- Customer satisfaction related
- Health, safety & Security, environment
- Employee satisfaction

It is evident from this overview that classification of maintenance performance indicators is not firm. Organizations need to decide which strategy they will follow in their effort, but the choice should be based on their organizational strategy. The strategy furthermore should be aligned with or shaped by their internal and external influencing factors. The most important factors for ensuring a successful operation of the organization should be taken into account, whether the emphasis is on cost, safety or employee satisfaction. Figure 10 presents the internal and external factors that influence maintenance performance as presented in the EN 15341 standard. The influencing factors are of course both industry and organizationally specific, and therefore has each plant its unique set of influencing factors shaping the operations.

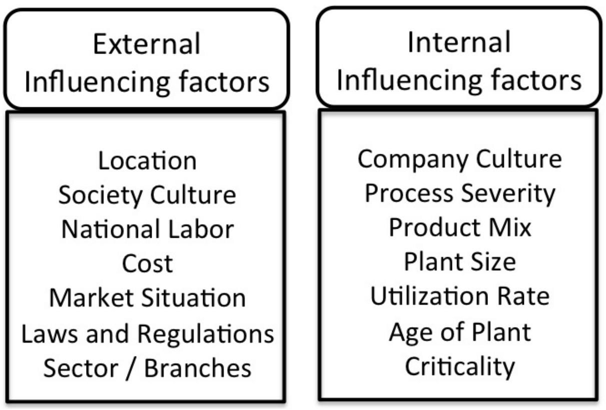

Figure 10 Internal and external factors that influence maintenance performance [59].

2.8.4 Leading and lagging indicators

Performance indicators can broadly be divided into two categories, leading and lagging indicators, based on their origins and context when used. The difference between these two groups can fundamentally be described by the notion of leading indicators being used for managing portion of the operations, whereas lagging indicators represent how well they have been managed [8]. Lagging indicators are probably the more commonly known type of measure since they are usually more visible for instance through financial reports. They present results of processes after the performance has been realized and are therefore rarely useable for taking immediate reactive actions once underperformance is identified [60]. Instead, once an unacceptable level is recognized for a lagging indicator, a look has to be taken on leading indicators to find the root cause for the underperformance in order to achieve improvements.

Leading indicators are measures, which report on situations that are causally related to desired outcomes [61]. In such a way they offer the advantage of stepping in to take corrective actions once signs of underperformance are evident, and preferably before any harm has taken place [52]. Sometimes so-called soft measures can be valuable as leading indicators, such as employee commitment or customer satisfaction since they offer indication of financial performance [52]. In the field of maintenance leading indicators are used to measure how well each of the steps in the maintenance process are carried out [8]. Table 2.2 shows recommended leading performance indicators for the maintenance function, which have been categorized into relevant groups by Smith and Hawkins [54]. This listing is however not complete and adjustments have to made in selection of these indicators for each organization. In addition should it be noted that some of those indicators can as well be lagging when applied to or combined with other performance indicators.

Table 2.2 Leading maintenance performance indicators [54].

Group	Performance indicator
Reliability/ Maintainability	• Mean time between failures (MTBF) by total operation, area and equipment • Mean time to repair (MTTR) for individual equipment • Mean time between repairs (MTBR) • Overall equipment effectiveness (OEE)
Preventive and predictive maintenance (PPM)	• PPM labor hours divided by emergency labor hours • Number of PPM work orders divided by corrective maintenance work orders as a result of PM inspections
Planning and scheduling	• Planned/scheduled compliance (percentage of all maintenance labor hours completed to schedule divided by the total maintenance labor hours) • Planned work per scheduled work
Materials management	• Stores service level (% of stock outs) • Inventory accuracy
Skills training	• MTBF • Parts usage
Maintenance supervision	• Maintenance control (unplanned labor hours divided by total labor hours) • Crew efficiency (work hours completed on schedule per estimated time) • Work order discipline (part of labor work accounted for on work orders)
Work process productivity	• Maintenance costs divided by net asset value • Total cost per unit produced • Overtime hours as percentage of total labor hours

Reliability, which is the cornerstone of power plant maintenance, can be expressed through the use of some closely related indicators. Mean time between failures (MTBF) is the average time that an asset functions before it fails and it is one of the most basic measurements that can be used for measuring reliability [8]. MTBF is calculated as the amount of days within a given period, in which the asset has be fully functional, divided by the number of incidents which have made the asset unavailable. Mean time to repair (MTTR) is the time from the functional failure until the asset becomes fully functional again. For a given period is the total unavailable time for the asset summed up and divided by the total amount of incidents. The bathtub curve is normally used for calculations of MTBF since it typically characterizes hardware failures. The bathtub curve describes how components are both vulnerable at the beginning of their use, which is called infant mortality, and at the end of their life. Between these two is the useful life, where effort is made to maintain the equipment. Each component or system has its own curve, which should be provided by the manufacturer.

David Parmenter on the other hand rejects the concepts of lead and lag indicators, expressing them as only partially covering the subject [44]. Instead he describes the performance measures as a three-layer system, consisting of:

- Key result indicators, which tell you how well you have done in a perspective.
- Performance indicators, which tell you what to do.
- Key performance indicators, telling you what to do to increase performance.

In his approach he presents the key result indicators those referred to as lagging indicators. However, he characterizes the PIs and KPIs as past-, current-, or future-focused measures. In his opinion the lead/lag indicators do not focus well enough on the latter two types of measures. This approach will on the other hand not be used as a reference guide in forming maintenance performance measurements, since Parmenter's approach is focused on the organization as whole and the maintenance indicators are only a subset in his model. The amount of indicators is also of concern for Parmenter, where he suggests that no more than 10 KRIs and 10 KPIs should be used in the organization. Kaplan and Norton recommend a maximum of 20 KPIs [62]. The reason for this amount of KPIs can be found in the fact that the system needs to be efficient and at the same time clear for all employees. Therefore a simple set of indicators offers a clear platform for managers to control the maintenance function, and often are some indicators only variations of each other [44].

2.8.5 Data collection

A system for data collection is required to be in place for establishing performance measurement system. For maintenance performance measurement system to be of any use, it is important that the system is technically user friendly, and that employees register the ritght data in the right way [20]. The reason behind this is that human errors or "pen-laziness" are the most common causes for insufficient data registration [33]. Therefore the employees must be provided with sufficient training for data registration and the business objectives at the strategic level must be understood by employees at all levels [20]. A common saying in the field of information and communications technology is 'Garbage in, garbage out', which certainly adheres here. Poor or incorrect data entered to the system can at best be of little use and at worst have counterproductive causes for the organization. As well should the system be set up in such a manner that errors are hard to make and information cannot be manipulated in order to improve performance indicators [52]. Once metrics get tied to compensations for employees they tend to manipulate the system in a way to profit themselves [52]. A further discussion about data collection can be found in Chapter 2.9.

2.8.6 Managing with performance indicators

Once a complete set of maintenance performance indicators has been chosen and implemented, the organization has only progressed half way towards victory. The reason is that without employees properly understanding the indicators, limited progress will be made towards improvements. The organizations themselves have to make sure that the soil is rich enough before any seeds are planted, i.e. employees must be well informed on the change initiative towards maintenance performance measurements. Clear processes have to be defined to react once abnormal values are discovered, but the form of the reaction process can differ between organizations. Various employees throughout the organizational hierarchy can use maintenance performance indicators, but nevertheless they always have to provide the information to the end user, irrespective of the technical maturity of the employee.

The ability to manage the maintenance function based on performance indicators is reliant upon how well they are presented. The end user wants the fewest indicators possible to manage the system in order to being able to take timely and accurate decisions [52]. Therefore key performance indicators are important in this aspect, since they combine several indicators into a single and simple number for presentation. A common method to present the indicators is through dashboards, which is a visual presentation of performance indicators and they should be a one-page display [44]. The visual presentation can be linear, as columns, pie charts, different color codes or other formats applicable and they can be viewed as trending, on a control chart or for a comparison [50]. Examples for visual presentation are shown in Figure 11. The choice between those alternatives in presenting the maintenance performance indicators' values depends on the intended use of the indicator, whether it's supposed to be used for a historical trending or a comparison to other indicators. As discussed earlier, in order to provide efficiency, the system should not be comprised of too many indicators, i.e. a dashboard should for instance not include more than 10 dials.

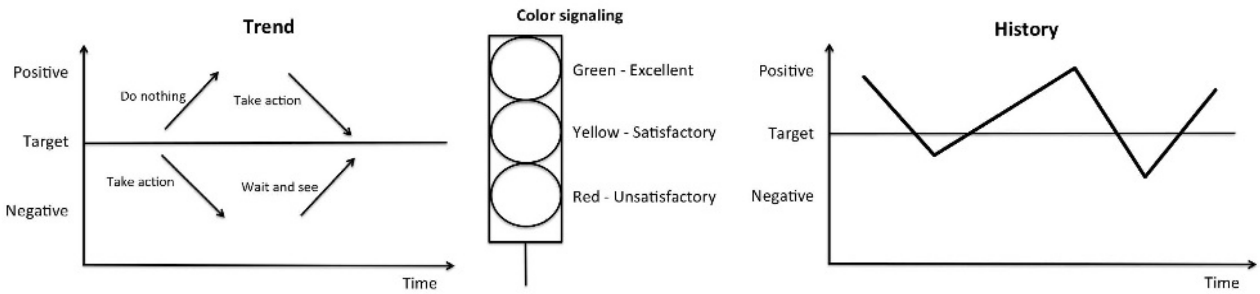

Figure 11 Examples of visual presentation of performance indicators.

Dashboards

Dashboards should be made for each category of indicators and also for each hierarchical level of the organization. Therefore should one dashboard be presented to the board, presenting key result indicators in accordance to the needs of the board. These could include operating expenditures, return on capital employed and reported incidents [44]. This dashboard should be reviewed and updated monthly or quarterly. For the maintenance manager the dashboard should include KPIs specific to the total plant maintenance and be trended and viewed weekly [8]. Here a mixture of leading and lagging indicators is presented. Examples of indicators are; MTBF, maintenance labor cost, maintenance material cost, percentage of overtime, unavailability, amount of corrective maintenance. Other dashboards could be used for maintenance staff, reliability, and maintenance stores [8]. It is important that the dashboard provides a means of digging deeper into the causes for underperformance when it is discovered. Therefore a direct link should be for managers to thoroughly analyze the values behind each KPI presented. For managers being able to conduct a further analysis they must fully understand the structure of the KPIs presented in front of them.

Scorecards

The Balanced Scorecard is a set or list of indicators, which are frequently used to group maintenance KPIs and show different faces of the maintenance function. The balanced scorecard is a holistic approach which groups both financial and non-financial measures to measure performance [62]. In any organization, the corporate objectives state the company's vision. A corporate strategy is formulated as the way to achieve these objectives. A corporate balanced scorecard is part of the corporate strategy to measure performance and compare it with the corporate objectives. These balanced scorecards are applied to different divisions and departments, right down to the employee level.

Similarly, maintenance PI can be translated from balanced scorecard perspectives and applied to the divisions, departments, sections and employee levels. The maintenance objectives are linked to critical success factors, key result areas and key performance indicators.

2.8.7 Pitfalls

Performance indicators also possess a darker side when not applied properly and handled with care. Michael Hammer gathered through his career as consultant information about performance measures and presented the '7 deadly sins of performance measurement' and how to avoid them. They are presented in Table 2.3.

Table 2.3 The 7 deadly sins of performance measurement and how to avoid them [51].

Sin	Description	Possible ways to avoid sin
Vanity	Measurements are chosen in such a way that they will inevitably make the organization, its people and especially the managers look good	- Not tying bonuses and other rewards to employees to results measured in terms of performance measures - Keep the needs of the customer (internal or external) in mind - Being critical when identifying the weaknesses of the organization
Provincialism	Organizational boundaries and concerns dictate performance metrics	- Being careful about how chosen performance metrics can affect other areas of the business
Narcissism	Measuring form one's own point of view, rather than from the customer's perspective	- Go to full length in acquiring detailed information about what really matters to customers and to which extension their expectations are fulfilled
Laziness	Assuming one knows what is important to measure without giving it adequate thought or effort	- Not jumping to conclusions, or measure what is easy to measure - Go through the effort of ascertaining what is truly important to measure
Pettiness	Measure only a small component of what matters	- Use metrics that capture the essence of what needs to be measured in a usable form - Use metrics systematically
Inanity	Implement metrics without giving any thought to the consequences of these metrics to human behavior and ultimately on enterprise performance	- Thoroughly analyze the possible effects of all metrics chosen before they are implemented
Frivolity	Not being serious about measure-ments in the first place	- Starting performance measurement program with a real intention and commitment

These sins and their respective measures for avoidance should be kept in mind during every performance measurement project. If management teams are not aware of these sins and their possible harm to the organization when they start the implementation process of monitoring performance, they may face the risk of committing one or more of these sins. An organization that finds itself in committing these sins will become unable to use its metrics to drive improvements in operating performance. The crucial aspect about performance measures is that “bad measurement systems are at best useless and at worst positively harmful” [51].

Performance measures are collected in most organization, but many of them do not use them at all [50]. It’s not enough to display some set of indicators in the organization if the information they present are not analyzed and used to take appropriate actions. Following the wide spread of computerized maintenance management systems, data collection has become an easy task and huge amounts of data are collected and stored. However, it is easy to get lost in the jungle of data if the organization does not sort out what information they really need. The key is to collect only performance measures that will actually be used, by measuring the critical few instead of the trivial many [50]. The first step is to decide what kind of performance related information is actually needed in order to increase productivity.

2.9 Computerized Maintenance Management Systems

To manage you must have controls, to have controls you must have measurements, to have measurements you must have information, to have information you must collect data [47]. Data collection is therefore a requisite for performance measurement systems. However, for such a system to be effective the collected data must as well be easily accessible and reliable. Conventionally this can be achieved through a manual system but with the development of computerized maintenance support, which emerged in the 1960's, the shift began towards automation [63]. Computerized maintenance management systems (CMMS) and Enterprise asset management systems (EAM) are offspring from this development. The main difference between these two lies in the fact that CMMS can be considered as a subset of EAM. The EAM comprises other aspects of the business in addition to maintenance, and this can for instance be inventory, accounting and human resource [64]. Therefore this discussion will be from the CMMS point of view, even though the boundaries between these two are not always clear. The CMMS is a software package that serves as maintenance information system. It provides access to information about manpower, maintenance policies and equipment for supervisors and maintenance managers. This can in turn improve effectiveness of maintenance activities [14]. The system maintains a computer database of stored maintenance data. The purpose is to provide a ground basis for managing maintenance operations and processes in a systematic and often cost-effective manner [63]. Through the system, maintenance activities can be planned, scheduled and results registered into the database. The system can be considered as being built around work orders, but assets are also an important aspect and their respective connection with work orders [65]. Figure 12 shows the key functions present in a typical CMMS.

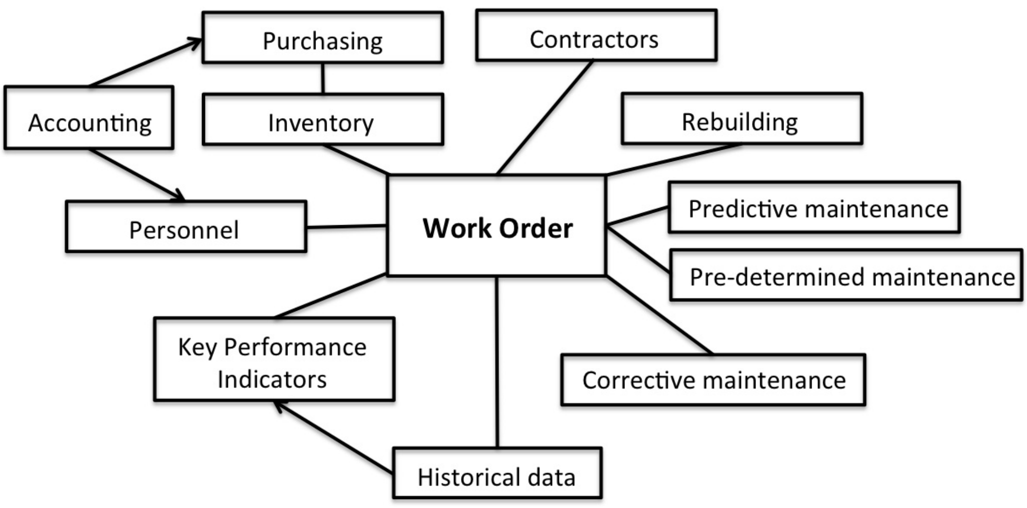

Figure 12 Key functions in a CMMS and how they are built around work orders.

The main advantages of using a CMMS lies in the possibilities it offers in scheduling and planning maintenance operations. This simplifies data storing and reporting can be done directly within the system. The computational power moreover provides the user the alternative to sort out useful information from the data and present statistical results [42]. Therefore, CMMS is useful when organizations seek to utilize maintenance performance indicators. However, one drawback of using the system for mathematical models is to sort out useful information from the ocean of stored data. Of course the aim is to improve effectiveness and provide support to management in decision-making, not bury them in a black hole of data. When work order forms only offer a window for typing descriptions they become of limited use to regards of statistical reports. Huge amount of time is needed in such cases to retrieve information manually, which of course cannot be considered effective. Checklists can support this automation of information gathering, but it must be considered that they are not always suitable. For the data to be of any use they must also have complete accuracy and the CMMS must be used completely by all employees responsible [47]. When these factors are in place, the system can bring huge advantage to the organization by producing quality data. The possibilities with the system are almost without limits but they depend of course on the software package used in the respective organization and how it is exploited. A recent survey made in the United States showed that majority of organizations were using less than 50 percent of the capabilities available in their CMMS [42]. The system has to reflect the organizational needs and at the same time it must be in line with the organization's maturity in terms of technicality and culture. A fully functional system, which is in line with the needs of the organization, can bring several advantages such as increased productivity, effective utilization of resources, better overview of operations and increased reliability [66].

A study among more than 600 maintenance departments distinguished six key functions that should be featured in every CMMS [47].

- Work order management
- Planning function
- Scheduling function
- Budget or cost function
- Spares management
- Key performance indicators

A survey conducted in 1985 showed that over 60 CMMSs were already on the market, and since then the number has been steadily rising [66]. Even though all these systems aim at providing similar functions regarding maintenance they differ in various aspects. Organizations therefore face a tough task in choosing appropriate vendor that suits their needs. When selecting a CMMS several factors must be kept in mind to ensure a successful implementation [54, 65, 67]:

- Functional requirements
- Fit the needs of the organization
- Adaptability of the system
- Ease of use
- Management support
- Low Learning Curve
- A Defined Maintenance work process

The choice must be made wisely since the implementation process is costly and time consuming. This fact creates some kind of lock-in effects for customers, which are not willing to jump back and forth between systems.

2.10 Summary

Maintenance procedures of geothermal power plants have to be derived from the organization's strategy in order to fulfill the stakeholder's interests. Various factors affect the demand on how geothermal power plants should be operated. Maintenance management is the cornerstone in satisfying these needs and the managers must be in the front line in leading improvement efforts in the field. Performance indicators provide great possibilities in keeping track of maintenance performance. In order to get hold of these possibilities the system must be structured wholly and in accordance with the organization's strategy. Leading indicators should be used to spot areas of improvement, and they have to be presented in a clear way for the end user.

Next chapter takes on the state of the art of maintenance performance measurements in Iceland.

3 State of the art in Iceland

This chapter provides a description of the organizations studied and an assessment of their current work procedures and how maintenance performance indicators are utilized. Three companies operate geothermal power plants in Iceland; Landsvirkjun, Reykjavík Energy, and HS Orka. They operate a total of six geothermal power plants and all of these companies were studied in this thesis. In order to obtain knowledge of the current status, interviews were conducted with employers in all the above-mentioned companies. In addition an interview was conducted with the managing director of DMM solutions, and therefore it is considered that all parties concerned were taken into account. Choice of interviewees was based on their experience and insight, as well as their responsibilities in the field. The interviews were in a non-structured way with open discussions offering both qualitative and quantitative analysis.

Icelanders have been considered a role model in the development of geothermal utilization. Iceland generates 99 percent of its energy from renewable hydroelectric and geothermal sources. The total installed capacity of geothermal energy in Iceland is 575 MWe [68]. The development of the geothermal industry can be seen in Figure 13. Note that Húsavík, which is labeled number 5, is not in operation anymore.

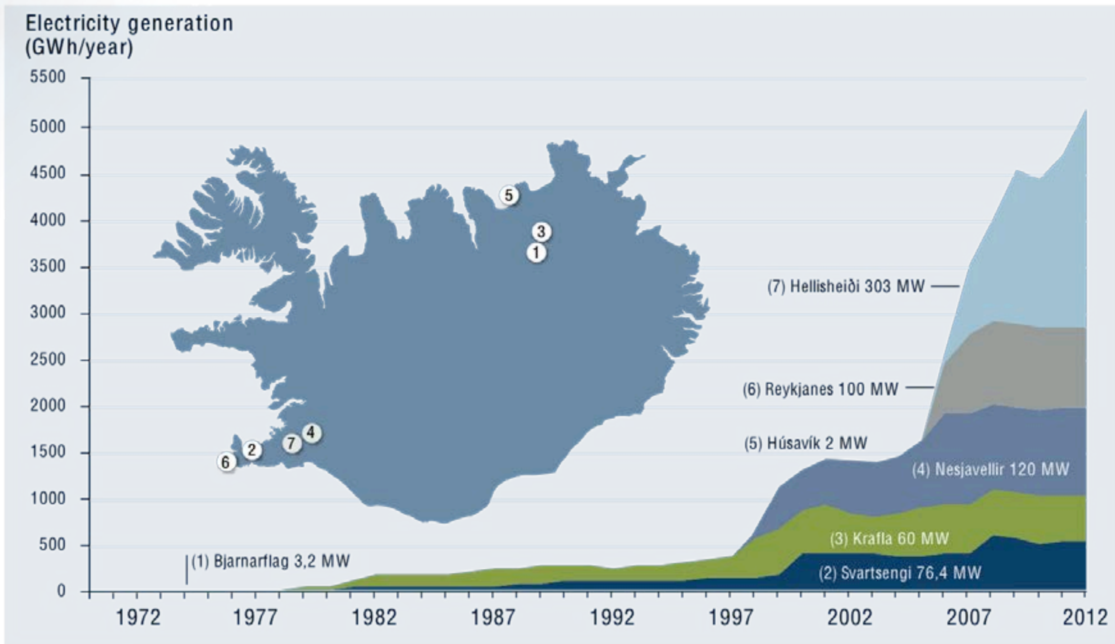

Figure 13 Geothermal electricity generation in Iceland [68].

3.1 The DMM system

All the geothermal power plant operators studied in this thesis use the same CMMS. The system is called Dynamic maintenance management system (DMM) and is developed by DMM Solutions. Development of DMM started in 1993 when the need for maintence activities increased in Svartsengi power plant, which is operated by HS Orka [69]. Prior to the computerization, maintenance activities had been managed with index cards, which is a manual paper storing system. The increased maintenance activities demanded a more sophisticated maintenance management system and the search for a computerized system began. Overa a dozen of CMMSs were considered, non of which were considered fulfilling the specific demands of geothermal power plants. This was for instance corrosion, scaling and especially learning from history to maintain the knowledge aquired. In addition, the setup was mainly in the form of checklists, which did not identify with the needs of the organization. A decision was therefore made to start development of a computerized maintenance management system within the organization in a collaboration with programmers in Iceland. From the beginning has the system been built from the bottom up, with the needs and demands of the mechanics in foreground [69]. This approach was adverse to most of the other systems available.

DMM is partially owned by all the organizations considered in this thesis and they form the customer base of DMM along with their associate companies and others in the energy sector. Only four customers of DMM are outside of the energy sector. Therefore a close relationship is between the clients and the supplier and this relationship has influenced the shaping of DMM [65]. One of the main strengths of DMM Solutions is in deed its proximity to its clients and how development of the system is focused on the specific needs of the energy sector. DMM strives for being ahead of its customers by offering them solutions they expect will come in handy. However, there is usually a great collaboration between DMM and its customers regarding development and which features would be appreciated or what could be improved in the system.

Programming of the system is arranged in such a manner that only one version is available to all customers. This version is then customized to the needs of each organization by switching on or off available features. Every year new modules or new main features are added to the system and current modules continuously improved based on feedback from users and new available IT techniques. Updates of the system are usually carried out annually at the end of the year or at the beginning of a new year, following a testing period in October and November. The development process is intertwined to the customer demands, with regular communication and meetings with customers. Such an approach ensures that the customers' demands are in foreground [69]. The success of DMM can therefore be considered as a result of the collaboration of the developer and the customers.

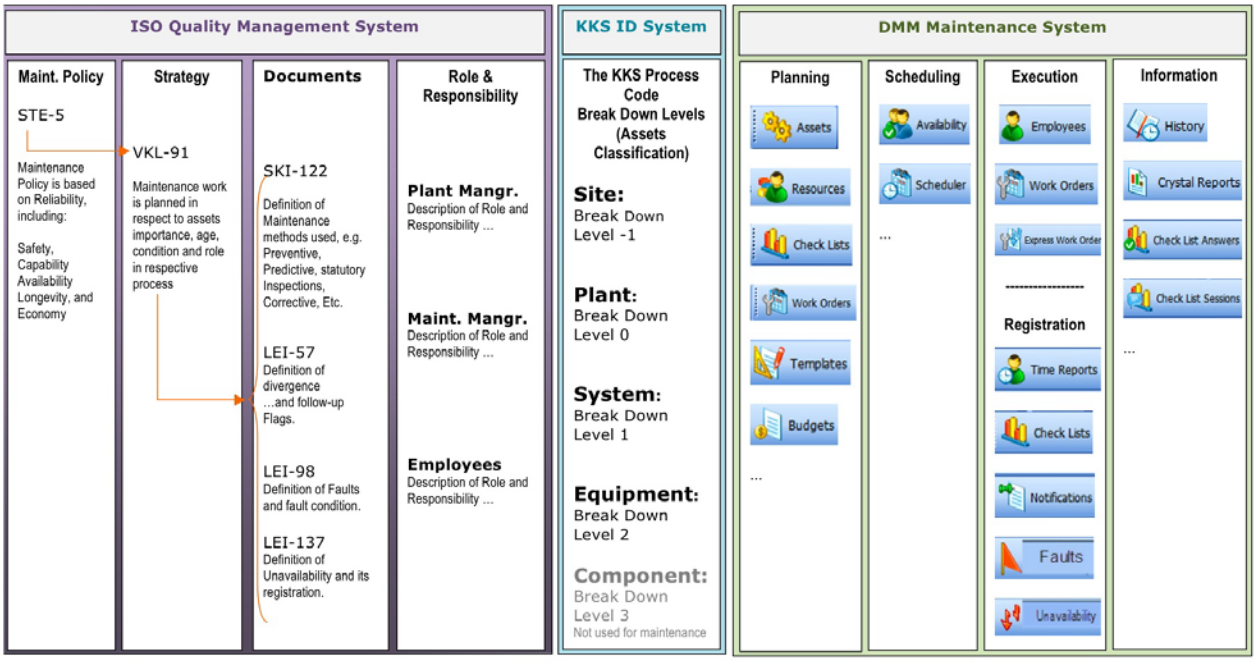

Figure 14 Structure of the DMM system at Landsvirkjun [33].

Plant numbering system must be integrated in the CMMS in order to control assets according to their hierarchical statue. All the Icelandic power plant operators studied in this thesis use the Kraftwerk Kennzeichen System (KKS) for coding all plant systems in DMM. The system was developed in Germany for power plants and therefore fits well to geothermal power plant operations. The advantage of the KKS is that it offers standardization of the coding, and information can therefore be moved more easily between systems or companies. Figure 15 shows the hierarchical structure of the KKS code. The component level is rarely used in DMM by any of the organizations, since the approach has been taken to place registrations on the equipment level. Doing this is much simpler for employees, but on the down side is that it doesn't provide for as detailed information processing.

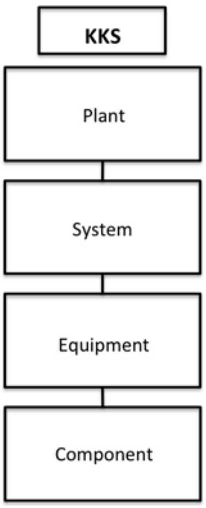

Figure 15 Hierarchical structure of the KKS code.

DMM plays an important role in monitoring maintenance performance in the Icelandic geothermal power plants, since it is the medium used for most data registration that directly falls under maintenance. Even though the system is regarded as a CMMS, it has been expanding in recent years towards becoming an enterprise asset management system (EAM). The boundaries between those two are not clear, but additions to DMM such as a comprehensive system for inventory, human resources and partially accounting have moved it closer to becoming an EAM [65]. This integration of new functions has progressed slowly in accordance with the customers' wishes and will probably end up as an EAM. The system is however programmed around work orders and assets, with the main objective to allow easy access to these and their respective maintenance history.

Work orders are used for registering all maintenance activities in the system and they are usually connected to assets. One of the main advantages of DMM is how it allows for viewing the maintenance history of assets. This information comes in handy when deviations occur and maintenance managers can go through the history of the equipment to figure out how to fix it or what went wrong in the first place. Standardized job descriptions are made for most routine maintenance activities to ensure standardize procedures. These job descriptions usually include as well estimations of human resources necessary and the use of spares. Once maintenance activities have been carried out, the outcomes are usually registered through work order reports or checklists. Checklists are used for various purposes such as for inspections, failure detection and condition assessments. To highlight any deviations detected during inspections or maintenance or repairs, flags are entered to the system. Many types of flags exist but the main purpose behind them is to create a single source of all deviations, which can be directed to maintenance managers in a simple manner. The manager can then take appropriate action by creating a relevant work order in response to the flag and assigning it to employees. Most types of flags include a checklist for the specific incident being flagged, and checklists can as well automatically create flags if any defection is detected in the registrations. A typical checklist for unavailability incudes for instance duration, whether it was scheduled, any harm caused, cause of unavailability and how it was fixed. Other types of checklists are used for inspections and measurements. Utilizing checklists offers an easy access to information gathered and numerical processing is easily achieved. The advantages of checklists include how easy it is to access information that the list has been designed to capture and the fact that errors are more harder to make than in normal blanks. On the downside is how registrations can become un-efficient when different information needs to be entered to the work orders and how specific they have to be.

A lot of work orders are allotted to routine work, but they can also be made in response with flags made in the system. These flags can be a response to; an inspection that has shown that maintenance is required, failure has taken place, or when maintenance work cannot be finished due to insufficient resources. The managers are responsible for defining the work orders in appropriate way and they are also responsible for approving finished work orders. Access control is used to make sure that only managers can add such work orders and assign them to other employees. This reduces the risk of wrong registrations by assigning clear responsibilities, which is in line with laws on responsibilities of management. However, big amount of defective registrations slide through the system, when shop floor workers don't fulfill their registration obligations, but the responsibility is still on the manager's side to make sure right information is registered.

Development of maintenance performance indicators within DMM has been an ongoing process for the past few years. This has both been due to requests from customers, but also in an effort of DMM solutions in being ahead of their customer needs by following the trends in maintenance management. Standards and workshops on the issue have been used as a basis for performance indicators work in addition to the customers' wishes. The most easily accessible data from basic registrations were among the first to be extracted to form performance indicators. This is for instance time and duration of work orders processed and information, which have been chosen as being of concern when flags are created. The checklists play an important role here, since they can be tailored to acquire all information that is considered important for each type of flag.

Dashboards are one of the methods that have been chosen for presenting performance indicators within the system. This method has been developed and offered to the customers. Behind each dial in the dashboard is a group of indicators that have been compiled into one single number on the scale 0 – 10. The underlying indicators can be given a different weight for the calculations, dependent on their importance. The dashboard gives a clear view of the processes, but they have however, not been developed for others than operations managers. It comprises of leading and lagging indicators that allow for immediate intervention when abnormal values appear along with providing overview of the business in general. DMM Solutions have just recently introduced the dashboard to their customers and it is based on one up to eight dials showing the key performance indicators, each with one to seven underlying indicators. Each of the eight indicators has to be customized for each organization based on its current status and goals. Because each dial may be comprised of several indicators there is a need that the managers understand the meaning of each dial in order to being able to use the dashboard for improvement purposes [65].

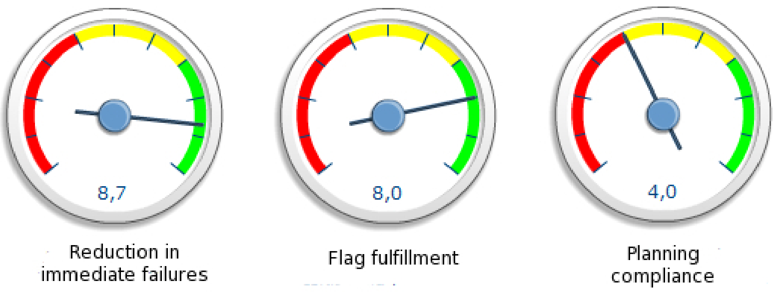

Figure 16 Part of the dashboard within the DMM system at Landsvirkjun [33].

Another useful method to present performance indicators in DMM is through so-called crystal reports, which can be defined based on any available data in the system. Such a report can for example take into account the unavailability of systems or components, comparison of estimated and available uptime and work order compliance. This report has been used by both maintenance managers and other managers in the organizations, but is still under development. One of the newest functions presented to the system is the use of GANTT charts to show work order compliance in real time. This is truly a leading indicator placed directly in front of the maintenance manager and shows whether work orders are being processed on time and within time limits. The advantage of offering such a chart within DMM is the possibility it provides to directly examine the work orders that are overdue in order to take appropriate actions.

3.2 Landsvirkjun

Landsvirkjun is the largest electrical producer in Iceland processing 75 percent of all electricity used in the country [70]. They operate 15 power stations in Iceland spread far and wide at 5 sites. Landsvirkjun operates two geothermal power plants; Bjarnarflag and Krafla which are both located in the North of Iceland. Bjarnarflag was the first of its kind in the country when it started its operations in 1969 with an installed capacity of 3 MWe, providing steam for industrial use and to the local district heating system. Krafla operates two 30 MWe turbines built in separate phases, the first started in 1977 and the second one in 1997.

Landsvirkjun owns and operates 15 power stations at 5 sites. The power plants are managed by the energy division, which is governed by the headquarters in Reykjavík. Each site is manned adequately to operate and provide the bulk of maintenance work. In general, maintenance is divided into 1st, 2nd, and 3rd line maintenance, including the functions outlined in Figure 17. Role of the maintenance manager is to manage 1st and 2nd line maintenance as well as contributing to 3rd line activities. Larger maintenance work which requires shut down, as is the case with 3rd line maintenance, is decided and planned for by centralized in-house departments that also provide any additional workforce, as required, by hiring contractors [33].

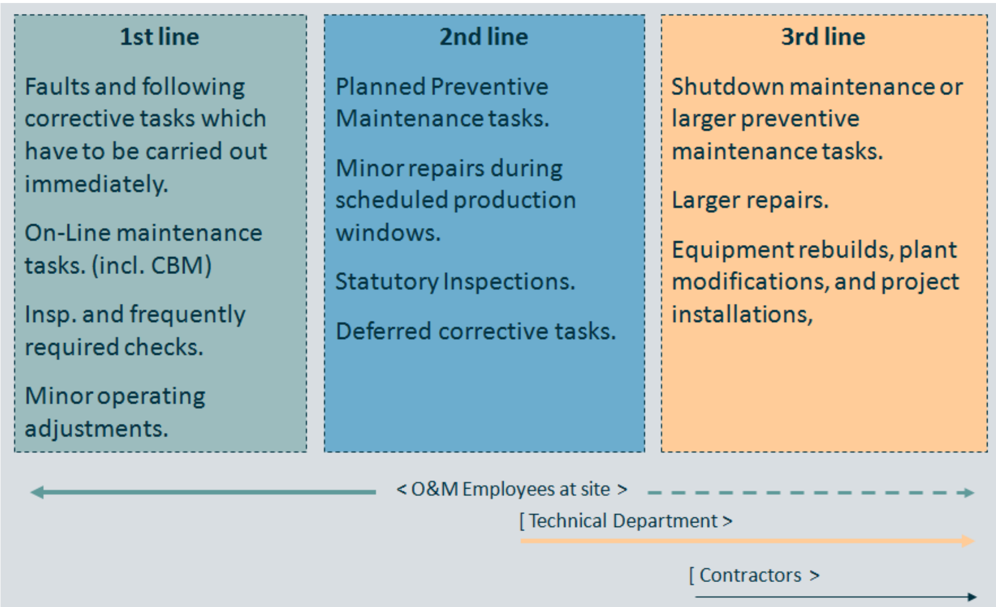

Figure 17 Lines of maintenance at Landsvirkjun, where the 1st line takes care of most routine work and is cooperates with the 2nd line in planned preventive maintenance tasks. The third line represent the outscourced jobs.

A decision was made by the company in 2001 to replace the former maintenance management system, an ERP system, with a new one: DMM, a CMMS system, the implementation of which was completed in 2003. Since then the system has been continuously improved and user skills have been developed in order to utilise it effectively. The organization has successfully completed the implementation of several standard certifications, such as the ISO 9001: Quality Management, ISO 14001: Environmental Management, and OHSAS 18001: Safety Management. Standardised processes support the data registration within DMM and the organization should therefore be better prepared to process performance indicators. Since then the system has been continuously improved and user skills have been developed in order to utilise it effectively. The organization has successfully completed the implementation of several standard certifications, such as the ISO 9001: Quality Management, ISO 14001: Environmental Management, and OHSAS 18001: Safety Management. Standardised processes support the data registration within DMM and the organization should therefore be better prepared to process performance indicators.

The DMM System has been successfully developed and works effectively with other systems within the Company. The system meets Landsvirkjun's needs within this sector although the conditions and procedures for each area may differ. Blanda Power Station is for instance far more developed than the geothermal power plants (GPP), the reason for which can be found in the fact that the maintenance procedures and the equipment in the GPPs differ from those in hydropower stations. The areas differ according to size and importance and processing methods hydro versus geothermal. Other factors include the location of the area with regard to access to services and in the case of hydropower stations, the nature of the water resource can also have an affect; glacial or bedrock. This is similar to the different challenges faced with the chemical composition of the working fluid. Another factor is also the willingness of employees to familiarise themselves with the solutions offered by the maintenance system. These include: XX

- The percentage of pre-planned projects.
- The detail with which projects are planned.
- The quality of the registration process, which is then utilised within the DMM system.

Availability calculations and the prioritisation of equipment has been a concern at Landsvirkjun and they have developed an advanced system for prioritising equipment and work types in DMM. The SCALE model is used in defining reliability and in the calculations of availability. One assumption is used regarding the bathtub curve, which typically characterizes hardware failures. The assumption is made that components are always operated within their useful life, while infant mortality and end of life periods are neglected.

DMM includes fully integrated spare parts registration and management and inventories to a degree. The stage of development differs between Landsvirkjun's power plants and some have taken full advantage of the material management function. This is however not the case in the GPPs where inventories are only partially registered into DMM, which provides little opportunity for analysis in the current form. These functions will eventually be made available to all sites. Employees register all their maintenance hours directly into DMM, which then exports the information to the accounting system. This approach simplifies all registrations in addition to providing the possibility of using the information to improve on planning accuracy in the future. By connecting cost figures to the man-hours, cost estimations become more clear and maintenance budget can be made based on more detailed numerical analysis. Cost figures are however merely used in DMM at Landsvirkjun for now. Reykjavík Energy is currently working on a similar working hours registration project with DMM Solutions.

Use of performance indicators for management purposes is mainly in the form of the crystal report being reviewed at weekly staff meetings where the failure and availability development of the past week is considered. However, this does not provide a direct solution but procedures are in place to act on deviations and to promote continuous improvements. This process could be improved by preparing more focused procedures to outline the deviations detected by measurements. The development of dashboards was initiated at DMM due to a request from Landsvirkjun. Dashboards have now been implemented into their system but this is still at the development level, where employees are familiarising themselves with the system and the company is deciding upon acceptable limits for their performance.

Up until now, Benchmarking has only been in the form of internal benchmarks, where the organisation has been developing their performance monitoring system and finding their base level. There are no plans in the near future to conduct an external benchmarking assessment, even though Landsvirkjun participates in a Nordic O&M benchmarking collaboration. This benchmarking group offers limited analysis of the indicators and lack of common definition of maintenance is evident [33]. However, this scene will probably provide them with the basis they need once they start their journey of benchmarking.

Table 3.1 Overview of maintenance performance indicators at Landsvirkjun.

	Possibility of monitoring indicator	Indicator monitored
Preventive and predictive maintenance		
System and equipment availability		
Component and system availability	✓	✓
Number of forced power reductions or outages because of maintenance causes	✓	✓
Total downtime	✓	✓
Scheduled downtime	✓	✓
Unscheduled downtime	✓	✓
Mean time between maintenance (MTBM)	✓	✓
Total Opertating time	✓	✓
Achieved up time during required time	✓	✓
Forced power reductions		
Number of forced power reductions and outages due to internal causes	✓	✓
Number of forced power reductions and outages due to external causes	✓	✓
Reliability of systems and components		
Number of corrective work orders issued	✓	✓
Mean time between failures	✓	✓
Mean time to repair (MTTR)	✓	✓
PM effectiveness		
Preventive maintenance compliance	✓	✓
Ratio of corrective work resulted from PM activities	✓	✗
PM work order backlog trend	✓	✓
Ratio of PM activities to all maintenance activities	✓	✓
Overdue of PM activities	✓	✓
Maintenance management		
Planning and scheduling		
Ratio of unplanned to planned working orders	✓	✓
Planning compliance	✓	✓
Schedule compliance	✓	✓
Ratio of corrective work orders executed to work orders programmed	✓	✓
Number of outstanding backlogs (urgent orders)	✓	✓
Planner to craft ratio	✓	✗
Work control		
Duration of repair	✓	✓
Repair time of components subject to technical specifications	✗	✗
Wrench time	✓	✗
Crew efficiency	✗	✗
Amount of maintenance rework	✗	✗
Supervision of craft worker ratio	✗	✗
Response time to call	✓	✗
Overtime maitnenance hours	✓	✓
Material management		
Stores service level	✗	✗
Number of works pending for spare parts	✗	✗
Stocks inventory turns	✗	✗
Stocked MRO inventory value as a percent of Replacement Asset Value (RAV)	✗	✗
Maintenance budget		
Cost effective maintenance		
Maintenance cost per kwh produced	✓	✗
Unplanned costs as percentage of total maintenance costs	✓	✗
Work orders completed within the determined costs (20%)	✓	✗
Preventive maintenance cost	✓	✓
Corrective maintenance cost	✓	✗
Annual mantenance cost as a percent of RAV	✗	✗
Total internal personnel cost spent in maintenance	✓	✗
Total contractor cost	✓	✗
Employee perspective		
Man hours used for continuous improvement	✓	✗
Training hours pr. Employee	✓	✓
Number of innovation carried out	✓	✓
Number of improvements suggested	✗	✗
Employee turnover rate	✓	✓
Employee satisfaction	✓	✓
Employee complaints	✓	✓
Health Safety and Environment perspective		
Number of failures due to maintenance creating environmental damage	✓	✓
Annual volume of wastes or harmful effects related to maintenance	✗	✗
Amount of rework	✗	✗
Number of failures causing damage to the environment	✓	✓
Number of injuries for people due to maintenance	✓	✓
Physical working environment	✓	✓
Workplace noise level	✓	✗
Number of failures causing injury to people	✓	✓
Number of failures causing potential injury to people	✓	✗
Safety attitude of employees	✗	✗

3.3 Reykjavík Energy

The history of Reykjavík Energy can be traced back to 1909 with the establishment of waterworks in Reykjavík. The first power plant, the hydropower plant by Elliðaár, started operation in 1921 and district heating was started in 1930. Currently the company operates four power plants, two hydropower plants with an installed capacity of 12 MWe and two geothermal plants. The GPPs are at Nesjavellir and Hellisheiði, starting operation in 1990 and 2006 respectively. The installed capacity at Nesjavellir is 120 MWe and in Hellisheiði is the capacity 303 MWe, which makes it the largest geothermal power plant in Iceland. Hot water is produced at both the geothermal power plants with a combined capacity of 433 MWt [71].

The DMM system has been in constant development within the organization since it's implement over ten years ago. The organization has successfully finished implementation of several standard certifications, such as the ISO 9001: quality management, ISO 14001: environmental management, and OHSAS 18001: safety management, which are the same standards as Landsvirkjun has adapted. The operation manager governs O&M of the two GPPs and centralized management takes place at Hellisheiði, where the maintenance manager is located for the GPPs. Maintenance teams are positioned at both locations, which carry out most of the maintenance operations.

Work procedures at Reykjavík Energy are well developed, which can be seen from their information handling, planning and follow-up on work orders. They have been improving on a systematic use of checklists and flags for the past few years, but checklists are currently only used for measurements and flags. Meantime between failures is considered as an important registration, and therefore a special checklist is in place for unavailability. Errors tend to slide into the system, such as registrations on wrong assets or date, but human resources are not sufficient to keeping up with all the entries.

The crystal report is the pillar in their registrations, where availability is for instance calculated and it takes both into account preventive and corrective maintenance. These reports are used in weekly meetings to review the last few weeks. Since they have only recently begun using these reports, employees have not obtained a deep understanding of how the figures work. Therefore they try to focus only on few indicators at each meeting while they are learning to apply the report. Therefore it can be hard for them to use the information to improve on the shown figures, but it is all a question about taking the time to get to know the indicators. Dashboards are also a part of their system and are placed in front of the maintenance managers. The dashboard came as a part of a recent update from DMM, and therefore they have not started to dig deep into the dials to use the dashboard. No written processes are in place to follow when underperformance is discovered in the crystal report or on the dashboard, but rather the maintenance manager must decide whether he will intervene and then how.

The opportunities in DMM to organize maintenance activities are not fully utilized, but an improvement work has begun in this field [33]. Material management is partially integrated into DMM since supplies are not registered to work orders when they leave the warehouse. Their future vision is that all spare parts will be directly linked into the system. Such an approach will give better overview of current inventory status and help in inventory reduction.

Reykjavík Energy is currently working on a few years long project with DMM Solutions in order to register all maintenance hours directly into the system and overall improving maintenance management within the organization. It includes for example estimated working hours, actual working time, and cost for each employee. The information will then be extracted directly to their accounting system. This will become of great advantage with regard to accounting in the company, since employees now have to make double registrations of their working hours. One of the opportunities that this will provide is to use the information acquired to better monitor their planning compliance. An assessment made on the use of maintenance performance indicators at Reykjavík Energy can be seen in Table 3.2. Similar to Landsvirkjun, availability and reliability registrations are well monitored at Reykjavík Energy. The planning and scheduling compliance and pm effectiveness are already partially monitored, but improvements in these areas are in progress through the ongoing registration project. Cost effectiveness is currently not monitored and the same goes for material management. Both of these aspects are however, included in future plans of improved registrations.

Table 3.2 Overview of maintenance performance indicators used at Reykjavík Energy.

	Possibility of monitoring indicator	Indicator monitored
Preventive and predictive maintenance		
System and equipment availability		
Component and system availability	✓	✓
Number of forced power reductions or outages because of maintenance causes	✓	✓
Total downtime	✓	✓
Scheduled downtime	✓	✓
Unscheduled downtime	✓	✓
Mean time between maintenance (MTBM)	✓	✓
Total Opertating time	✓	✓
Achieved up time during required time	✓	✓
Forced power reductions		
Number of forced power reductions and outages due to internal causes	✓	✓
Number of forced power reductions and outages due to external causes	✓	✓
Reliability of systems and components		
Number of corrective work orders issued	✓	✓
Mean time between failures	✓	✓
Mean time to repair (MTTR)	✓	✓
PM effectiveness		
Preventive maintenance compliance	✓	✗
Ratio of corrective work resulted from PM activities	✗	✗
PM work order backlog trend	✓	✓
Ratio of PM activities to all maintenance activities	✓	✗
Overdue of PM activities	✓	✗
Maintenance management		
Planning and scheduling		
Ratio of unplanned to planned working orders	✗	✗
Planning compliance	✗	✗
Schedule compliance	✓	✓
Ratio of corrective work orders executed to work orders programmed	✗	✗
Number of outstanding backlogs (urgent orders)	✓	✓
Planner to craft ratio	✗	✗
Work control		
Duration of repair	✓	✓
Repair time of components subject to technical specifications	✗	✗
Wrench time	✓	✗
Crew efficiency	✓	✗
Amount of maintenance rework	✗	✗
Supervision of craft worker ratio	✗	✗
Response time to call	✗	✗
Overtime maitnenance hours	✗	✗
Material management		
Stores service level	✗	✗
Number of works pending for spare parts	✗	✗
Stocks inventory turns	✗	✗
Stocked MRO inventory value as a percent of Replacement asset value	✗	✗
Maintenance budget		
Cost effective maintenance		
Maintenance cost per kwh produced	✓	✗
Unplanned costs as percentage of total maintenance costs	✗	✗
Work orders completed within the determined costs (20%)	✓	✓
Preventive maintenance cost	✗	✗
Corrective maintenance cost	✗	✗
Annual mantenance cost as a percent of Replacement asset value	✗	✗
Total internal personnel cost spent in maintenance	✓	✓
Total contractor cost	✓	✓
Employee perspective		
Man hours used for continuous improvement	✓	✗
Training hours pr. Employee	✓	✓
Number of innovation carried out	✓	✓
Number of improvements suggested	✗	✗
Increase in teamwork	✗	✗
Employee turnover rate	✓	✓
Employee satisfaction	✓	✓
Employee complaints	✓	✓
Health Safety and Environment perspective		
Number of failures due to maintenance creating environmental damage	✓	✓
Annual volume of wastes or harmful effects related to maintenance	✗	✗
Amount of rework	✗	✗
Number of failures causing damage to the environment	✓	✓
Number of injuries for people due to maintenance	✓	✓
Physical working environment	✓	✓
Workplace noise level	✓	✗
Number of failures causing injury to people	✓	✓
Number of failures causing potential injury to people	✓	✗
Safety attitude of employees	✗	✗

3.4 HS Orka

All the municipalities in Suðurnes formally founded Heating Plant of Suðurnes in 1974 after decades of research of the geothermal resources in the area. The purpose was to utilize geothermal heat to build heat exchange plants and to connect the towns of Suðurnes to the system [72]. HS Orka is now a part of Alterra Power corp. which owns several renewable energy productions, with an total capacity of 616 MWe. HS Orka operates two geothermal power plants, Svartsengi and Reykjanes, producing both electrical energy and serving district heating. Svartsengi began hot water production in 1976 and electricity production started in 1980. Installed capacity of the power plant is 75 MWe and 150 MWt. Reykjanes power plant is only an electric energy plant and started its production in 2006. Current installed capacity is 100 MWe [73].

Development of DMM started within HS Orka, and the system has been in constant development since then. HS Orka on the other hand are quite smaller than the two other companies and resources for development are not comparable. Maintenance managers at HS Orka think DMM is fulfilling their current demands and little weight is put on performance measurements [74]. They have emphasized on historical traceability for assets and registering thoroughly all-major overhauls. These registrations are quite good and therefore they can easily trace the history of each system, which is what they have considered as most important. The organization’s employees are not too keen on changing unless they have a clear vision of the benefits that could result from the changes. This can be well understandable since they see no reason to change a system, which they believe is working well in its current form. An example of this is when the older mechanics refused to take computer lessons, but this is slowly changing with more forward thinking younger employees. It is well understandable that they have not laid emphasis on performance measurements in their operations. Like stated before, they are running their power plants on minimum resources, facing site-specific problems such as the sea salt, but still they are running the power plants quite smoothly. They have to prioritize their activities and understandably are performance indicators not in the foreground. They have up to now mainly been accepting the updates provided by DMM Solutions, which have included some form of performance indicators, but they have not been pursuing those. It is however important for them that they try to keep up with the advancements introduced to them, because otherwise this attitude may strike them from behind when competitors will be capable of taking full advantage of the possibilities offered by performance indicators.

Similar to the other organizations, are checklists mainly used for routine measurements and when flags are created. Downtimes and failures are of most concern for the maintenance managers and checklists are used in such cases. Maintenance managers are supposed to classify work orders into relevant groups, such as PM and CM, but tendency is to classify broad selection of maintenance work as corrective maintenance including many routine jobs or small adjustments. This skews the registrations and statistical processing becomes unreliable. The reason for this misalignment in registrations may be found in the fact that they have not gone as thoroughly through the job of clearly defining their maintenance approaches and plan as the other GPPs operators [69]. They have slowly been building up a database of work order descriptions, but a big amount of information still only exists in the head of the employees.

Material management is maintained within the accounting system and regular status checks are made on the inventory. This system has proven to be working well for them and they have no intention of changing their inventory system. No overview was however provided by HS Orka on which statistical methods are currently used to assess the inventory levels. Cost figures are limited used in their DMM [74]. Dashboard has been integrated to their DMM system as a part of the annual upgrade. The employees are still getting used to the system and understanding the indicators and therefore the dashboards have yet not been put into effect in HS Orka, but it is in the pipelines [74]. The crystal reports have on the other hand been taken into effect for several reporting types. The main visual presentation of leading indicators in their maintenance management is the GANTT chart, which was recently introduced to the system. This has proven to be a good addition to DMM, and gives the maintenance managers a better overview of the current status. In Table 3.3 is given an overview of maintenance performance indicators at HS Orka. These indicators are almost identical to the ones at Landsvirkjun and Reykjavík Energy. The main difference between HS Orka and the other two is lack of work control monitoring at HS Orka.

Table 3.3 Overview of maintenance performance indicators at HS Orka.

	Possibility of monitoring indicator	Indicator monitored
Preventive and predictive maintenance		
System and equipment availability		
Component and system availability	✓	✗
Number of forced power reductions or outages because of maintenance causes	✓	✓
Total downtime	✓	✓
Scheduled downtime	✓	✓
Unscheduled downtime	✓	✓
Mean time between maintenance (MTBM)	✓	✗
Total Opertating time	✓	✓
Achieved up time during required time	✓	✓
Forced power reductions		
Number of forced power reductions and outages due to internal causes	✓	✓
Number of forced power reductions and outages due to external causes	✓	✓
Reliability of systems and components		
Number of corrective work orders issued	✓	✓
Mean time between failures	✓	✓
Mean time to repair (MTTR)	✓	✓
PM effectiveness		
Preventive maintenance compliance	✓	✗
Ratio of corrective work resulted from PM activities	✗	✗
PM work order backlog trend	✓	✓
Ratio of PM activities to all maintenance activities	✗	✗
Overdue of PM activities	✗	✗
Maintenance management		
Planning and scheduling		
Ratio of unplanned to planned working orders	✗	✗
Planning compliance	✓	✓
Schedule compliance	✓	✓
Ratio of corrective work orders executed to work orders programmed	✗	✗
Number of outstanding backlogs (urgent orders)	✓	✓
Planner to craft ratio	✓	✗
Work control		
Duration of repair	✓	✓
Repair time of components subject to technical specifications	✗	✗
Wrench time	✗	✗
Crew efficiency	✗	✗
Amount of maintenance rework	✓	✓
Supervision of craft worker ratio	✗	✗
Response time to call	✗	✗
Overtime maitnenance hours	✓	✗
Material management		
Stores service level	✓	✓
Number of works pending for spare parts	✓	✓
Stocks inventory turns	✓	✓
Stocked MRO inventory value as a percent of Replacement asset value	✓	✗
Maintenance budget		
Cost effective maintenance		
Maintenance cost per kwh produced	✓	✗
Unplanned costs as percentage of total maintenance costs	✗	✗
Work orders completed within the determined costs (20%)	✓	✓
Preventive maintenance cost	✗	✗
Corrective maintenance cost	✗	✗
Annual mantenance cost as a percent of Replacement asset value	✗	✗
Total internal personnel cost spent in maintenance	✓	✓
Total contractor cost	✓	✓
Employee perspective		
Man hours used for continuous improvement	✓	✓
Training hours pr. Employee	✓	✓
Number of innovation carried out	✓	✓
Number of improvements suggested	✓	✗
Employee turnover rate	✓	✓
Employee satisfaction	✓	✓
Employee complaints	✓	✓
Health Safety and Environment perspective		
Number of failures due to maintenance creating environmental damage	✓	✓
Annual volume of wastes or harmful effects related to maintenance	✓	✓
Amount of rework	✓	✓
Number of failures causing damage to the environment	✓	✓
Number of injuries for people due to maintenance	✓	✓
Physical working environment	✓	✓
Workplace noise level	✓	✓
Number of failures causing injury to people	✓	✓
Number of failures causing potential injury to people	✓	✓
Safety attitude of employees	✗	✗

3.5 Summary

Historical traceability of components is important for all organizations and detailed reports are held for every major overhaul. On these aspects has the focus in the registrations been, which is in line with the structure of DMM. Employees have developed sophisticated work procedures, which have been shaped by the site-specific circumstances. The culture of the staff is well aligned with the strategy of the organizations and they are fully aware of what is expected from them. During the change initiatives for improved data registrations in recent years there is no sign of resistance among employees towards the change. This is in line with Theory O, where cooperation with employees is the key to develop human capability. All the organizations are taking a lot of time to develop and implement the performance measurement systems, which allows the employees to better adapt to the changes. By reviewing the four foundation stones of implementation of PIs as presented by Parmenter it can be seen that all of the foundations have been fully or at least partially fulfilled. The only aspect, which can only be considered as partially fulfilled is the integration of measurement, reporting and improvement of performance, which is still under development in all the organizations. These foundation stones should be considered as dynamic and in order to maintain the MPM system, the organization has to be constantly reviewing their procedures of performance monitoring.

The Icelandic geothermal power plants are heavily reliant upon their CMMS provider, DMM Solutions, in providing means for calculating performance indicators. The companies themselves can affect the product offer from DMM by pushing on for updates, but they can also develop performance indicators in-house. In order to be able to produce PIs several factors must be fulfilled. This includes a clear pathway of registration in such a manner that needed information can be easily extracted from the data and data quality. Among all the organizations is an issue with data quality, since errors can easily be spotted in their entries, which skews PIs and reduces the validity of given numbers.

Among all organizations is availability a big concern, with MTBF and MTTR calculated at each site. Big projects, such as overhauls of turbines, are also of concern and detailed reports are made on each project in order to learn from the job before the next one is taken on. Material management is not of big concern by any of the maintenance managers, even though inventories can amount for tens of millions of dollars in each organization. They all agree on that the system could be better used in optimizing human resources utilization, even though Landsvirkjun has implemented employee working hours into the system and Reykjavík Energy is undergoing the same changes. The organizations have different approaches towards maintenance management and DMM registrations. Table 3.4 gives information about the size and scale of each of the organizations in order to better understand these differences.

Even though no numerical assessment is made on the recorded performance indicators at the organizations it should be noted that many factors affect how they ‘score’ on the their performance indicators. The internal and external influencing factors play their role, which in return shapes the maintenance approaches. The amount of outsourced maintenance work, centralization of the maintenance team and maintenance capacity and resources all heavily influence the figures obtained for each organization. Even though some organizations would obtain a low score on some of these factors it does not mean that they are performing worse than the competitors. It only shows how the different approaches ‘badly’ affect the operation in one aspect, while a high amount of outsourcing would lead to a lower amount of tied up capital, which is usually not considered as a maintenance performance indicator. Establishing external benchmarks in the industry can for the same reasons be hard to accomplish without any adjustments or taking these factors into account. No benchmarks are presented for the maintenance function in this thesis and the reason is mainly because of how specific they are. Comparing different industries therefore only partially fulfills the needs of the organizations, and since the author of this thesis could not find any comprehensive benchmarking study for geothermal power plants, no benchmarks will be presented here. However, in Chapter 2.7 is a reference made to several sources of benchmarking databases for the maintenance function.

Table 3.4 The geothermal power plant operators in numbers based on their annual reports for the year 2012.

	Landsvirkjun	**Reykjavík Energy**	**HS Orka**
Installed capacity	1860 MWe	434 MWe	174 MWe
Thereof geothermal	63 MWe	423 MWe	174 MWe
Number of turbines	40	13	12
Geothermal turbines	3	11	12
Total employees	232	453	134 (75)
O&M staff in geothermal	13	36	25
Production in 2012	12486 Gwh	3503 Gwh	1316 Gwh

Cost has not been a big part of the DMM system and it is only used occasionally in the GPPs. The progress towards more detailed cost registrations has already begun at Reykjavík Energy and Landsvirkjun and cost figures will be a growing part of the data registrations for the next few years. The reasons can be found in the benefits it provides in estimation of maintenance budget and the support it provides to management. Maintenance budget can now only be seen in the annual reports of the organizations, where an estimate has been made for how much should be spent on maintenance. With the approach of including all cost figures into DMM, accurate estimations can be more easily achieved. Instead of the management board deciding how much they are willing to spend on maintenance each year, the maintenance managers could instead show it black and white how much it will cost to maintain the equipment for the next year in order to the most cost effective manner. As for now figures such as total maintenance cost, replacement asset value and average inventory value of maintenance materials are far out of reach of the organizations in the current system. Health, safety and environment are already monitored along with employee satisfaction, even though it is not restricted to the maintenance alone. The same adheres for the employees, for which the employee satisfaction is regularly surveyed.

Maintenance managers are loaded with responsibilities in all of the GPPs considered, where they are in the role of planning, scheduling, managing and improving. This is consistent with the leaders role as shown in Figure 5, where the leader is supposed to plan, organize, implement, and control. However, all the maintenance managers are drowning in responsibilities, and they often have a tough time keeping up with the demands on them. Therefore they often neglect the role of controlling since this role gets pushed behind when new tasks show up and gain all the attention of the manager. The role of controlling can be fragile for these reasons and in the smaller organizations where resources are limited, such as HS Orka, this role almost always gets left over. In order to gain any advantages from performance indicators it is necessary that someone has the responsibility of the controlling role and has the time and resources to step in and take action.

One of the most valuable assets of the organizations is the knowledge of their employees. At the same time they must be aware that the company can become too reliant upon their employees if their work procedures are not registered anywhere else than in the employee’s minds. They have this great tool available through DMM for building valuable databases on work order descriptions and common procedures. Hence they should use this tool to gather the information it is built to keep track of. The next chapter will provide an ideal maintenance performance measurement system for geothermal power plants.

4 Proposed MPM system

Several aspects have to be considered when formulating a maintenance performance measurement (MPM) system. First it should be stated that the system developed and presented here is shaped and affected by the opinions and knowledge level of the author. In order to being able to provide as comprehensive system as possible, measures were taken to consider the system from as many perspectives as possible. The maintenance managers are the ones who will be using the system the most and they are as well the ones that know the maintenance operations best. Therefore they are in a good position for deciding which indicators would come in handy in maintenance management. They may on the other hand be accustomed to the system as it currently is and therefore it can be hard for them see other possibilities than the ones already in use. To gain a broader overview of maintenance performance indicators in the process of formulating a MPM system, the standard ÍST EN 15341 – Maintenance key performance indicators was considered as a primary source for formulating performance indicators [59]. When several sources provided similar definitions of the same indicator, the definition provided in the standard was chosen for the proposed system. The reason for that is because by using a single definition, which is made for producing universal indicators, comparison between organizations becomes more easily achieved. A big portion of the chosen indicators is also presented in Global Maintenance and Reliability Indicators published through the collaborative work of the European Federation of National Maintenance Societies and the Society for Maintenance and Reliability professionals [75]. There are harmonized indicators between the two organization presented and explained to allow for a more simple implementation. These explanations are used to provide a better understanding of each indicator. The author of this thesis did not find any published work with a holistic set of maintenance performance indicators for geothermal power plants. The study that comes closest to the field of GPPs is a report for nuclear power plants (NPP) led by the European Commission's Joint Research Centre. The report is named Monitoring the effectiveness of maintenance programs trough the use of performance indicators and was conducted under the network of Safety of Eastern European Type Nuclear Facilities (SENUF) [58]. Since safety issues are of big concern in NPPs therefore the focus of the report mainly taken from the safety perspective. The system proposed by SENUF is however, comprehensive and covers as well most of the aspects of concern in GPPs. Furthermore, the work of Smith and Mobley and the Physical Asset Management Handbook by John Mitchell included a comprehensive MPM system for the maintenance function, and therefore they were taken into account as well to obtain an even broader perspective to the matter at hand [8, 49].

Most of the sources are unanimous about the importance of dividing the maintenance performance measurement system into hierarchical level, which represent the hierarchical structure of the organizations at hand [49, 58, 59]. Three hierarchical levels were chosen to represent the levels of the GPPs, and they are strategic/organizational level, tactical/managerial level, and functional/operational level.

Within each hierarchical level are indicators classified into relevant areas. Based on the literature and the operational context of the organizations, five areas were considered as essential. To represent all the important aspects of maintenance in geothermal power plant was the SCALE model taken into account, where Safety, Capability, Availability, Longevity, and Economy all affect the reliability of the plant. The perspectives chosen based on these sources are cost effectiveness and productivity to support an economic operation of the organization, quality perspective to fulfill the demands of the customer, and then HSE and employee perspectives to support the foundation of the organization in respect to the employees, environment and the community. The perspectives are listed below.

- Cost Effectiveness Perspective
- Quality Perspective
- Productivity Perspective
- Health Safety and Environment perspective
- Employee Perspective

The respective performance indicators within each group can be seen in Table 4.1 – Table 4.5 and each table is followed by a brief description for each of the indicators. A mixture of leading and lagging indicators is used at the tactical and functional level, while the strategic level is mainly based on lagging indicators. The SMART test is used for all the indicators chosen, since they should all be specific, measureable, attainable, realistic and timely. The letter and number to the far left in the tables indicate a made-up coding system for the indicators based on their perspective name and rank. When applicable, the respective indicator number of from the ÍST EN 15341 standard is provided in brackets behind each indicator. Note that the numbering system in the standard is only as a means of identification, not to indicate importance or ranking.

The idea behind this proposed system is not to overturn the current MPM systems at the GPPs, but moreover to support the work already taking place. Therefore a progress will be gained towards this system, by constantly improve the current system with a regular integration of new performance indicators. A total overturn of the current system would not serve any purposes, since it is now fulfilling most of the customer demands and changes are always tough on employees, especially when they have to abandon usual work procedures. This is therefore only a question of how each organization is willing to integrate this system into their procedures.

Table 4.1 The cost effectiveness perspective.

Levels:	**Strategic**	**Tactical**	**Functional**
CE1	Total maintenance cost (E1)		
CE2	Maintenance cost/kwh produced (E3)		
CE11		Total contractor cost (E10)	
CE12		Total cost of maintenance materials (E11)	
CE13		Total internal personnel cost spent in maintenance (E8)	
CE111			Corrective maintenance cost (E15)
CE112			Preventive maintenance cost (E16)

CE1. This indicator gives a good assessment of the value created by maintenance and the equation for this indicator is $E1\colon \frac{Total\ maintenance\ cost}{Asset\ replacement\ value} * 100\%$. The "best in class" organizations spend less maintaining their assets, even though they achieve high reliability and asset utilization. This indicator provides valuable information for both maintenance managers as well as board members and should be reviewed quarterly. It should be considered as the cornerstone of justifying maintenance expenditure. Asset replacement value is the dollar value that would be required to replace the production capability of the present assets in the plant. Total maintenance cost is the total expenditures for maintenance labor, materials, contractors, services and resources.

CE2. This indicator is both clear and understandable for everyone concerned, whether it is board member or shop floor worker. This figure can be easily evaluated in comparison with the value of the end product, the electricity. The equation is $E3{:}\,\frac{Total\ maintenance\ cost}{Quantitiy\ of\ output} * 100\%$ and it should be reviewed annually or quarterly by maintenance managers, board members and accounting personnel.

CE11. This indicator gives an assessment of how big portion of the total maintenance cost is due to hired contractors. By using this indicator, managers can more easily see how well the current maintenance policy in terms of outsourcing is working. Calculated as $E10{:}\,\frac{Total\ contractor\ cost}{Total\ maintenance\ cost} * 100\%$ and it should be reviewed monthly by maintenance or plant managers.

CE12. This is the total cost incurred for materials needed to maintain, repair and operate the plant's assets. The equation is $E11{:}\,\frac{Total\ cost\ of\ maintenance\ materails}{Total\ maintenance\ cost} * 100\%$ and it should be calculated monthly and reviewed by maintenance managers. This indicator should be analyzed in consideration with other dimensions of maintenance spending to spot possible areas of improvement.

CE13. This indicator should be reviewed and compared to the total contractor cost, since these two indicators sum up the total personnel cost of maintenance. This cost is much more fixed in the operation compared to the contractor cost, and this aspect should be considered when this indicator is reviewed. It is calculated as $E8{:}\,\frac{Total\ internal\ personnel\ cost\ spent\ in\ maintenance}{Total\ maintenance\ cost} * 100\%$ and should be reviewed monthly or quarterly by plant/maintenance manager.

CE111. The amount of corrective maintenance cost should be considered in terms of the chosen maintenance strategy and this indicator is a good sign of whether the strategy is working out. It is calculated as $E15{:}\,\frac{Corrective\ maintenance\ cost}{Total\ maintenance\ cost} * 100\%$ and gives an evaluation of the effectiveness of preventive maintenance. Maintenance mangers should review it monthly.

CE112. This indicator should be considered in terms of the corrective maintenance cost and together they provide an evaluation of the effectiveness of preventive maintenance. It should be calculated on a monthly basis by maintenance managers, $E16{:}\,\frac{Preventive\ maintenance\ cost}{Total\ maintenance\ cost} * 100\%$.

Table 4.2 The quality perspective.

Levels:	Strategic	Tactical	Functional
Q1	Total operating time (T1)		
Q2	Achieved up time during required time (T2)		
Q11		Total operating time (T6)	
Q111			MTBF (T17)
Q112			MTTR (T21)
Q113			Total operating time (T15)
Q114			Number of failures

The quality perspective focuses on the capability of the plant in delivering on their promises and guarantees. Therefore is the customer needs in foreground, which should in fact be the most important influencing factor in the operations and considered as a critical success factor.

Q1 and Q11. Gives management a good overview of the plant's availability related to maintenance. It is calculated by $T1: \frac{Total\ operating\ time}{Total\ operating\ time + Downtime\ due\ to\ maintenance} * 100\%$ and should be reviewed weekly by the maintenance manager.

Q2. This indicator is called operational availability and should be and should be reviewed weekly by the maintenance manager, but quarterly or annually by the board or management. It gives an assessment whether targets are met in the planning and operation. Calculated as $T2: \frac{Achieved\ up\ time\ during\ required\ time}{Required\ time} * 100\%$.

Q111. One of the most widely used indicators for monitoring maintenance performance of repairable assets or components. By trending the value gained through the indicator, the asset reliability can be obtained for critical components. Calculated as $T17: \frac{Total\ operating\ time}{Number\ of\ failures} = MTBF$ and review rate is equipment dependent. It should be used at either asset or component level. Root cause failure analysis or failure mode and effects analysis should be used to identify opportunities to improve reliability if mean time between failures is low for a component.

Q112. Mean time to repair is the average time needed to restore an asset to its full operational capabilities after a failure. This is a measure of asset maintainability, expressing the probability that a machine can be restored to each required state within a specified interval of time. Calculated as $T21: \frac{Total\ time\ to\ restoration}{Number\ of\ failures} = MTTR$ and should be monthly and reviewed by maintenance mangers.

Q113. This indicator takes into account the amount of incidents causing downtime in the operation and calculated as $T15: \frac{Total\ operating\ time}{Number\ of\ maintenance\ work\ orders\ causing\ downtime} * 100\%$.

Q114. The amount of failures gives an indication of the preventive maintenance effectiveness and should be considered in comparison with the immediate corrective maintenance indicator. The reason is that because

Table 4.3 The productivity perspective.

Levels:	**Strategic**	**Tactical**	**Functional**
P1	Maintenance efficiency		
P11		Percentage of planned maintenance (O5)	
P111			Percentage of unplanned maintenance (O16)
P112			Immediate corrective maintenance man-hours (O11)
P113			Number of work orders performed as scheduled (O21)
P114			Amount of rework
P115			Response time for maintenance
P116			Backlog of maintenance activities
P117			Overtime (O21)
P118			Planning compliance

The productivity perspective focuses on the internal capabilities of the plant in terms of maintenance planning and execution. Ensuring both efficient and effective maintenance operations will eventually reduce maintenance costs and improve reliability.

P1. The maintenance efficiency can be assessed through the overall equipment effectiveness (OEE) factor, which takes into account several aspects of the maintenance function. It is calculated as

$$OEE = (Availability) * (Performance\ rate) * (Quality\ rate)$$

Where the availability is given by Q1, the performance rate taking into account minor stoppages, idling losses and reduced output losses, and the quality rate takes into account rework and startup losses.

P11. The amount of planned maintenance should be as high as reasonably possible and as well aligned with the maintenance policy. A higher percentage here means that emergency maintenance is directly reduced. The objective is to minimize critical equipment failures. The indicator is calculated as $O5\colon \frac{Planned\ and\ scheduled\ man\ hours}{Total\ maintenance\ man\ hours\ available} * 100\%$ and should be reviewed monthly by maintenance managers.

P111. The corrective maintenance has to be considered along with the preventive man-hours along, but also the immediate corrective man-hours. The reason is that the amount of corrective maintenance alone does not indicate the effectiveness of the maintenance procedures. Nevertheless it does provide a means of better planning and scheduling the maintenance activities. Calculated as $O16\colon \frac{Corrective\ maintenance\ man\ hours}{Total\ maintenance\ man\ hours} * 100\%$ and should be reviewed monthly.

P112. One of the most important indicators, since immediate corrective maintenance is one of the most costly activities in the operations and should be actively monitored to minimize the amount of such work. Gives a clear indication of the effectiveness of the preventive maintenance activities and should be reviewed weekly by plant and maintenance managers. Calculated as $O11\colon \frac{Immediate\ corrective\ maintenance\ time}{Total\ downtime\ related\ to\ maintenance} * 100\%$.

P113. The schedule compliance is a measure of adherence to the weekly maintenance work schedule expressed as a percent of total number of scheduled work orders, and reflects the effectiveness of the work scheduling process. Should be reviewed weekly and is calculated as $O22\colon \frac{Number\ of\ work\ orders\ performed\ as\ scheduled}{Total\ number\ of\ scheduled\ work\ orders} * 100\%$.

P114. The amount of rework is a clear indicator of maintenance effectiveness. A close care should be given to this indicator regarding outsourced maintenance activities and when procedures or components are changed.

P115. The response time for maintenance gives an indication of the load factor for the maintenance staff along with the schedule compliance.

P116. The backlog of maintenance activities is closely related to the response time and gives quantification of how well the maintenance activities are managed. The backlog should be divided into a planned and unplanned backlog.

P117. One of the aspects of carrying out maintenance work according to preventive maintenance is to minimize the amount of overtime needed for maintenance by planning maintenance activities in advance and in accordance with the resources at each time. The overtime should be reviewed weekly by maintenance manger and is calculated as $O21\colon \frac{Overtime\ internal\ maintenance\ man\ hours}{Total\ internal\ maintenance\ man\ hours} * 100\%$.

P118. Planning compliance is a measure of how precise the resource estimations are in the planning process. This is a good feedback for maintenance planners, since it gives an indication of soft spots in the planning process and allows for adjustments in the procedures.

Table 4.4 The health safety and environment perspective.

Levels:	Strategic	Tactical	Functional
HE1	Number of failures due to maintenance creating environmental damage (T3)		
HE2	Annual volume of wastes or harmful effects related to maintenance (T4)		
HE111			Amount of rework
HE112			Number of failures causing potential damage to the environment (T13)
HE3	Number of injuries for people due to maintenance (T5/O6)		
HE12		Physical working environment	
HE13		Workplace noise level	
HE113			Number of failures causing injury to people (T11)
HE114			Number of failures causing potential injury to people (T12)
HE115			Safety attitude of employees

Concerns for health, safety and environmental issues has been growing in the world in recent years and one manifestation of these concerns is an increased demand for registering all such impacts in production companies.

HE1. Valuable indication of the environmental impact, which is caused by the operations and provides an input to environmental reports. Should be reviewed quarterly by maintenance managers and management and calculated as $T3: \frac{Number\ of\ failures\ due\ to\ maintenance\ creating\ environmental\ damage}{Calendar\ time}$.

HE2. Valuable indication of the environmental impact, which is caused by the operations and provides an input to environmental reports. Should be reviewed quarterly by maintenance managers and management and calculated as $T4: \frac{Annual\ volume\ of\ wastes\ or\ harmful\ effects\ related\ to\ maintenance}{Calendar\ time}$.

HE111. The amount of rework is an indication of the quality of the maintenance and also increases amount of unnecessary repairs needed in the operations. This in return affect the environment in terms of resources needed and possible impacts related to the failures.

HE112. By focusing on the percentage of the failures, which might cause damage to environment, improvements can be achieved more easily in the field. Maintenance managers should review this indicator monthly.

$$T13: \frac{Number\ of\ failures\ causing\ potential\ damage\ to\ the\ environment}{Total\ number\ of\ failures} * 100\%$$

HE3. Gives an indication of the working conditions in the plant and should be reviewed monthly since all injury incidents should be taken seriously and effort made to prevent them. $T5: \frac{Number\ of\ injuries\ for\ people\ due\ to\ maintenance}{Working\ time} * 100\%$

HE12-13. The physical working environment can be measured by the organization and these conditions give an indication of the likelihood of injuries and accidents to employees.

Table 4.5 The employee perspective.

Levels:	Strategic Tactical Functional
E1	Man hours used for continuous improvement (O8)
E11	Number of improvement topics
E111	Training hours pr. Employee (O23)
E2	Employee turnover rate
E21	Employee satisfaction
E211	Employee complaints

Even though this perspective does not have to be a part of the maintenance performance measurement system, since it could belong to an overall performance management system, then it is considered as a part of this for few reasons. First of all, this perspective should look solely at maintenance employees because of their specialized work procedures and extreme working conditions they can find themselves in.

E1. Continuous improvements (CI) are one of the cornerstones of monitoring maintenance performance, since without continuous improvement the gain from the MPM system become only minimal compared to what it is capable of providing. The art of CI has to be nurtured through every day work, and a favorable soil must be made for the employees. The system should appreciate all improvement suggestions made by employees. The indicator is calculated as $O8\colon \frac{Man\ hours\ used\ for\ continuous\ improvement}{Total\ mainteance\ personnel\ man\ hours} * 100\%$ and should be calculated quarterly to track the resource investment made in maintenance improvement.

E111. The key to qualified employees is to provide them with sufficient training and refresher courses. The indicator is calculated as $O23\colon \frac{Number\ of\ maintenance\ internal\ personnel\ man\ hours\ for\ training}{Total\ inernal\ maintenance\ man\ hours} * 100\%$ and should be reviewed monthly by maintenance mangers and annually by the management.

E2. Employee turnover rate gives an important indication on how the operations are really working out. This is because the employees can be easily affected if some aspects in the operations don't hold.

4.1.1 Using the system

The list of indicators presented in Tables 4.1 – 4.5 should only be used as a reference, and they may change with time when new approaches or society demands are brought about. By using such a harmonized set of indicators, comparison between companies becomes more easily achievable. The ÍST EN 15341 standard uses for these reasons a denominator for most of the indicators in order to obtain a value that can be compared between organizations. Common denominators include total maintenance cost, replacement asset value, and total maintenance man-hours. It is evident that in order to obtain these denominators must the MPM system be fully functional and detailed. Therefore, it is unrealistic for organizations, which are beginning their journey with PIs to have these denominators in place. The first step when implementing or improving MPM system is to begin with the critical few and then slowly build on top of them as employees get more used to the system. When setting an initial baseline in the organization, there is no need to use the denominators, since it will ensure that the system grows with the organization and doesn't become too complex right from the start. Once the employees have become used to the system and the system runs smoothly, then the comparable values can be obtained with the denominators and used for benchmarking purposes.

In order to gain advantages from monitoring maintenance performance indicators, there have to be in place ways to present the indicators, ways to interpret them and pathways for intervention when underperformance is discovered. Dashboards and the crystal reports are an excellent way of presenting the PIs. The dashboards must be customized for each responsible individual, which is supposed to use the system, for maintenance manager, maintenance staff, purchasing manager, etc [8]. Most of the indicators are aimed at the maintenance managers or plant managers, which are the ones responsible for planning, scheduling and managing maintenance activities. Therefore it is reasonable that big amount of indicators, which are aimed at improving on these figures are directed towards the ones responsible. However, the mechanics, or shop floor workers, also need to be given a feedback on their performance. Indicators that can be directed to these employees include for instance work orders performed as scheduled, amount of rework and response time.

Once the organizations have implemented a performance measurement system based on common indicators, benchmarking becomes a realistic possibility for them. As they are now developing their internal benchmarks, they will soon be able of comparing themselves with other organizations. The benchmarking can either be done within the Icelandic geothermal power plant industry or the organizations can search abroad for companies in similar industries. The Nordic benchmarking program, which Landsvirkjun is a part of could provide them with a pathway to take the first steps towards external benchmarking.

4.2 Summary

The system presented here will provide a firm ground for implementing or improving a MPM system, by taking into multiple aspects in the operation and the hierarchical levels of the organization. It should be considered that even though the indicators are placed in a single hierarchical order, this hierarchy isn't very firm and the indicators should be considered as more mobile with the possibility of traveling up and down in the hierarchical system. In the next chapter a comparison will be made between the state of the art in Iceland and the proposed system in order to spot the gap between those two.

5 Discussion and Summary

Initially the following research questions were stated:

1. Which possibilities are available for geothermal power plants to monitor maintenance performance?
2. How are the Icelandic power companies applying these possibilities for monitoring the results of their maintenance efforts?
3. How can the maintenance performance measurement system be improved at the Icelandic geothermal power plants? Which factors or parameters should be taken into account and how should they be used?

Answers to these questions can be found throughout the thesis, but here will a review and discussion be provided for each of the questions to summarize the answers.

1. Even though no source were be found on maintenance performance measurement system for GPPs there are many other sources and industries, which can be adapted to the GPPs industry. An overview was provided for MPM and performance indicators in general through a literature review study. A system can be developed based on many assumptions and the direction chosen should be in line with the organizational strategy within each company. The SCALE model represents one of the influencing factors for performance indicators, since the MPM system has to be aligned with the reliability definitions within the company. Even though the indicators themselves are the centroid of the system, many other aspects must be taken into account. This applies for instance to the development of the system, data collection, how indicators are presented and then processed in order to gain improvements. Access to registered data and data integrity play here a big role as well. Even the organizational culture is important, since commitment and relationship with employees is essential for every change initiative to become successful. For advanced companies in the field of maintenance performance measurements the use of benchmarks can provide them with the extra power to become best in class. Comparison between companies is however, not always simple, since the influencing factors shape the results from the performance monitoring. Therefore, a use of standardized indicators can provide a more firm ground for comparison between organizations.

2. The development of MPM system has already started few years ago and a good progress has been made in these years. The first step in this progress is to understand the processes and this knowledge is already in place within all the organizations. The system is becoming a more holistic system with improvements and additions being made to it every year. The organizations are however still developing and getting accustomed to the measurements. Therefore, they are not yet on the level of taking full advantage of the possibilities provided through MPMs. The fact that all the organizations have chosen to develop the MPM system in such a 'slowly but surely' manner has reduced the risk of them getting trapped in some of the '7 deadly sins of performance measurements'. They understand the risk that could be associated in jumping on board and starting monitoring all sorts of indicators, which haven't been considered wisely. The close relationship

between DMM Solutions and its customer has been beneficial for all parties, who all contribute to the development of maintenance performance indicators.

3. Many possibilities are available to monitor the maintenance function more effectively as Chapter 4 reveals. The perspectives, which were chosen, could be considered as representing all the important aspects of the maintenance function. These perspectives are cost effectiveness, quality, productivity, health safety and environment, and employee perspective. They are viewed along the three level hierarchies of the organizations and each perspective includes a set of performance indicators. The target group for the chosen indicators is the maintenance managers and plant managers.

By comparing the proposed system and the state of the art in Iceland several gaps can be identified. Monitoring maintenance performance has just in recent years gained attention by the organizations and they have already started to take advantages of them. All of the organizations are progressing towards an improved system but they are still quite a long way from the ideal set of indicators and work procedures. Registration forms, quality of registrations, calculation ability of the system, and understanding of the performance indicators are among the factors that keep the current systems back from instantly becoming the ideal system. To following bullet points are made to summarize the gap identified between the organizations and the proposed system.

- The organizations have not yet developed a comprehensive set of indicators to cover the whole maintenance function.
- Methods for responding to underperformance have not been fully developed, such as the concept of continuous improvement.
- The plan, do, check, act iterative cycle of maintenance management is not in full effect, due to a lack of monitoring and management review.
- Maintenance managers are loaded with tasks and responsibilities and do not have much time for maintenance performance monitoring.
- The denominators, which allow for an easy comparison, will not be in effect within the organizations until in few years.

As mentioned in Chapter 4 there is no need for the organizations to use the denominators right a way as suggested in the EN 15431 standard, and presented in the formulas accompanied most of the indicators. The denominators can be hard to calculate and therefore they don’t become a necessity until the intention is to use the indicators for external benchmarking purposes. The DMM system plays an important role in utilizing MPIs in the organizations, and even though the pressure on not severe on providing PIs they have manage to develop such a system. It is for sure that they have just started on their journey, and the future in registrations will certainly be found on tablets where employees will get direct access to PIs.

5.1 Recommendations

A systematic approach has to be taken within the organizations to take fully advantages of MPM systems. It takes into account the maintenance policy, culture of the organization, technical- and knowledge level of the organization and training of employees.

5.1.1 Dashboards

Use of several types of dashboards, which are specific for each level of the organization are necessary when using them. The user must as well fully understand the figures behind each indicator in order to being able of taking appropriate actions. The reason is that without the proper knowledge of the system and the indicators, the maintenance manager won't be capable of implementing necessary improvement efforts. Once the organizations have realized these opportunities and integrated improvements into their systems, the basis has been set for continuous improvements.

5.1.2 Health, Safety and Environment

The attention for operational health and safety, such as BS OHSAS-18001, has been growing fast during the last decades. The same goes for environmental aspects, as with ISO 14001. Landsvirkjun and Reykjavík Energy have obtained certifications in both of these fields. The organizations are in addition obliged by the Icelandic government to file annually a so-called 'Green accounting' where the environmental impact of the production is assessed. Direct access to this information through DMM would certainly support their operation by providing efficient method of assessing these numbers.

Another aspect is electricity consumption for the operation of the power plants, which can be substantially high at some instances. Even though this energy can cost as little as nothing during times out side of peak hours, such a waste can have both financial and environmental impacts. Therefore it would be interesting to monitor the energy consumption in order to locate soft spots in the operation where energy is being wasted.

5.1.3 Further use of the component level

Problem with many of the registrations in the organizations is that they are not componenent- or even system specific, but rather only belonging to the power plant as a whole. This is for instance the case for MTBF and related indicators, and when they are only on such a level it is hard to use them for improvement purposes. Therefore a recommendation would be to fully integrate the component level in KKS code within DMM in order to take full advantage of the possibilities available. The reasons behind this choice is however based on the complexity of using the component level for all registrations. This is fully understandable and with more detailed registrations increases the amount of errors inevitably, which will reduce data integrity. Therefore should this choice be taken from within each organization where the alternatives have been weighed in accordance with the possible loss or gain, depending on the direction chosen.

5.2 Further work

Even though this work is aimed at the Icelandic geothermal industry the proposed system is well applicable in other production industries as well. Adaptations are always needed for the framework to align it with the situation at each organization, no matter if the intended destination is in the geothermal industry or not. Therefore can this framework and the

An interesting aspect would be to further develop the indicators for environmental aspects and employee satisfaction since the development in society has been leaning towards these concepts during the last decade or so. The organizations are already taking these factors into account, but improvements are needed in case of the intention would be to integrate the information into the green accounting. The next steps in this project would be to implement the factors in the GPPs, which are not already part of their framework, along with aligning internal processes to respond to changes in the indicators.

The fact that this set of indicators presented in this thesis is mainly directed towards the maintenance managers has raised the question whether a similar set of indicators should be developed for the mechanics. The mechanics do not get detailed enough information on their performance through the indicators presented here.

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