*Energies* **2014**, *7*, 4169-4184; doi:10.3390/en7074169

OPEN ACCESS

*energies*

**ISSN 1996-1073**

www.mdpi.com/journal/energies

*Article*

# Geothermal Power Plant Maintenance: Evaluating Maintenance System Needs Using Quantitative Kano Analysis

**Reynir S. Atlason *, Gudmundur V. Oddsson and Runar Unnthorsson**

Centre for Productivity, Performance and Processes, Department of Industrial Engineering, Mechanical Engineering and Computer Science, University of Iceland, Hjardarhagi 6, 107 Reykjavik, Iceland; E-Mails: gvo@hi.is (G.V.O.); runson@hi.is (R.U.)

* Author to whom correspondence should be addressed; E-Mail: rsa3@hi.is; Tel.: +354-660-5725.

*Received: 14 May 2014; in revised form: 18 June 2014 / Accepted: 23 June 2014 / Published: 1 July 2014*

**Abstract:** A quantitative Kano model is used in this study to identify which features are preferred by top-level maintenance engineers within Icelandic geothermal power plants to be implemented in a maintenance tool or software. Visits were conducted to the largest Icelandic energy companies operating geothermal power plants. Thorough interviews with chiefs of operations and maintenance were used as a basis for a quantitative Kano analysis. Thirty seven percent of all maintenance engineers at Reykjavik Energy and Landsvirkjun, responsible for 71.5% of the total energy production from geothermal resources in Iceland, answered the Kano questionnaire. Findings show that solutions focusing on (1) planning maintenance according to condition; (2) shortening documentation times; and (3) risk analysis are sought after by the energy companies but not provided for the geothermal sector specifically.

**Keywords:** geothermal; maintenance; system; Kano analysis

## 1. Introduction

The diminishing access to easily retrieved energy sources will ultimately have a great effect on the quality of life of a large portion of the Earth's population, even larger than it does at present time [1]. It is therefore of the utmost importance that the sources that are now utilized, whether fossil fuels or not, are harvested in the most efficient manner. To do so, power plants providing electricity or other sources of energy, such as hot water, need to put pressure on efficient operations. One of the factors that needs to be constantly under scrutiny is the maintenance and operation of the power plants. If the operation and maintenance are not carried out in an efficient manner, the resource will not be utilized to its fullest potential and the power plant can be prone to serious problems. Maintenance is generally divided into three categories, reactive, time-based and condition-based, where the second and third are often combined as simply preventive maintenance. To schedule or monitor such tasks, a wide range of methods is available, where parts are inspected or monitored to determine when the part is to be serviced, repaired or replaced. The maintenance procedures of fossil fuel power plants have been under development for much longer than those of geothermal power plants, which is a sector still in its infancy compared to the fossil fuel industry. The conditions geothermal power plants operate under are however very different in nature from those observed in fossil fuel power plants. One of the biggest difference is the steam purity, where the steam used in fossil fuel power plants is much cleaner than the steam used in geothermal power plants. As a result, solutions already provided to the fossil fuel energy sector can only be used in the geothermal sector in a very limited way.

This article explores solutions that are wanted by chief engineers at the Icelandic geothermal power plants, and that are believed to further improve the maintenance operations. This was done by conducting thorough interviews on site with chief maintenance engineers. A need analysis was then conducted amongst the total population of maintenance engineers responsible for 71.5% of all geothermal energy utilization in Iceland in an attempt to prioritize the requirements put forward by power plant engineers for further development.

## 2. Maintenance

Most people face reactive maintenance on a daily basis. However, when a breakdown leads to downtime of a factory, or risks lives, as is the case on airplanes, more advanced methods are equipped. Various maintenance methods have been recorded from ancient history, where large scale constructions were kept up and running. Proper maintenance can lead to financial savings even though it can require financial expenditures to begin with. Often, downtime can be very expensive for companies since no output is derived from their operations. A company might therefore minimize and plan downtime by replacing certain parts frequently, or even learn how to predict the failure of given parts. Different management methods for maintenance have been developed throughout history. Failure driven, often regarded to as reactive maintenance, time based maintenance and condition based maintenance are claimed to be the most employed methods [2–5]. It has been estimated that 55% of maintenance methods in the average maintenance program is reactive, 31% is time-based, 12%is predictive and the last 2% accounts for other methods [6]. The main methods will be discussed in further detail in the following sections.

### *2.1. Reactive Maintenance*

Studies, as recently as in 2000, show that this method is still the most dominant one. It has been stated that majority of maintenance activities on average facilities are considered reactive [6]. The advantages of such methods are that a minimum amount of staff is required for the program [6]. However, unplanned costs related to increased downtime, increased labor cost because of downtime, cost for repair of equipment and perhaps secondary equipment which got damaged along with the primary failure are the examples of disadvantages of reactive maintenance [6]. Reactive maintenance essentially aims to restore a given system to a functional state after it has failed [7].

### *2.2. Preventive Maintenance*

As described, reactive maintenance simply waits for parts to become inoperable. This has proven costly for companies for reasons described above. The quality of equipment is bound to deteriorate with time, and eventually break down. However, by looking retrospectively at breakdown statistics, failure can be minimized. Time based and condition based maintenance are considered to be preventive. The following sections will discuss these methods in greater detail.

#### 2.2.1. Time Based Maintenance

Time-based (also known as calendar based) maintenance tries to schedule maintenance at predetermined intervals, such as amount of produced goods, hours of running machine, mileage or condition [8]. It is, however, considered to be the second least cost efficient maintenance method after reactive maintenance [9]. The aircraft industry however had some problems with time based maintenance. It was shown that time based maintenance was a difficult approach in an industry as rapidly developing as the aircraft industry, also, it was shown that failure likelihood was not expected to rise with ageing parts [10]. Time-based maintenance is generally based on the assumption that one rule fits all. However, each system is operated in a unique environment and is subjected to different conditions. After all, more efficient maintenance is less costly for airlines. The airline industry is an example of an industry that has to have maintenance management issues very clear, since during their business hours, a minor failure can have catastrophic effects, for human lives and subsequently their business. In 1965, the first computerized time-based maintenance system was created by Mobil Oil to manage lubrication on mobile equipment, it was the Midec program [8].

#### 2.2.2. Condition Based Maintenance

Like time-based maintenance, condition based maintenance (CBM) seeks to replace parts before they fail. However, the difference is that instead of the rule of scheduled intervals or amount of use, CBM in modern time is a lot based on observation data [8]. Maintenance is therefore scheduled when a certain condition has been met within the system under study, be it pressure, vibration or anything else that could indicate failure in near future [11]. CBM systems are often not used within industries even though the possibility may seem obvious, this has been speculated to because of the low maturity level of the CBM systems [12].

## 3. Geothermal Power Plants Studied

In Iceland, there are three energy companies that operate geothermal power plants. They are, HS (Hitaveita Sudurnesja) Energy, Reykjavik Energy and Landsvirkjun. Reykjavik Energy, and Landsvirkjun contributed to this research. In total, these companies operate four geothermal power plants. However, each company operates their power plants under different geological condition. This section will provide a description of the power plants under study. It will further outline the different geological conditions at the different sites where the power plants are located. Data was gathered from the literature as well as from the energy companies. The data from Hellisheidi is from brine water leaving the separators, this is also the case for the data at Nesjavellir [13,14]. The chemical composition data for Krafla was also gathered from an ISOR (Islenskar Orkurannsoknir) report, from the KG-26 hole after it was deepened to 2000 m [15].

### *3.1. Hellisheidi*

The Hellisheidi geothermal power plant is owned by Reykjavik Energy and began its electric production in 2006 [16]. The plant is located on the southern part of the Hengill geothermal field, a detailed location can be seen on Figure 1. It produces approximately 303 MW of electric power and 133 MW of hot water through a double flash process. Around 50 wells have been drilled to harness hot water for the power production [17]. Reykjavik Energy provided data about the fluid chemical composition when it leaves the separators. One can see that the fluid consists mostly of $SiO_2$ (822 mg/kg), Na (213 mg/kg), Cl (170 mg/kg), K (38.4 mg/kg), and $SO_4$ (19 mg/kg) [13].

**Figure 1.** Location of the power plants under study. Locations of the plants are as follows: (**1**) Krafla; (**2**) Hellisheidi; (**3**) Nesjavellir and (**4**) Bjarnarflag. Images retrieved from Google maps software.

### *3.2. Nesjavellir*

Also located on the Hengill geothermal field, Nesjavellir geothermal power plant produces 120 MWe and 300 MWt. Experimental wells were drilled, where each well was providing up to 60 MWt, with a usable 30 MWt. Construction of the plant began in 1987, and the first phase was completed in 1990. In the same year, four holes, generating 100 MWt were connected to the production. in 1995 an additional hole was drilled and connected and the production capacity increased to 840 liters per second. Today, 26 holes have been drilled. Temperatures at Nesjavellir have been recorded as high as 380 °C. It is estimated that the current production can continue for the next 30 years [18]. The brine at Nesjavellir consists mostly of Silicon dioxide ($SiO_2$), Sodium (Na), Chlorine (Cl) and Sulfate ($SO_4$).

### *3.3. Krafla*

No geothermal power plant is located further north in Iceland than Krafla. The plant is currently producing 60 MWe of power from two 30 MW Mitsubishi turbines. Construction began in 1974 when test wells were drilled. In 1975 construction of the plant began and in 1977 production began. Initially the plant only operated using one turbine, the second turbine was installed in 1996 and began producing in 1997 [19]. The brine at Krafla consists mostly of $SiO_2$ (790 mg/kg), Cl (608 mg/kg), Na (356). Of gases, the plant can be expected to release around 40 mg/kg of $H_2S$ and 235 of $CO_2$.

### *3.4. Bjarnarflag*

In 1969, Landsvirkjun began operations in Bjarnarflag, Icelands oldest geothermal power plant. The plant is also the smallest operated within the country, producing 3 MW. The power plant uses one back pressure turbine with a single Curtis wheel for its production. Plans are currently underway to increase the capacity of the power plant up to 90 MW [20].

## 4. Methodology

To identify which maintenance systems are used at the Icelandic geothermal power plants, interviews were carried out. The head of power plant operations and the technical supervisor at Reykjavik Energy were interviewed, as well as the head of maintenance management at Landsvirkjun. These two companies are responsible for 71.5% of all energy production from geothermal resources in Iceland. In addition, a quantitative Kano need analysis was carried out among specialists and heads of operations within the energy companies, in order to identify which features are considered mandatory and which would improve the maintenance efficiency further. There were therefore more substantially more participants in the Kano survey than were interviewed. The interviews were conducted in order to get a sense of what to include in the Kano survey. The interviews were focused on the following issues:

- Identify what measures are currently taken in the geothermal power plants when it comes to maintenance;
- How data is used to improve maintenance;
- Identify which solutions are desirable for the power plants.

A quantitative Kano model [21] was utilized to perform a need analysis with regards to the maintenance management systems at the Icelandic geothermal power plants. Interviews were also conducted at the power plants with chief engineers who are in charge of operations and maintenance. A specialist in questionnaires from the University of Iceland was consulted before the study was conducted to provide support with the construction of the questionnaire.

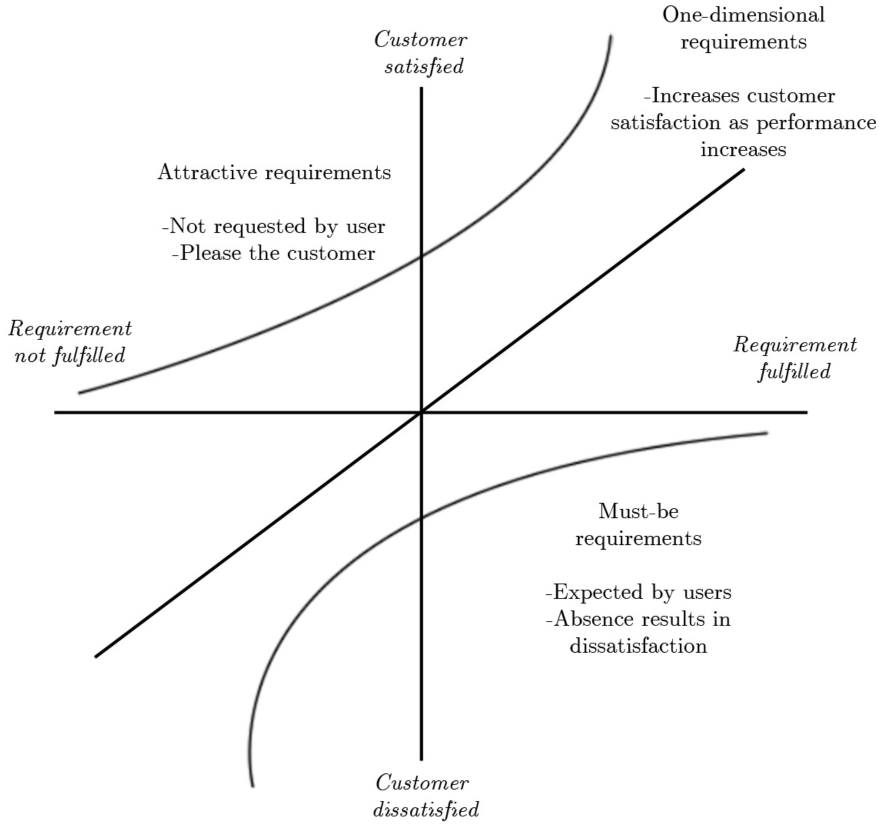
### *4.1. Interviewees and Population*

To gain further understanding of the requirements by the energy companies, detailed interviews at the power plants were conducted. Those include the chief operations engineers at the power plants who are in direct contact with operations and maintenance on site. The purpose of the interviews was to identify what solutions are already being used, and identify which solutions are portrayed as attractive by the chief engineers. The input from chief engineers and maintenance staff proved essential when the Kano questionnaire was constructed. The proportion of answers retrieved from the energy companies amounted to 37.5% of employees directly engaged in operation and maintenance issues. The answers include the total population of heads of operations, engineers with high level of expertise who are in charge of large maintenance activities. The total amount of answered questionnaires amounts to 12, from the employees mentioned above. We assume that the translations from the questionnaire do not have effects on the results.

### *4.2. The Kano Model*

The Kano model of customer satisfaction was initially introduced in 1984 [22]. The survey based method is used to analyze given qualities of a product and how customers may perceive them. The model classifies three different product requirements which customers react to in a different manner when met [23]. First are so called "Must-be requirements". When not fulfilled, dissatisfaction is experienced by the user. However, those requirements are taken for granted by the user, therefore, their fulfillment does not increase the customer satisfaction. As an example of a must-be requirement as defined by Kano is the Internet connection ability in smartphones. When a customer buys a smartphone, he expects it to have the ability to connect to the Internet wirelessly. Failure to meet this requirement results in user dissatisfaction. The second criteria requirements are so called "One dimensional requirements". Those requirements have a linear connection to the satisfaction of the customer. As the requirement is fulfilled in an efficient manner, the customer becomes more satisfied. As an example of this may be the fuel usage of a car. The less fuel used, the more satisfied will the customer become. The last requirements can be regarded as the most important [23]. Those requirements are regarded as "attractive requirements". Such a requirement was not expected by the user and its absence would therefore not result in less satisfaction. Its appearance however increases the customer satisfaction greatly. There seems to be a tendency for "attractive requirements" to become "must-have" requirements over time. For example, the ability to interact with the cellular telephones through a touchscreen was considered an attractive requirement when it originally became available on the public market. However, over time, this functionality has become a "must-have" requirement in many countries. Figure 2 shows the relationship between those requirements and customer satisfaction.

**Figure 2.** Relationship between customer satisfaction and requirement fulfillment according to Kano models [22].




Kano modeling can prove helpful to product development. A product that already is fulfilling a must-be requirement should perhaps not be developed to fulfill that requirement further as it would not increase the user satisfaction. A Kano model can provide a better perspective of the product that is under development by showing which requirements or criteria improve the customer satisfaction the most. During the development stage, some trade offs may be inevitable. A Kano model can assist with such trade offs by showing which feature results in the greatest user satisfaction.

The method of using the Kano model is gathered straight from the field of product development. Despite of being qualitative in nature, Kano models have shown to be an effective tool in the product development process. However, quantitative versions of the Kano model have been presented, such as the Analytical Kano Model, or A-Kano [24]. In this study we use a quantitative analysis of the Kano model presented by Wang and Ji [21]. Upcoming sections will describe the methodology.

#### 4.2.1. Quantitative Kano Model—The Questionnaire

After visualizing the market segment that is to be studied, a questionnaire is constructed. The questionnaire consists of questions about the functional requirements of a product. Each functional requirement consists of two questions, one functional and one dysfunctional. For example, if being asked about the weight of a cellular telephone, the customer might be asked "If the phone is as light as a matchbox, how do you feel?" and then subsequently "If the phone is heavier than a matchbox, how do you feel?". Each question has five possible outcomes, (1) I like it that way; (2) It must be that way;

(3) I am neutral; (4) I can live with it that way; (5) I dislike it that way. A form as is shown in Table 1 is then used to evaluate each functional requirement, be it attractive, one-dimensional, must-be, indifferent, reverse or questionable. An experienced researcher in the field of psychology provided guidance when the questionnaire was constructed. This was done to improve the structure and clarity of the questionnaire as well as to make the questions non-biased. It was decided to randomize the order of the questions, that is, the functional and dysfunctional form of each question does not come in perfect sequence. The questions are instead in a random order. This was done to avoid the respondents to answer one question with relation to the other. The questionnaire was then distributed amongst specialists and heads of operations within all geothermal power plants operated by Reykjavik Energy and Landsvirkjun, which were all heads of operations and 37.5% of operation and maintenance employees within the companies, and at the same time the majority of such employers in Iceland.

**Table 1.** The table used to evaluate the classification of the functional requirements (FR) by the customer [25].

| | CR's | Dysfunctional | | | | |
|---|---|---|---|---|---|---|
| | | **1. Like** | **2. Must be** | **3. Neutral** | **4. Live with** | **5. Dislike** |
| Functional | 1. Like | Q | A | A | A | O |
| | 2. Must-be | R | I | I | I | M |
| | 3. Neutral | R | I | I | I | M |
| | 4. Live with | R | I | I | I | M |
| | 5. Dislike | R | R | R | R | Q |

A = Attractive; M = Must-be; R = Reverse; O = One-dimensional; I = Indifferent; Q = Questionable.

#### 4.2.2. Quantitative Kano Model—Computation

Based on the findings of the questionnaire and subsequently identifying the nature of the combined answers (Attractive, one-dimensional *etc.*), it is possible to calculate two values, namely customer satisfaction (CS) and customer dissatisfaction (DS). the CS value can be expressed as [21]:

$$CS_i = \frac{f_A + f_O}{f_A + f_O + f_M + f_I}$$

Let $f_A$ denote the number of attractive, $f_O$ the number of one-dimensional, $f_M$ the number of must-be and $f_I$ indifferent responses. Similarly, to calculate the $DS_i$ the following equation can be used:

$$DS_i = \frac{f_O + f_M}{f_A + f_O + f_M + f_I}$$

Subsequently, two points are located for each functional requirements (FR). These points define the customer satisfaction if the FR is fully implemented or fully excluded from the product. These points can be plotted as (1, $CS_i$) and (0, $-DS_i$) [21]. To find the relationship functions, one must first identify if the FR is a must-be, one-dimensional or attractive. This is done by finding the mode of the answers for that particular FR. The relationship function can be shown as $S = f(x, a, b)$, where $S$ is the customer satisfaction, $x$ the level of fulfillment, $a$ and $b$ are the adjustment parameters for the Kano categories of customer requirements. For one dimensional attributes the function is $S = a_1x + b_1$ where $a_1$ denotes the slope and $b_1$ is the DS value when customer requirement (CR) $(x)$ is at 0. Entering CS and DS points into the equation we get $a_1 = CS_i + DS_i$ and $b_1 = DS_i$. The function for one-dimensional product attributes can be seen as: [21]:

$$S_i = (CS_i - DS_i)x_i + DS_i$$

If the CR is an attractive attribute, the function can be seen to be exponential. the function is therefore modified to be $S = a_2e^x + b_2$. However, we now get $a_2 = (CS_i - DS_i)/e - 1$ and $b_2 = -(CS_i - eDS_i)/e - 1$. We can therefore see that the function for such attributes is [21]:

$$S_i = \frac{CS_i - DS_i}{e - 1}e^{x_i} - \frac{CS_i - eDS_i}{e - 1}$$

For must-be attributes, the function can also be estimated using an exponential function. In the case of must-be attributes the function is $S = a_3(-e^{-x} + b_3)$. We acquire $a_3$ and $b_3$ by using [21]:

$$a_3 = \frac{e(CS_i - DS_i)}{e - 1}$$

and

$$b_3 = \frac{eCS_i - DS_i}{e - 1}$$

The function for must-be attributes can therefore be plotted as [21]:

$$S_i = -\frac{e(CS_i - DS_i)}{e - 1}e^{-x} + \frac{eCS_i - DS_i}{e - 1}$$

### *4.3. Functional Requirements*

After interviewing chief engineers at the power plants, functional requirements were identified. These requirements were identified because of either (1) current lack of fulfilling the requirements using current solutions; (2) the requirements had not been attempted to be fulfilled in any solution currently used by the power plants. The requirements were based on the possibilities of using data currently gathered by the power plants. The data is often in the form of time between failures, type of maintenance procedures and "real time" condition monitoring. The functional requirements to be investigated are shown below (dysfunctional and functional version of each requirement is presented in the Appendix):

1. Know the effect of one maintenance procedure on other parts in the power plant. This can apply later in time. For example, a maintenance procedure is carried out at one time, which causes an unusual failure later in time in a different part of the plant. Would it prove valuable to know the connection between these factors;
2. Knowing the effects of postponing the maintenance procedure on mechanical components;
3. Have detailed, pre made, protocols for large scale maintenance procedures;
4. Shorter time to document maintenance procedures;
5. Provide suppliers with information about the predicted failure of certain parts in order to shorten waiting times;
6. Predict individual workers (or workers unit) workload based on predicted mechanical failures;

7. Plan maintenance according to the predicted state of the part instead of planning for all possible outcomes;
8. Base power plant inventory on failure predictions.

These requirements provided the basis for the questionnaire.

## 5. Results

From the interviews, it was evident that the main focus of the chief engineers were the intervals between major maintenance on the steam turbines. Currently, the turbines are scoped annually and full, planned stops are conducted quadrennially. It was seen that two requirements were frequently mentioned that are considered to be of major importance to improve the maintenance procedures of the power plants. Firstly, risk assessment method to determine the operational effects if a turbine is not maintained on a scheduled time, instead postponing the maintenance for some period. Secondly, detailed protocols for maintenance based on the predicted condition of the turbines are needed.

For example, if a certain condition is observed, clear protocols are currently not available to address the known condition but are instead tailor made by chief engineers for each case. Detailed protocols, more similar to protocols known in the medical or aerospace sector, are needed. Where protocols are pre-defined and are deployed based on some observed condition. We also identified that inventory was mentioned and the possibility to further minimize it. Twelve responses were gathered from staff members highly involved in maintenance procedures at the power plants. Even though the sample is relatively small, it represents the majority of employees highly involved in daily maintenance operations at the power plants studied. The Kano analysis of the data shown in Table 2 reveals that the greatest customer satisfaction will be reached if the condition of a part which requires major maintenance activities can be predicted to some extent. The attractive requirements are shown in Figure 3, the one dimensional requirements are shown in Figure 4.

**Table 2.** Function calculations for customer requirements.

| Customer Requirements | CS Point | DS Point | $a$ | $b$ | $f(x)$ | $S = af(x) + b$ |
|---|---|---|---|---|---|---|
| *One- dimensional* | | | | | | |
| (1) Relationship of effects | (1, 0.9) | (0, −0.8) | 1.7 | −0.8 | $x$ | $f(x) = 1.7x - 0.8$ |
| (2) Effects of postponing | (1, 1) | (0, −0.57) | 1.57 | −0.57 | $x$ | $f(x) = 1.57x - 0.57$ |
| *Attractive* | | | | | | |
| (3) Predefined detailed protocols | (1, 0.43) | (0, −0.38) | 0.47 | −0.85 | $e^x$ | $f(x) = 0.47e^x - 0.85$ |
| (4) Short documentation time | (1, 1) | (0, −0.27) | 0.73 | −1.0 | $e^x$ | $f(x) = 0.74e^x - 1$ |
| (5) Supplier need avareness | (1, 0.88) | (0, −0.13) | 0.58 | −0.71 | $e^x$ | $f(x) = 0.58e^x - 0.71$ |
| (6) Knowledge of future workload | (1, 0.89) | (0, −0.12) | 0.58 | −0.70 | $e^x$ | $f(x) = 0.58e^x - 0.7$ |
| (7) Plan maintenance according to condition | (1, 0.75) | (0, −0.42) | 0.60 | −1.1 | $e^x$ | $f(x) = 0.86e^x - 1.1$ |

**Figure 3.** Attractive functional requirements retrieved using a Kano analysis. Functions are shown in Table 2.

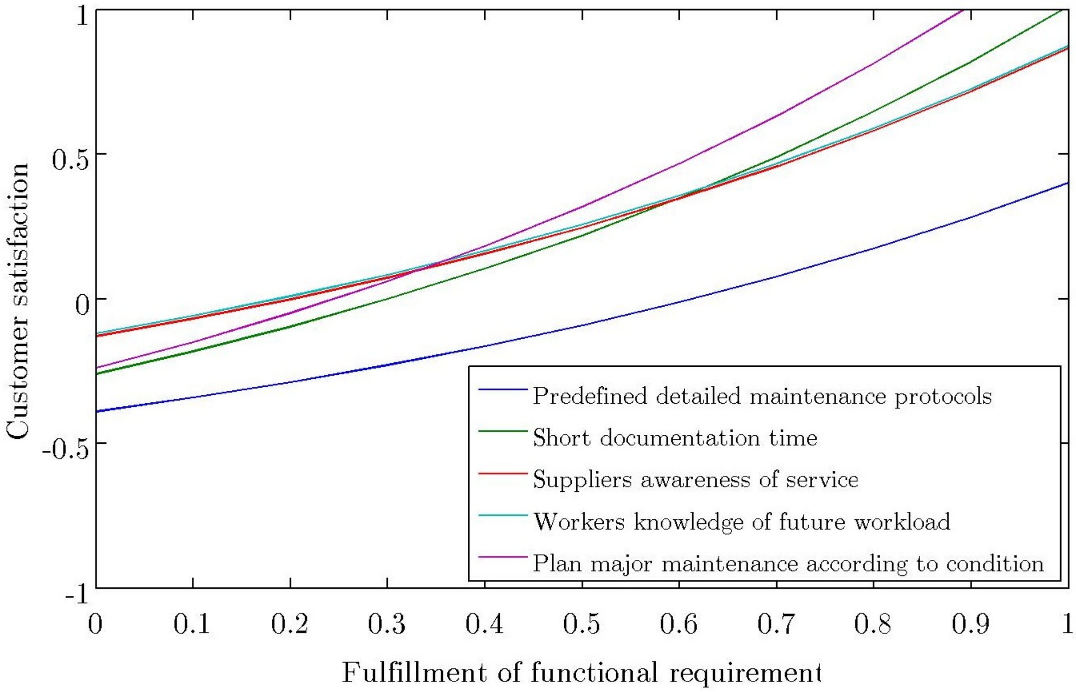
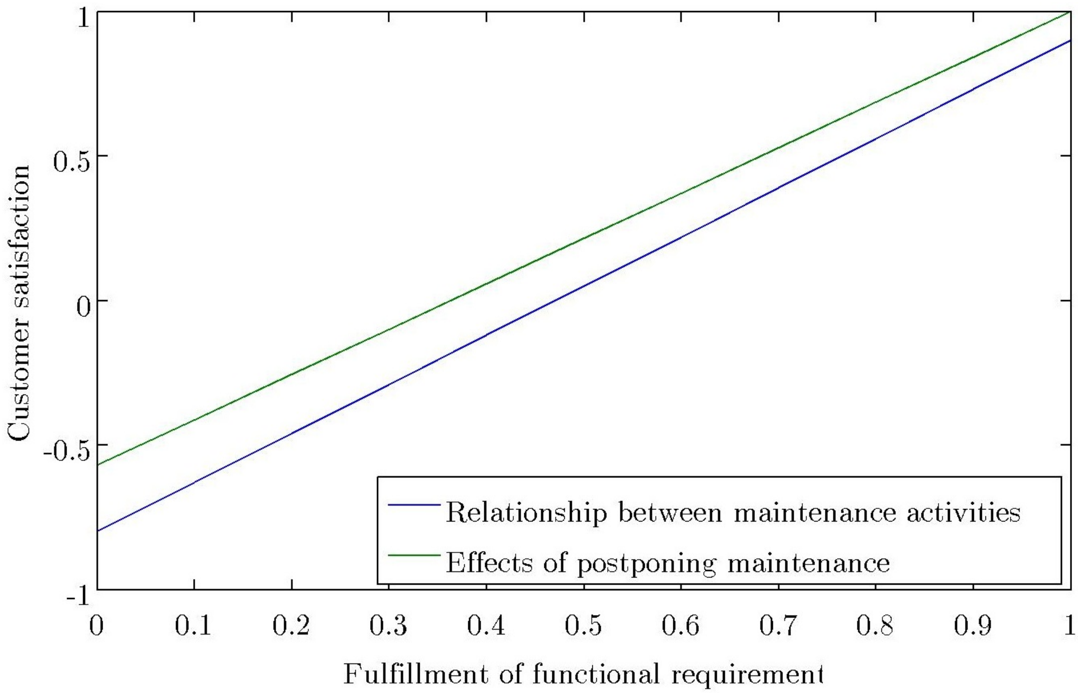



**Figure 4.** One dimensional functional requirements obtained using linear functions in Table 2.




Shortening the time which it takes to document maintenance was also found to offer high customer satisfaction if shortened. The ability to know the operational and operational effects of postponing maintenance procedures was found to offer linear relationship to customer satisfaction. In fact, if that particular functional requirement is addressed fully, it will provide almost the same customer satisfaction as planning major maintenance procedures according to their known, or predicted condition. However, addressing the attractive requirement of planning major maintenance according to known or predicted condition will bring more satisfaction earlier than the one dimensional requirement of knowing the effects of postponing. The attractive requirement of having predefined protocols for major maintenance activities did not bring as high customer satisfaction as other functional requirements, even though its importance was discussed in some detail by the chief engineers. One of the functional requirements (Base power plant inventory on failure predictions) which was to be studied returned mostly questionable results from the Kano table. Therefore, no tangible results were to be calculated for that particular functional requirement.

In this study, both the interviews and the Kano analysis were used to prioritize which solutions or methodologies should be developed by, or for, the power plants. Based on this study, the following prioritizations can be made:

- Develop a method where the condition of a part (such as a turbine) can be predicted before it requires maintenance. The maintenance is then conducted and planned based on such predictions;
- Shorten the time needed for standard documentation by the employees. This solution should also allow for easier collection of maintenance data;
- Risk analysis for important parts. It frequently mentioned by chief engineers how valuable the knowledge of postponing maintenance could be. Developing the methodology would be result in high customer satisfaction according to the Kano analysis, which further confirmed what had previously been seen in the interviews.

As can be seen in Table 2, the results for one-dimensional and attractive requirements are shown but must-be requirements are absent. This can be explained by the fact that solutions that are currently being addressed or fulfilled to some extent were intentionally not included in the Kano analysis.

## 6. Conclusions

In this study, we investigated which functional requirements desired by the engineers working at the two largest power companies in Iceland to improve their maintenance procedures if available. The desired solutions are currently not available, or not being deployed by the geothermal sector in Iceland. The Kano model was found useful to further understand and formalize what had previously been observed in meetings on site. The previously mentioned results should serve as a roadmap for upcoming steps in product development for the geothermal sector and which solutions are needed by the power plants to further improve their maintenance procedures. Using the approach of investigating the power plants, their needs and requests for solutions should in essence provide greater likelihood of producing solutions that will be accepted and used by the plants than addressing needs that are perhaps currently being addressed (must-have requirements). The reason for functional requirement number 8, (planning of inventories based on failure predictions) not showing tangible results is most likely to be found in the formulation of the functional and dysfunctional forms of the question in the questionnaire. The results from the Kano questionnaire as well as the interviews underline the possibilities in predictive maintenance in the geothermal sector. A great deal of data is currently being gathered, which has the potential to serve as the backbone in predictive modeling. It was seen that the greatest interest from the power companies is currently in the field of predictive maintenance. It is therefore likely that solutions addressing the desired functional requirements by the power companies will be deployed by the Icelandic geothermal sector. Chief engineers at the power plants emphasized the importance of having pre-defined protocols for most maintenance activities. The Kano model however showed that fulfilling that particular requirement would return the lowest customer satisfaction of all the functional requirements analyzed. This may be because of different views of chief engineers and the maintenance staff. This study can serve as a guide for industries looking to serve the geothermal sector in the field of maintenance. The study indicates which requirements are sought after and expected to further improve the maintenance procedures in Icelandic geothermal power plants.

**Acknowledgments**

Our gratitude goes to GEORG (Geothermal Research Group) for financial support. Saemundur Gudlaugsson, Gudmundur Hjaltalin at Reykjavik Energy and Thrandur Rognvaldsson and Steinn A. Stensson at Landsvirkjun for assisting with the research. Also, the support from Ragna Benedikta Gardarsdottir, Associate Professor in psychology from the University of Iceland is acknowledged.

**Author Contributions**

All authors contributed to the conceptualisation of the article. Reynir S. Atlason carried out the main body of research. Gudmundur V. Valsson and Runar Unnthorsson reviewed the work continually.

**Appendix**

Below are the questions used in the Kano questionnaire. First is the functional requirement shown, then the functional version of the question, followed by the dysfunctional version.

1. Know the effect of one maintenance procedure on other parts in the power plant. This can apply later in time. For example, a maintenance procedure is carried out at one time, which causes an unusual failure later in time in a different part of the plant. Would it prove valuable to know the connection between these factors.

    Functional: "How would you feel if you knew the effects of your work on other parts of the power plant?" (2) (The number shown in brackets behind each question indicates when it appeared in the questionnaire.)
    Dysfunctional: "How would you feel if the causes of failures would not be known, as long as the failure is solved?" (16)

2. Knowing the effects of postponing the maintenance procedure on mechanical components.

    Functional: "How would you feel if you knew the effects on the equipment if maintenance is postponed?" (6)
    Dysfunctional: "how would you feel if maintenance is carried out on predefined times, without exceptions?" (9)

3. Have detailed, pre made, protocols for large scale maintenance procedures.

   Functional: "How would you feel if precise, exact protocols, describing what should be done and how, would be existent for large maintenance procedures?" (13)
   Dysfunctional: "How would you feel if each large maintenance job would be planned individually as a single occurrence?" (16)

4. Shorter time to document maintenance procedures.

   Functional: "How would you feel if it would only take you approximately one minute to document a standard maintenance procedure?" (5)
   Dysfunctional: "How would you feel if it would take you more than five minutes to document a standard maintenance procedure?" (12)

5. Provide suppliers with information about the predicted failure of certain parts in order to shorten waiting times.

   Functional: "How would you feel if suppliers could foresee your orders and plan accordingly?" (7)
   Dysunctional: "How would you feel if suppliers react to orders as they are made (but not before)?" (14)

6. Predict individual workers (or workers unit) workload based on predicted mechanical failures.

   Functional: "How would you feel if you knew your workload ahead of time?" (4)
   Dysfunctional: "How would you feel if your workload is known when (not before) jobs are assigned to you?" (8)

7. Plan maintenance according to the predicted state of the part instead of planning for all possible outcomes.

   Functional: "How would you feel if you could plan maintenance according to the condition of the equipment in question?" (3)
   Dysfunctional: "How would you feel if you needed to prepare for every possible outcome when maintenance is conducted?" (10)

8. Base power plant inventory on failure predictions.

   Functional: "How would you feel if you could plan the power plants inventory based on predicted failures?" (1)
   Dysfunctional: "How would you feel if the inventory is constantly well loaded and guaranteed that spare parts are always available?" (11)

## Conflicts of Interest

The authors declare no conflict of interest.

## References

1. Lambert, J.G.; Hall, C.A.; Balogh, S.; Gupta, A.; Arnold, M. Energy, eroi and quality of life. *Energy Policy* **2014**, *64*, 153–167.

2. Davies, A. *Management Guide to Condition Monitoring in Manufacture*; Manufacturing Series; Institution of Production Engineers: London, UK, 1990.
3. Gits, C. Structuring maintenance control systems. *Int. J. Oper. Prod. Manag.* **1994**, *14*, 5–17.
4. Niebel, B.W. *Engineering Maintenance Management*, 2nd ed.; Industrial Engineering Series; CRC Press: Boca Raton, FL, USA, 1994.
5. Pintelon, L.; Gelders, L. Maintenance management decision making. *Eur. J. Oper. Res.* **1992**, *58*, 301–317.
6. Sullivan, G.; Pugh, R.; Melendez, A.; Hunt, W. *Operations & Maintenance Best Practices*; U.S. Department of Energy: Washington, DC, USA, 2002.
7. Gits, C. Design of maintenance concepts. *Int. J. Prod. Econ.* **1992**, *24*, 217–226.
8. Levitt, J. *Complete Guide to Preventive and Predictive Maintenance*; Industrial Press: New York, NY, USA, 2003.
9. Cosar, E. A Wireless Toolkit for Monitoring Applications. Master's Thesis, Helsinki University of Technology, Helsinki, Finland, 2009.
10. Nowlan, F.S.; Howard, F.H. Reliability-Centered Maintenance. Department of Defence, Australian Government: Canberra, Australia, 1978.
11. Reichard, K.; van Dyke, M.; Maynard, K. Application of sensor fusion and signal classification techniques in a distributed machinery condition monitoring system. In Proceedings of the SPIE International Society for Optical Engineering, Orlando, FL, USA, 25–28 April 2000; pp. 329–336.
12. Bengtsson, M.; Olsson, E.; Funk, P.; Jackson, M. Design of condition based maintenance system—A case study using sound analysis and case-based reasoning. In *Condition Based Maintenance Systems—An Investigation of Technical Constituents and Organizational Aspects*; Malardalen University: Eskilstuna, Sweden, 2004; p. 57.
13. Gunnlaugsson, E. *Chemical Composition of Separator Fluids at Hellisheidi Geothermal Power Plant*; Technical Report; Reykjavik Energy: Reykjavik, Iceland, 2013.
14. Gunnlaugsson, E. *Chemical Composition of Separator Fluids at Nesjavellir Geothermal Power Plant*; Technical Report; Reykjavik Energy: Reykjavik, Iceland, 2013.
15. Fridleifsson, G.; Ármannsson, H.; Mortensen, A.K. *Geothermal Conditions in the Krafla Caldera with Focus on Well KG-26*; Iceland Geosurvey: Reykjavik, Iceland, 2006.
16. Hellisheidi Geothermal Plant. Available online: http://www.or.is/en/projects/hellisheidi-geothermal-plant (accessed on 30 June 2014).
17. Hellisheidavirkjun. Available online: http://www.or.is (accessed on 27 June 2014).
18. Nesjavellir Power Plant. Available online: http://www.on.is/en/power-plants (accessed on 30 June 2014).
19. Landsvirkjun. Krafla Geothermal Power Plant. Available online: http://www.landsvirkjun.is/Fyrirtaekid/Aflstodvar/kroflustod (accessed on 30 June 2014).
20. Mannvit. Bjarnarflag Geothermal Power Plant. Available online: http://www.mannvit.com/GeothermalEnergy/ProjectExampleinfo/bjarnarflag-geothermal-power-plant (accessed on 30 June 2014).
21. Wang, T.; Ji, P. Understanding customer needs through quantitative analysis of kano's model. *Int. J. Qual. Reliab. Manag.* **2010**, *27*, 173–184.

22. Kano, N.; Seraku, N.; Takahashi, F.; Tsuji, S. Attractive quality and must-be quality. *J. Jpn. Soc. Qual. Control* **1984**, *14*, 39–48.
23. Sauerwein, E.; Bailom, F.; Matzler, K.; Hinterhuber, H.H. The kano model: How to delight your customers. *Int. Work. Semin. Prod. Econ.* **1996**, *1*, 313–327.
24. Xu, Q.; Jiao, R.J.; Yang, X.; Helander, M.; Khalid, H.M.; Opperud, A. An analytical kano model for customer need analysis. *Des. Stud.* **2009**, *30*, 87–110.
25. Berger, C.; Blauth, R.; Boger, D.; Bolster, C.; Burchill, G.; DuMouchel, W.; Pouliot, F.; Richter, R.; Rubinoff, A.; Shen, D.; *et al.* Kano's methods for understanding customer-defined quality. *Cent. Qual. Manag. J.* **1993**, *2*, 3–35.