Consultancy Services for the Plant Audit in various Pump Stations and Reservoirs (OP18REFCS03)

Technical Report for VILLAMOR Pump Station (Excluding Electrical Testing)

reference: OP18REFCS03-GHD-VIL-REP-G001B

Final

GHD Ply Ltd.

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Title:
Final Report for Villamor Pump Station

Theme:
Plant Audit and Asset Management

Report Period:
2019

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Copies: 1

Page Numbers: 95

Date of Completion:
May 2, 2019

Executive Summary

VILLAMOR Pump Station has six (8) pumps (6 booster pumps and 2 storage pumps). Based on preliminary assessment on historical corrective and preventive intervention records, significant degradation has been observed for pumps, which experienced high frequency of failure on bearing and coupling components. Statistically, it is evident from the time series data in the period from 2014 to 2018 on power consumption and production that more power has been incurred while the availability of the pump system is less.
Based on the results of testing, reliability, and life cycle cost analysis, GHD recommends to execute a set of preventive intervention program that involves periodic replacement of pump components and frequent inspection/testing to collect historical data sufficient to estimate the reliability of pumps and the system. The intervention program can be done in the first year of the next 5 years preventive intervention plan that are reflected in the optimal time window shown along with the impact curves.
Furthermore, GHD recommends Maynilad that optimal time window to execute the intervention program shall take into consideration of network analysis which will enable Maynilad to set priorities to perform intervention program not only for Pagcor station but also for other stations. In addition, Maynilad might consider to combine intervention programs of a group of stations as it will be also optimal when preparing the bid.

Contents

Chapter 1

Introduction

1.1 General introduction

The station is located in Villamor area (refer to Figure 1.1). It has a total capacity of 676,266 m^3/day and pumps the treated water to a discharge line serving the an area in Villamor, Metro Manila. The schematic diagram showing its connectivity is in Figure 1.3.

Figure 1.1: Pagcor PS $[14°31'40.74''N, 121°1'23.10''E]$

Figure 1.2: Pump gallery

This PS has been reported by the Client to experience considerable degradation with regard to inefficiency of operation, higher power consumption, and more frequent breakdowns of assets leading to the increase in maintainability and decrease in availability.

The Client has therefore awarded GHD and its sub-consultants (RB Sanchez and APSI) to conduct a plant audit project with an expectation to establish rigorous asset management framework based on reliability study and to determine optimal intervention program for the next five (5) years.

1.2 Objectives

The objectives of this work are as follows

- To evaluate the current operating condition of PS as compared to the original design intent and to provide recommendations for improving the operational efficiency and lowering operating cost;
- To be able to determine an optimal intervention program for the PS in the next 5 years with reference to the recommendations from the assessment and audit based on life cycle cost; and equipment efficiency study whether the equipment is subjected to replacement or repair. These equipment are:

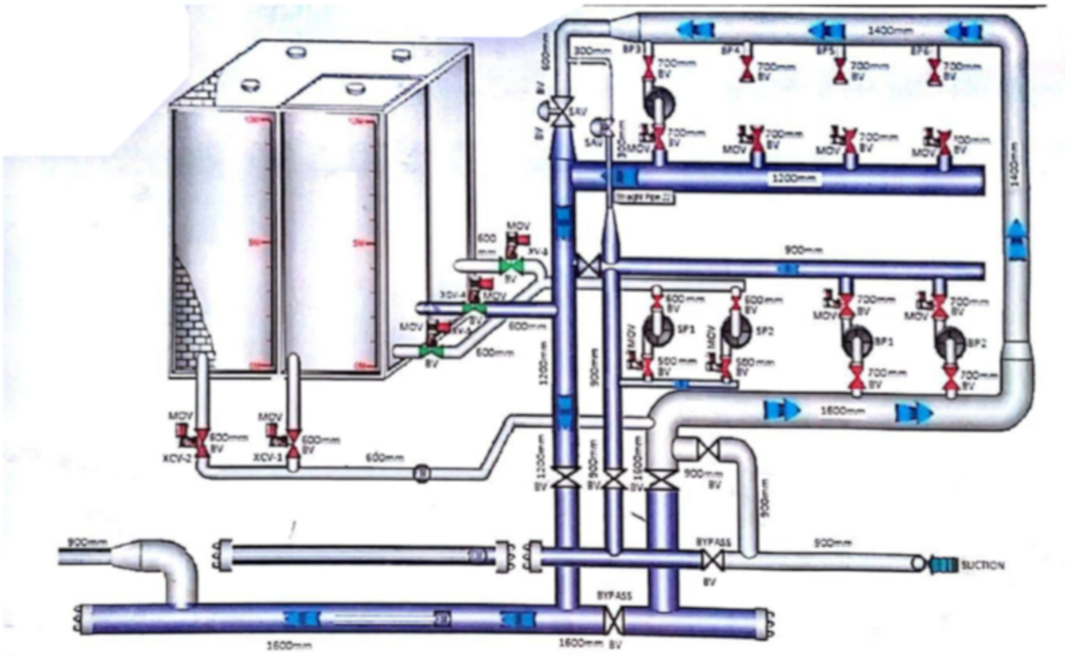


Figure 1.3: Schematic diagram

- ◦ Pumps;
- ◦ Motors;
- ◦ Generators;
- ◦ Electrical System and Protective Device;
- ◦ Substation (Transformer, Switchgears);
- ◦ MCC (VFDs, Soft starters, Circuit Breakers, and Protective Devices);
- ◦ Motorize Valves.

1.3 Scope of Work

Scope of Work (SOW) has been defined in the Contract Agreement and be in compliance with the GHD technical and financial proposal and the agreements made during a number of project meetings (refer to minutes of meeting of the project).

It is important to note that the electrical audit and analysis is not part of this report as the test has been deferred due to operational constraint. Maynilad will decide to give a specific time window to conduct electrical test. Thus, this report will be updated to next revision once the electrical tests are completed.

1.4 Limitations

Results of the study with analysis, conclusion, and recommendations are only within the scope of work and agreements, and particularly under the following major constraints:

- Operational constraint: It was not possible to shutdown the entire PS for visual inspection of assets, particularly mechanical assets;
- Incomplete historical data: It was a matter of fact that Maynilad has not established an asset management system, thus data regarding historical intervention is limited and incomplete, leading to non-optimal reliability analysis;

1.5 Glossaries

Following glossaries are defined and used in the report:

Level of Services (LOS)

A Level of Services (LOS) is any value or expectation of asset managers and beneficiers regarding the functionality and serviability of an asset of a system of assets.

Intervention

Intervention is a generic and global term used to refer to non-physical and physical activities on assets. It encompasses do-nothing, or do somethings like repair, maintenance, rehabilitation, renewal, investment, and inspection and testing.

Corrective Intervention (CI)

A Corrective Intervention (CI) is an intervention executed without proper and systematic plan. An CI is often incurred by failure/breakdown of assets. In most of cases, it incurs significant negative impacts (e.g. cost to repair, disruption of service, loss in revenue).

Preventive Intervention (PI)

A Preventive Intervention (PI) is an intervention executed with proper and systematic plan. Note that an PI is executed on asset that is still working but not provide adequate level of services.

Intervention Type

An Intervention Type (IT) is a specific and well-defined type of work/task that can be executed on/for an asset (e.g. replacement of a bearing for a pump).

Intervention Strategy (IS)

An Intervention Strategy (IS) is a set/collection of intervention types.

Intervention Program (IP)

An Intervention Program (IP) is a set/collection of intervention strategies for one asset or more than one assets of the same system.

Work Program (WP)

A Work Program (WP) is an execution program consisting of Intervention Program and management program (e.g. project management, procurement) that shall be implemented in order to realize/actualize the Intervention Program.

Chapter 2

Preliminary Assessment and Data Gathering

GHD did conduct preliminary assessment on a set of data provided by Maynilad. The data set includes a number of records on daily production and power consumption and intervention reports issued after Maynilad experienced failure/breakdown of assets.

The assessment provided a base for GHD to generate the Inspection Testing Plan (ITP) [7] aiming to gather necessary data for conducting reliability study. The ITP has been reviewed by Maynilad, together with the Work Safety Permit (WSP), prior to execution of visual inspections and testings at the site [4].

2.1 Maynilad's data

Maynilad provided a set of data as shown in Table 2.1

Table 2.1: Data provided by Client.

No.	Data	Remarks
1	Production and power consumption from 2014 to 2018	Recorded in excel fiels. Data set is incomplete but can be considered acceptable for the study
2	As-built drawings	Both in CAD and PDF format
3	Intervention records	Refer as activity, preventive and corrective maintanance reports. Note that the numbers of records are limited.
4	Asset registry	Asset registry was incompleted as confirmed by the IAM team of Maynilad.
5	Specifications and technical manuals	Includes pressure graph, bearing information

2.1.1 Intervention records

The provided data set does not includes reports of intervention activities which are mentioned in two associated excel files named "Maintenance Works Dashboard 2015" and "South Maintenance Monitoring Dashboard 2017". Particularly, the most important historical data concerning specific failure of components of pumps with elapsed time is missing. Thus, the provided information is not useful for detailed reliability study on frequent failure of assets at component level.

The problem with missing specific failure data was due to a matter of fact that Maynilad still has not come up with preventive maintenance program within the overall asset management framework. The IAM team has recently established with expectation to generate short-term, medium-term, and long-term preventive intervention program. In close discussion with Maynilad, GHD learns that Maynilad has a regular/frequent activities for check-up (e.g. monthly and quarterly), however, recorded data has not been digitalized and the data itself has not aligned well with the asset registry.

Table 2.2 presents highlights on intervention data on pumps.

Table 2.2: Highlight of intervention data on pumps.

Pumps	Description of PI/CI	Date
BP3	- Conducted assessment due to reported strong vibration and unusual sound at pump of BP3	2/8/2017
	- Checking the alignment using manual dial gauge, Pull out 450KW Motor to give way the replacement of inner pump bearing of BP3. Pull out and replaced of inner pump bearing of BP3	2/8/2017
	- Continuation of pull out of pump drive coupling of BP3	2/9/2017
	- Assist PNOM Personnel to pull out of BP3 pump coupling and cleaning of 2 pcs exhaust fan and isolation transformer	2/10/2017
	- Installation of pump drive coupling and 450 kw motor, alignment of pump and motor, and splicing of cable of BP3.	2/17/2017
	- Pull-out impeller of BP3 for preventive maintenance; Check inner and outer pump bearing and mechanical seal.	3/17/2017
	- Cleaning of Impeller, bearing housing and other parts of BP3.	3/18/2017
	- Check-up BP1 and Greasing of Pump drive coupling	4/6/2017
	- Installation of bearings and pump impeller of BP3	4/8/2017
	- Continues Troubleshooting of BP3	4/16/2017
	- Installation of BP3 pump cover and alignment of Pump and Motor	4/20/2017
BP1	- Replacement of inner and outer bearing and inner mechanical seal of pump BP1	8/2/2017
	- Replacement of mechanical seal of BP1	8/3/2017
	- Continuation of installation of BP1 pump	8/10/2017
	- Cleaning and re-greasing of drive coupling of BP4; Conduct vibration and temperature of inner and outer pump and motor bearing	12/26/2017

2.1.2 Interview data

GHD conducted an interview session on 07/12/2018. Results of the interview are summarized in the minutes [5], with the following highlights.

- No further data is available aside from the provided set presented in earlier section;
- There is an existing regular check-up for assets but data is not digitalized and the information is only generic;
- Spare parts are not stocked for most of components, except for bearing. Regarding service delivery, the required discharge pressure remains the top priority in pump operation modulation and sequencing. Critical parts and components for VFD and bearing are usually stacked to have spared in case of emergency repair and replacements. The consumables on the other hand, are not stacked but ordered in advance for use in maintenance activities;
- No visual bank of assets;
- No standard testing regime that follows a regular scheme based on optimality;
- Pumps are operated based on pressure and not manual;
- No existing PI/CI procedure to be followed;
- No expansion plan is forecasted;
- There is a problem with the inflow of incoming water, leading to lower level of reservoir chambers that has affected pump operations occasionally;

- no historical data on pump efficiency, which is a simple yet useful value in determining pump performance. The main impediment in the individual pump efficiency is the measurement of flow produced by each pump. The existing configuration of the pump-motor and piping system do not cater to conventional methods of flow determination;
- No intervention records for FDAS. It was revealed that different version on operation and functionality of the FDAS was reported by both guard and site operators.

2.1.3 Asset hierarchy

During the bidding phase, Maynilad did provide the first draft of the Asset Registry (AR) that describes a hierarchy of eight (8) levels. Figure 2.1 visualizes the hierarchy with brief description presented in Table 2.3.

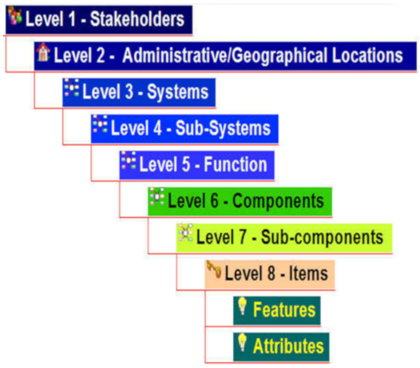


Figure 2.1: Asset Hierarchy

Table 2.3: Condition state definition - Multiple.

Asset hierarchy	Description
Level 1	Stakeholder level. For example, an pump station belongs to MWSI
Level 2	Geographical locations/ or administrative zone (e.g. a pump station belong to Quezon city or Makati)
Level 3	System (e.g. the entire pump stations and reservoir system)
Level 4	Sub-system (e.g. one specific pump station and reservoir such as the Lamesa PSR)
Level 5	Functional system (e.g. booster system or storage system)
Level 6	Component (e.g. Suction line, Reservoir line and Tank)
Level 7	Sub-component (e.g. Suction pipe and fittings, Concrete reservoir, pump)
Level 8	Items (e.g. valve, bearing, motor)

GHD received the latest version of the AR with 101 assets for this PS. The full list of assets is given in the excel file provided by Maynilad in 2018. GHD has developed a MS Access program to convert the data in the excel file to a relational database structure. Per agreement with Maynilad, GHD will only verify level 7 of the AR with the actual site condition for the study [6].

2.2 Preliminary assessment

Assessment on the lastest provided intervention records reveals that the provided pertinent data is incomplete and cannot be used as representative data for a complete reliability study.

It is also confirmed from the provided data that the Client has done regularly check-up on GENSETs to ensure that it provides adequate level of services in case of emergency. To date, no failure records has been observed for the GENSET.

Further evaluations and tests have to be conducted to identify the areas for improvement of preventive measures in mitigating corrective measures and study the ways to strengthen preventive measures to improve operating conditions and life of pump components.

Improving the reliability of the pump stations for the next coming years require evaluation of the existing pump station conditions and maintenance practices, particularly assessment of the pump and its components. With that, areas for improvement of operation and maintenance be addressed through action items that come from the resulting recommendations.

In order to capture a relatively good picture on the reliability of the pump system and its associated assets, a number of tests shall be conducted.

2.3 Summary of the inspection test plan (ITP)

A complete write-up on testing shall be referred to the ITP [7], which has been submitted, reviewed, and approved by the Client. This section only provides highlights to help readers keeping abread of the flow of the report.

2.3.1 Mechanical Audit

The Mechanical Tests to be conducted are enumerated and discussed hereunder including their background and applications, standards used if applicable, and the equipment to be used. During testing, the following are the assumptions and considerations:

- The operation of the pumps cannot be interrupted (at day time when demand is high).
- The valve settings then cannot be adjusted to produce different flow rates.

2.3.1.1 Structural Inspection for Pump Discharge and Suction Line

This activity measures the current thickness of the existing pipelines at the pump vicinity using ultrasonic thickness gauging. The flow regime especially around the elbow and possibly corrosion and scaling conditions are to be predicted from the measurements of this test.

Following procedures will be executed.

Step 1: Locate and mark testing points

At a minimum of two (2) meters away from the pump intake/discharge flange, the test points shall be marked at 3, 6, 9 and 12 o'clock positions and at one (1) meter interval along the pipes, additional test sections with same set points shall be added as long as available beneath the immediate ground level (Figure 2.2 and Figure 2.3). Note that there will be no testing at section 4 as indicated in the figure as it falls on the control valve. The next 1 meter away from the pump flange will be considered instead.

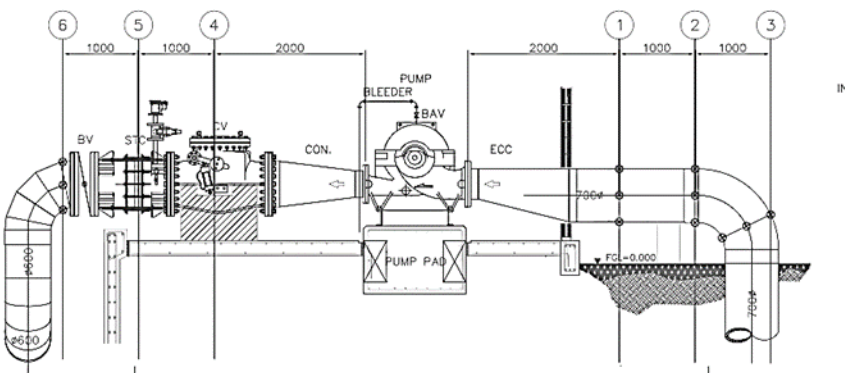


Figure 2.2: Sample pump layout and testing points

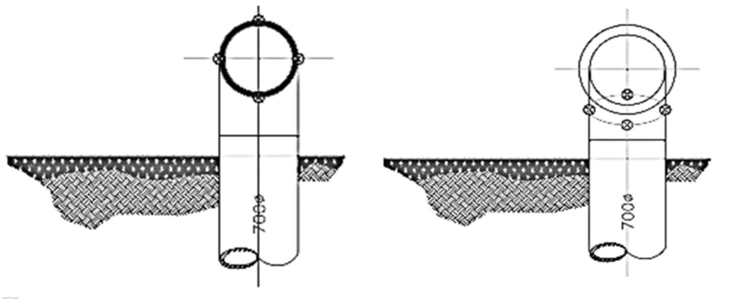


Figure 2.3: Test Points - Cross sectional view of Section 1 and Section 3

Another set of test points shall be for the elbows and will be determined from the flow direction considering the probable points of most thinning from turbulent water flow (Figure 2.4).

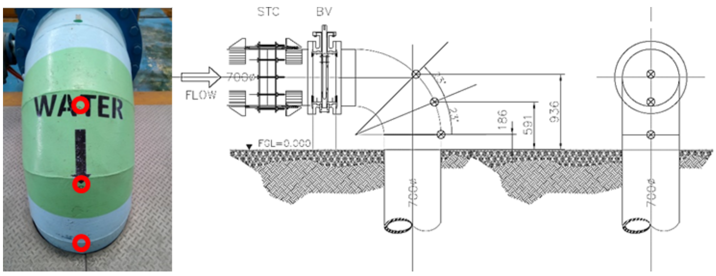


Figure 2.4: Sample test points for elbow

Step 2: Prepare test point surfaces

- Wipe the surface free of dirt (no need to remove paint)
- Using a chalkstone (erasable), mark x on the test point

Step 3: Apply sufficient couplant on test point surface

- Use petroleum jelly/Vaseline as couplant

Step 4: Set transducer probe on test point

Step 5: Read and record value as indicated on module display

Record values shown on the screen (Figure 2.5).

Step 6: Clean test point after reading

2.3.1.2 Unit Flow Measurement

The activity measures pump capacities. Pump efficiency is then calculated using the measured values.

Step 1: Locate Sensor Position Point Area and mark all points to be taken.

- Observe required offset distance from fittings/pump to consider the fully developed flow. At least 10 times the diameter distance away from the suction/discharge of the pump if applicable, otherwise consider at least 2D distance away from the fittings. This is to ensure the flow will be stable and fully developed for flow measurement accuracy (Figure 2.6).

Figure 2.5: UTG reading

- Otherwise, test at near turbulent zones and consider normalizing the flow. Refer to Figure 2.7:

Figure 2.6: Set points for straight pipe with developed flow

Figure 2.7: Set points for straight pipe with flow turbulence

Step 2: Pipe Specification Input on the Flow Meter.

- Identify nominal pipe size with equivalent parameters such as schedule designation, equivalent thickness, OD, and etc.
- Input outside diameter.
- Input pipe thickness.
- Input pipe material (carbon steel).
- Input pipe medium (water).

Step 3: Prepare test point surfaces

- Clean the surface of pipe with a sandpaper and steel brush or any suitable abrasive materials, exposing the base metal.

Step 4: Install transducers at set points

- Apply enough couplant that it covers transducers sensors to ensure an acoustically conductive connection to the pipe. Also apply couplant on the test point surface (Figure 2.8).
- Clamp the transducers at the side of pipe using metal chains, straps or mounting rails Observing proper spacing and alignment. Note flow direction and install transducers at

either 0 or 45 degrees, whichever would give more stable reading (Figure 2.9, Figure 2.10, Figure 2.11)

- Wait for the module to display "System Normal" before reading. Inspect set-up for any fault and properly reinstall if signal is poor/low (no reading)

Figure 2.8: Applying couplant

Figure 2.9: Clamping the transducers

Figure 2.10: Transducer installation on straight pipe with developed flow

Figure 2.11: Transducer installation on straight pipe with flow turbulence

Step 5: Data gathering

Read and record all necessary data measurement by the equipment, (i.e. flow, fluid velocity, sound velocity, Reynolds number, etc.)

Figure 2.12: UFM Measurement Display

Step 6: Remove transducers and restore paints

Remove the transducers and restore the surface of pipe after measurement.

2.3.1.3 Suction and Discharge Pressure Measurement

The activity measures each pump suction and discharge pressure. The pump efficiency is then calculated using the measured values.

Step 1: Disassembly of existing Pressure Gauge

- Inspect for any leaks or unusual noise before proceeding: If anything is detected, report immediately to the operator;
- Close gate valve located before the pressure gauge and wait for the pressure reading to drop;
- Remove the pressure gauge: (1) Hold the adapter steady with one wrench and the grip the stationary socket of the pressure gauge with another; (2) Loosen the pressure gauge then remove it.

Step 2: Installing the Pressure Gauge

- Prepare the connections: (1) Clean the connections before installing; (2) Put Teflon tape on the pressure connection of the gauge;
- Install the pressure gauge: (1) Mount the pressure gauge on the adapter then hand tighten the arrangement; (2) Further tighten the assembly using a pair of wrenches: hold the adapter steady with one wrench and the grip the stationary socket of the pressure gauge with another; (3) Tighten the assembly;
- Inspect the assembly again.

Step 3: Reading the pressure

- Slowly open the gate valve: Observe any leaks or unusual noise;
- Measurement: (1) Wait until reading is stable; (2) Record the pressure as indicated.

Step 4: Restoring the earlier gauge

- Inspect for any leaks or unusual noise before proceeding: If anything is detected, report immediately to the operator;
- Close gate valve located before the pressure gauge and wait for the pressure reading to drop;
- Remove the pressure gauge: (1) Hold the adapter steady with one wrench and the grip the stationary socket of the pressure gauge with another; (2) Loosen the pressure gauge then remove it;
- Prepare the connections: (1) Clean the connections before installing; (2) Put Teflon tape on the pressure connection of the gauge;
- Install the pressure gauge;
- Mount the pressure gauge on the adapter then hand tighten the arrangement;
- Further tighten the assembly using a pair of wrenches: hold the adapter steady with one wrench and the grip the stationary socket of the pressure gauge with another;
- Tighten the assembly.

2.3.1.4 Parameters

Parameters was recorded using visual inspection form, interview questionnaire, and testing results. Main parameters are listed, but not limited to, in the Table 2.4. Raw data is enclosed in the Appendix.

Table 2.4: Main parameters to be collected.

Parameters	Symbol	Remarks
Pipe thickness Gauge	t	mm
Pump Capacity	Q	Gpm/cmh
Suction Pressure	Ps	mH2O
Discharge Pressure	Pd	mH2O
Vibration Data	-	-
Head	H	mH2O
Efficiency	e	%

2.3.2 Fire protection and safety (FDAS) audit

It was confirmed at site that there is no FACP and the devices are only battery operated smoke detectors "KIDDE" brand.

This smoke alarm warning device is a "stand-alone" system in which device detects and measure smoke particles and emits an audible sound but is not connected to any of the manual call point and bell that were installed separately in the pump station. There is no monitoring panel to tell where the zone/ area of the fire is and also the exact location of the fire. Table 2.5 lists major assets of the FDAS.

Table 2.5: Main parameters to be collected.

Assets	Quantity	Unit
Smoke detectors	8	pcs
Call points	2	pcs
Bell sounder	2	pcs

The Emergency and fire fighting equipment consists of the following :

- Fire extinguishers Dry Chemical (Red color)
- Fire extinguishers HCFC (Green color)
- Emergency lighting
- Exit signages
- Exit Doors
- PPE cabinet
- Fire hose cabinet
- Evacuation plan for every floor

FDAS audit was conducted in the period from October 30, 2018 to November 16, 2018. Audit on FDAS has been conducted following sequences

Step 1: Assign (1) one person on the Fire Alarm Control Panel to operate / accept the fire alarm activation and another group/person to conduct spraying on the device, communicate using two way radio.

Step 2: Conduct spray of smoke detector tester (SOLO brand or any) directly on the smoke detector device for not more than 1 sec, repeat action until detector is activated. Note : If detector fails to respond after 3 tries, device will declared faulty (Figure 2.13-a).

Step 3: Hear and visually check strobe light and sounder every time you activated the smoke detectors.

Step 4: Remove device and clean, allow particles to disperse. Then return to socket (Figure 2.13-b).

Step 5: Check that strobe light is functioning/ blinking after returning. Note original status if no light is visible. Check that the control panel breaker feeding the device is reset (Figure 2.13-c).

Step 6: Repeat steps 2, 3, and 4 on different locations until all the devices are tested.

Step 7: Conduct testing for manual call point /manual pull station by pressing the device, hear if the alarm bell / buzzer is activate after you trigger the device (Figure 2.13-d).

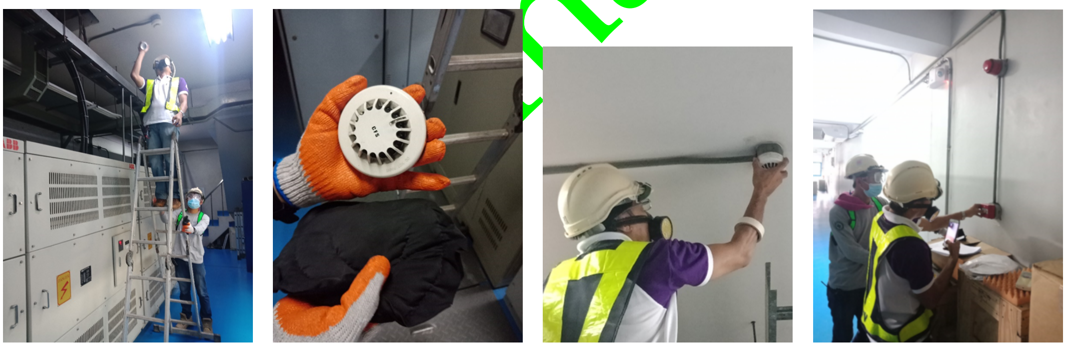
Step 8: Check bells and buzzer audibility.

Step 9: Return Manual Call Point /Manual Pull Station on stand by position. Repeat it on all device.

Step 10: Make a record for the fault device.

Step 11: Record the status of FACP and reset the panel until the fault clear on trouble.

Step 12: Conduct closing of activities to all concerned .



(a) (b) (c) (d)

Figure 2.13: FDAS testing

2.3.3 Vibration and structural assessment

This activity measures the vibrations of the pump and motor at the drive and non-drive ends. The data will be used to address pump vibration problems such as cavitation, pump flow pulsation, bent pump shaft, pump impeller imbalance, shaft misalignment and bearing problems.

Following procedures will be executed

Step 1: Test location identification

Locate the testing points on drive and non-drive ends of pump and motor (Figure 2.14).

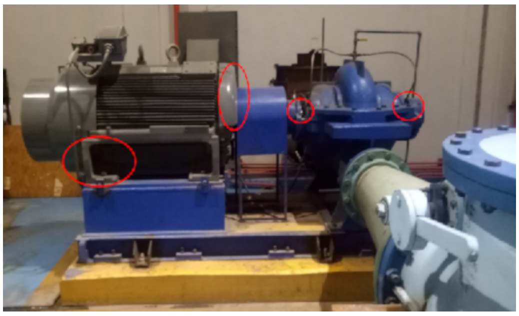


Figure 2.14: Drive and Non-Drive Testing Areas for Vibration

Step 2: Set transducer probe on test point. Observe HIRAC for access to elevated positions

Step 3: Read and record value as indicated on module display

Figure 2.15: Vibration Reading using Analyser (Left – vertical mount, Right – horizontal mount)

2.3.4 Workplace environment management

Maynilad sent 2 WEM service reports, the first was conducted last November 6 and December 20, 2013, and the second on November 11 2015 and January 20, 2016. The WEM methodology included the measurements of Total Nuisance Dust (TND) concentration, temperature and relative humidity, illumination and noise levels. The tests were done inside the office and on the booster area where the pumps operate.

Results of the tests show that the office premises are well below the minimum count for TND concentrations, above the minimum recommended lighting requirement and below the permissible noise level as required by the Occupational Safety and Health Standards of DOLE. The booster area complies satisfactorily for minimum recommended lighting requirement; the noise level as measures exceeds the permissible level and so requires ear safety protection whenever in the area

GHD/RBSanchez conducted WEM tests at designated locations (Figure 2.16) to record values of parameters presented in Table 2.6.

Table 2.6: WEM Parameters.

Parameters	Symbol	Units
Dry Bulb Temperature	tdb	oF/oC
Relative Humidity	RH	%
Sound Intensity	-	dB
PM 2.5 Count	PM2.5	ug/m^3
Visible useful light	-	Lux

2.4 Database

GHD developed an MS Access program that functions as a database used to record data collected from visual inspections and testings. The database has been developed using the concept of

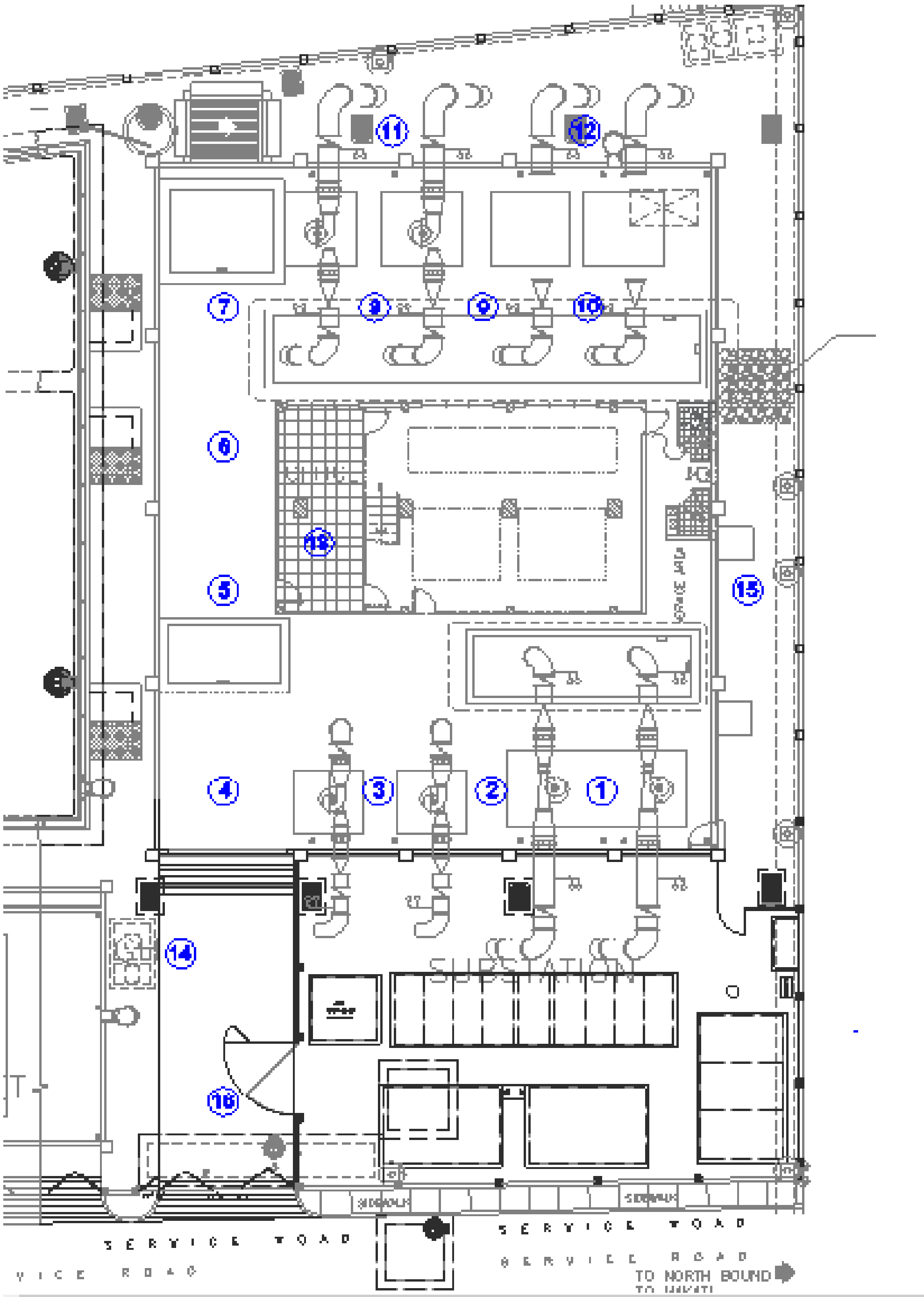


Figure 2.16: Testing locations

Relational Database Management System (RDMS), which is a must to record data systematically. The benefits of using the database are

- Eliminate redundancy and repeatition of same data
- Eliminate incorrect data entry that is often found when working with excel files
- Provide linkages among asset hierarchy
- Provide ease for programing (e.g. reliability modeling and life cycle cost analysis)
- Support Maynilad AIM team to learn the benefits of using RDMS in developing an integrated Asset Management System for now and future

- Provide compatibility with any CMMS that is often using other RDMS such as Microsoft SQL Server, Oracle SQL server, or MySQL platform
- Provide ease for compilation of desire tables for further analysis using SQL (Structure Query Language)
- Provide ease for importing/exporting to different extension formats (e.g. flat, csv, xlsx)
- Provide a strong background for Maynilad team to migrate recording practices to Web-based that will be part of GHD's recommendation for future usage.

The MS Access database is then migrated into MySQL server, which is far more powerful database system that is used also to migrate, compile, and store all production and power consumption data into a single table. Main reasons behind the development of the MySQL server are for statistical computing with R and for faster compilation of queries.

GHD will provide these two sets of database as part of our deliverable and will provide training for Maynilad team to learn how to use the database in an efficient approach.

Chapter 3

Methodology

3.1 The Integrated Asset Management Approach (IAM)

We proposes an Integrated Asset Management (IAM) approach with its framework shown in Figure 3.1 for executing this project. The IAM approach will eventually be beneficial to Clients as it will lay a foundation to build up a systematic asset management plan for the future.

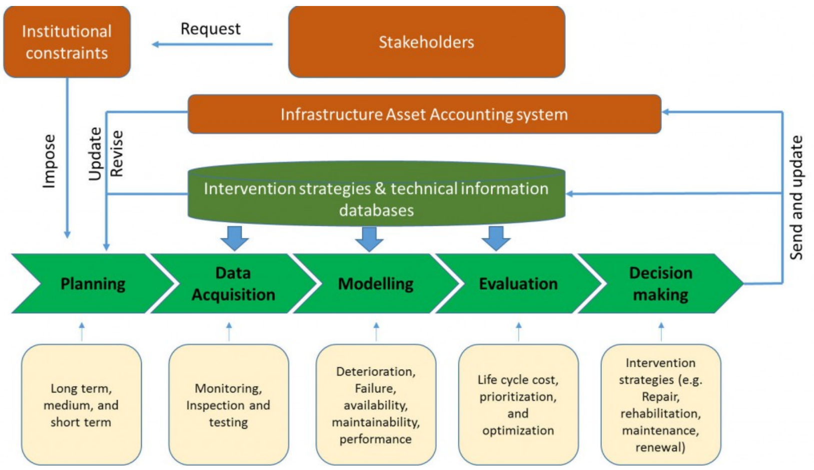


Figure 3.1: Integrated asset management approach (adopted from POM+ http://www.pomplus.vn)

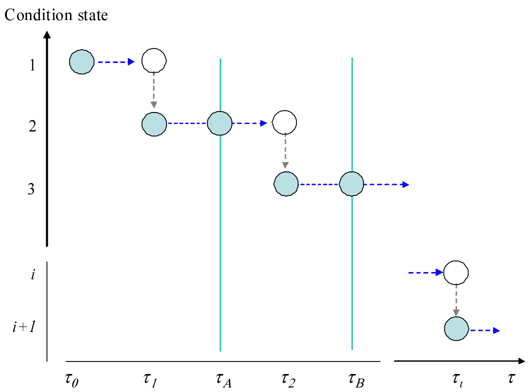
As can be seen in Figure 3.1, we sees the overall picture of works that should be executed in close connection to each other in order to make a full cycle of asset management effectively.

Works associated with auditing equipment and facilities of pump stations and reservoirs, coming up with a preventive maintenance program, tendering, and detailed design can be described explicitly using the framework in Figure 3.1. For example, various type of data concerning physical and operational condition and performance of equipment and facilities will be collected, filtered, and analyzed (Data Acquisition); the data will be further used for modeling purposes (e.g. prediction of failure rate, draw deterioration curve, reliability and efficiency); life cycle cost analysis will be then performed for each equipment and for its system. In this process, either prioritization or optimization technique can be used; finally a set of preventive maintenance intervention strategies will be generated for decision making purposes.

3.2 Deterioration process and rating index

In order to analyze and forecast the deterioration of assets, it is necessary to accumulate time series data on the CS of the assets. The historical deterioration process of an asset is described in Figure 3.2. This figure shows the deterioration progress of a component that has not been repaired. In reality, there exists uncertainty in the deterioration progress of the asset, and moreover, the CS at each point in the time axis is restricted by the time, at which, visual inspection is carried out.

In this figure, τ represents real calendar time (the expression "time" will be used instead throughout this paper). The deterioration of the asset starts immediately after it begins to operate at time τ_0. The CS of an asset is expressed by a rank J representing a state variable i $(i = 1, \cdots, J)$. For a component in the good or new situation, its condition state is given as $i = 1$, and increasing of CS i describes progressing deterioration. A value of $i = J$ indicates that an asset has reached its service limit. In Figure 3.2, for each discrete time τ_i $(i = 1, \cdots, J-1)$ on the time-axis, the corresponding CS has increased from i to $i+1$. Hereinafter τ_i is referred to the time a transition from a CS i to $i+1$ occurs.



Note) In this example, the deterioration process of a infrastructure component if expressed in terms of calendar time $\tau_1, \tau_2, ..., \tau_i$, and condition state of the section is increased in unitary units.

Figure 3.2: Transition Time of Condition State (adopted from [18]).

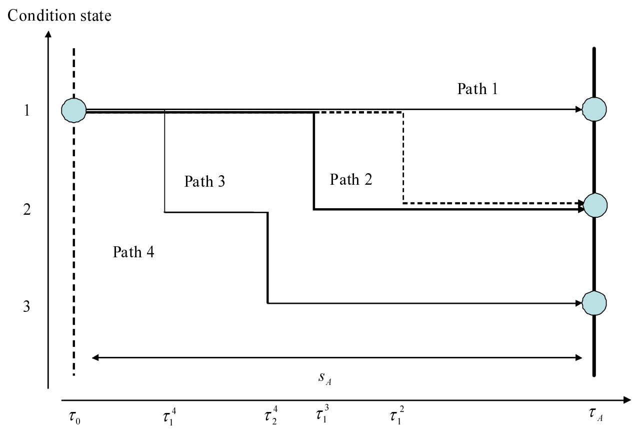
Information regarding the deterioration process of an asset can be acquired through periodical visual inspections. However, information on the CS based on continuous visual inspection is difficult to obtain. In this case, the initial inspections is carried out at times τ_A on the time-axis. It is supposed that at time τ_A the CS observed by inspection is i $(i = 1, \cdots, J-1)$. The deterioration progress in future times is uncertain. Among the infinite set of possible scenarios describing the deterioration process only one path is finally realized.

Figure 3.3 shows four possible sample paths. Path 1 shows no transition in the CS 1 from initial time τ_0 to first inspection time τ_A. In paths 2 and 3, CS has advanced to one upper CS at the calendar times τ_1^2 and τ_1^3 respectively. The CS of these two paths observed at time τ_A become 2. In a periodical inspection scheme, the point times τ_1^2 and τ_1^3 in which the CS has changed from 1 to 2 are not determined. In addition, path 4 shows transitions in the CS at times τ_i^4 and τ_{i+1}^4 during the inspection interval. The CS observed at time τ_A becomes 3. That is, in spite of the transitions in the CS are observable at the time of periodical inspection, it is not possible to obtain information about the times in which those transitions occur.

Figure 3.4 further describes the deterioration process inferring the inspection approach and how the CS is assumed. In this figure, it is assumed that the CS at the calendar time τ_{i-1} has changed from $i-1$ to i. The calendar time τ_{i-1} is assumed to be equivalent to $y_i = 0$. The time represented by the sample time-axis is referred from now on as a "time point", and differs from "time" on the calendar time axis. The times τ_A and τ_B correspond to the time points y_A and y_B on the sample axis. It can be seen that $y_A = \tau_A - \tau_{i-1}$, $y_B = \tau_B - \tau_{i-1}$.

Information on the CS i at the beginning of the calendar time τ_{i-1} cannot be obtained in a periodical inspection scheme. Therefore, time points y_A and y_B on the sample time-axis cannot be correctly obtained either. For convenience of description, it is assumed that the information at the time a point is known in order to develop the model, despite this assumption is not necessarily essential. The following paragraph discusses that even without information at time points y_A and y_B an exponential hazard model can be estimated.

In the case the CS of an asset at time τ_i (time point y_C) is assumed to change from i to $i+1$, the period length in which the CS has remained at i (referred as the life expectancy of a CS i) is represented by $\zeta_i = \tau_i - \tau_{i-1} = y_C$. The life expectancy of a CS i is assumed to be a stochastic

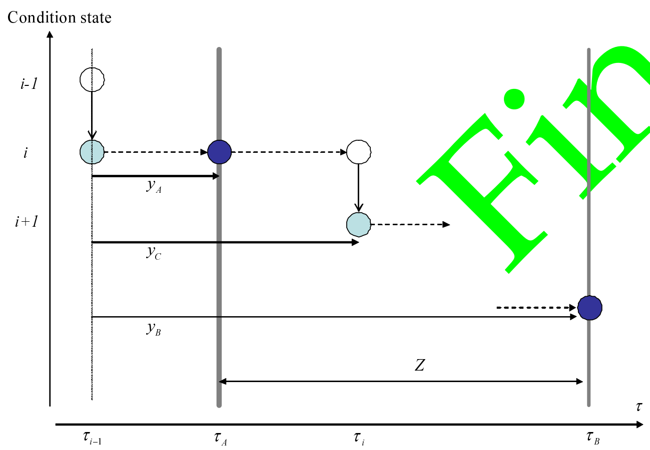


Note) In this example, the deterioration process of an asset is expressed in terms of four different sample paths. In paths 2 and 3 the CS has advanced to one upper CS at the calendar times τ_1^2 and τ_1^3 respectively. In path 4, the CS has increased one state at each time τ_1^4 and τ_2^4. However, in the case of a periodical inspection carried out at times τ_A the CS at any point in time between inspections cannot be observed.

Figure 3.3: Transition Pattern of Condition State.

variable ζ_i with probability density function $f_i(\zeta_i)$ and distribution function $F_i(\zeta_i)$. Random variable ζ_i is defined in the domain $[0, \infty]$. The distribution function is defined as

$$F_i(y_i) = \int_0^{y_i} f_i(\zeta_i) d\zeta_i. \tag{3.1}$$



Note) In the case the condition state changes from $i-1$ to i at the calendar time τ_{i-1} the inspections carried out at times τ_A and τ_B will also correspond to the points in time y_A and y_B when using τ_{i-1} as the time origin. The figure shows a sample deterioration path in which the condition state has advanced in one unit to y_c in the interval time $\tau_{i-1} - y_C$. However, observations at time τ_{i-1} are not possible in a periodical inspection scheme, so there is no way to obtain observation at y_A, y_B and y_C. Nevertheless, it is possible to use the information contained in $z = y_C - y_A \in [0, Z]$.

Figure 3.4: Model of Deterioration Process.

The distribution function $F_i(y_i)$ represents the cumulative probability of the transition in the CS from i to $i+1$. CS i is assumed to be observed at initial time $y_i = 0$(time τ_A). The time interval measured along the sample time-axis until the time point y_i is $\tau_{i-1} + y_i$. Therefore, using the cumulative probability $F_i(y_i)$, the probability $\tilde{F}_i(y_i)$ of a transition in the CS i during the time points interval $y_i = 0$ to $y_i \in [0, \infty]$ is defined by $\tilde{F}_i(y_i)$:

$$\text{Prob}\{\zeta_i \geq y_i\} = \tilde{F}_i(y_i) = 1 - F_i(y_i). \tag{3.2}$$

The conditional probability that the CS of an asset at time y_i advances from i to $i+1$ during the time interval $[y_i, y_i + \Delta y_i]$ is defined as

$$\lambda_i(y_i)\Delta y_i = \frac{f_i(y_i)\Delta y_i}{\tilde{F}_i(y_i)}, \tag{3.3}$$

where the probability density $\lambda_i(y_i)$ is referred as the hazard function.

3.3 Condition State (CS) definition

Condition of an asset can be described either by a range of discrete condition state (CS) or by continuous values of one or more than one parameters such as cracking, thickness, and corrosion. In asset management practice, discrete range of CS is often for the following reasons:

- It can be converted/mapped from continuous value of monitoring data;
- It is convenient for non-technical persons and managers;
- It is suitable for determination of intervention strategy and thus for life cycle cost modeling.

Assets in pump stations are different in category and functionality, thus it is not easy to define a universal range of CSs. However, it is possible that a generic range of CSs can be used to map appropriately different type of assets. In this project, following definitions are used for multiple CSs (Table 3.1) and binary state (Table 3.2) systems.

Table 3.1: Condition state definition - Multiple.

CS *i*	Definition	Require Intervention	Remarks
1	New/likely new and provide adequate LOS	No	Good (None/Insignificant)
2	Install <=5 years, provide adequate LOS	No	Acceptable (Minor)
3	Moderate aging, not provide adequate LOS, observed moderate breakdown	Yes	Damaged (Significant)
4	Moderate aging, not provide adequate LOS, require frequent CI and PI	Yes	Poor (Extensive)
5	Aging and not provide adequate LOS	Yes	Safety is endangered

Table 3.2: Condition state definition - Binary.

CS *i*	Definition	Require Intervention	Remarks
0	Not provide adequate LOS	No	
1	Provide adequate LOS	Yes	

3.4 Technical efficiency

Technical efficiency is a coefficient measured as the ratio of actual parameter value and expected/design parameter value. In case of PSs, TE is often discussed around the value of pump efficiency (η), which is a factor that accounts for the kinetic energy lost during the operation [8]. The PE is a product of the followings:

- Hydraulic efficiency (primarily, disk friction against the liquid with impeller shrouds). This efficiency is contributed by the speed and impeller geometry. Shock losses during rapid changes in direction along the impeller and volute can also resulted in additional shock losses;
- Volumetric efficiency (recirculation losses at wear rings, interstage bushes and other);
- Mechanical efficiency (friction at seals or gland packing and bearings)

Hydraulic efficiency and volumetric efficiency are used at the design stage of PS when there is a need to determine suitable pump or group of pumps that satisfies the designed LOS. Whilst, mechanical efficiency is used to determine operational efficiency once pumps are in used.

The mechanical efficiency (η_m) is estimated based on the equation 3.4

$$\eta_p = \frac{P_W}{P_B} \tag{3.4}$$

Where P_W and P_B are water power and brake power, respectively.

Following equations are used to calculated the P_W and P_B:

$$P_{W(kW)} = \gamma \times H \times Q \tag{3.5}$$

$$P_{B(kW)} = P_E \times e_m \tag{3.6}$$

where

P_W	*Water power (kW);*
P_B	*Brake power (kW);*
P_E	*Electric power (kW);*
Q	*Water flow rate (m^3/s);*
H	*Head produced by pump (m_{H_2O});*
η_e	*Motor efficiency (%);*
γ	*specific weight of fluid (water) (kN/m^3).*

3.5 Reliability

3.5.1 Qualitative and Operational Analysis

3.5.1.1 Failure Mode and Effects Analysis (FMEA)

An FMEA is often the first step of a system reliability study. It involves reviewing as many components, assemblies, and subsystems as possible to identify failure modes, and their causes and effects. FMEA is an inductive reasoning (forward logic) single point of failure analysis and is a core task in reliability engineering, safety engineering and quality engineering.

A successful FMEA activity helps identify potential failure modes based on experience with similar products and processes—or based on common physics of failure logic. It is widely used in development and manufacturing industries in various phases of the product life cycle.

Functional analyses are needed as an input to determine correct failure modes, at all system levels. The FMEA is in principle a full inductive (forward logic) analysis, however the failure probability can only be estimated or reduced by understanding the failure mechanism. Hence, FMEA may include information on causes of failure (deductive analysis) to reduce the possibility of occurrence by eliminating identified (root) causes.

3.5.1.2 Reliability Centered Maintenance (RCM)

Reliability-centered maintenance (RCM) is a process to ensure that systems continue to do what their user require in their present operating context. It is generally used to achieve improvements in fields such as the establishment of safe minimum levels of maintenance. Successful implementation of RCM will lead to increase in cost effectiveness, reliability, machine uptime, and a greater understanding of the level of risk that the organization is managing. It is defined by the technical standard SAE JA1011, Evaluation Criteria for RCM Processes.

Reliability centered maintenance is an engineering framework that enables the definition of a complete maintenance regimen. It regards maintenance as the means to maintain the functions a user may require of machinery in a defined operating context. As a discipline it enables machinery stakeholders to monitor, assess, predict and generally understand the working of their physical assets. This is embodied in the initial part of the RCM process which is to identify the operating context of the machinery, and write a Failure Mode Effects Analysis (FMEA). The second part of the analysis is to apply the "RCM logic", which helps determine the appropriate maintenance tasks for the identified failure modes in the FMEA. Once the logic is complete for all elements in the FMEA, the resulting list of maintenance is "packaged", so that the periodicities of the tasks are rationalised to be called up in work packages; it is important not to destroy the applicability of maintenance in this phase. Lastly, RCM is kept live throughout the "in-service" life of machinery, where the effectiveness of the maintenance is kept under constant review and adjusted in light of the experience gained.

RCM can be used to create a cost-effective maintenance strategy to address dominant causes of equipment failure. It is a systematic approach to defining a routine maintenance program composed of cost-effective tasks that preserve important functions.

3.5.2 Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is a logical and graphical method to represent the chain of events leading to failure of system [17, 19]. The method has been used widely for assessment of reliability of industrial and nuclear power plants. It has been proved to be a suitable approach to identify critical assets of a plant that require special attention.

A set of representative FTA graphs for a typical pump station is illustrated in this subsection.

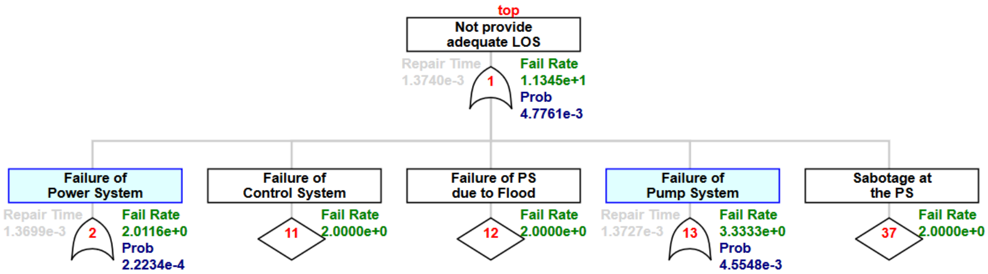


Figure 3.5: Fault Tree - Causes of Failure

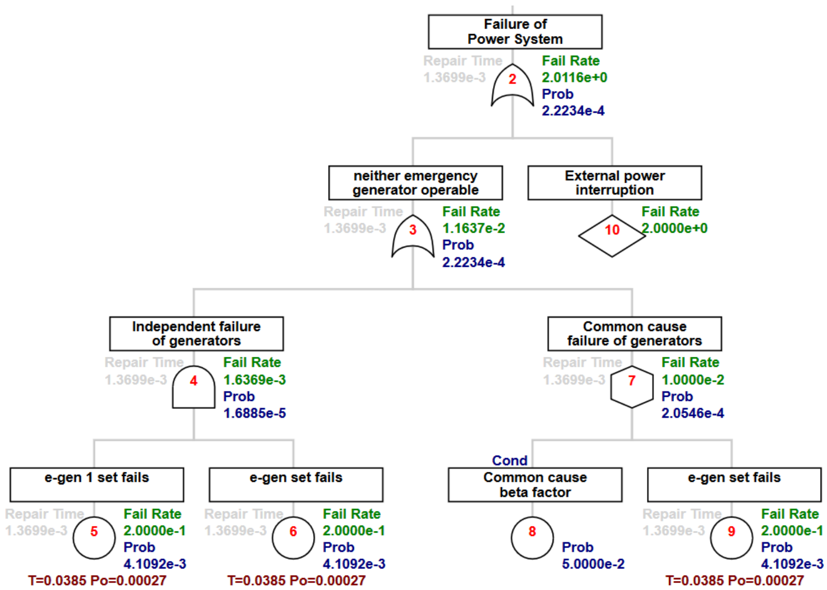


Figure 3.6: Fault Tree - Failure of Power System

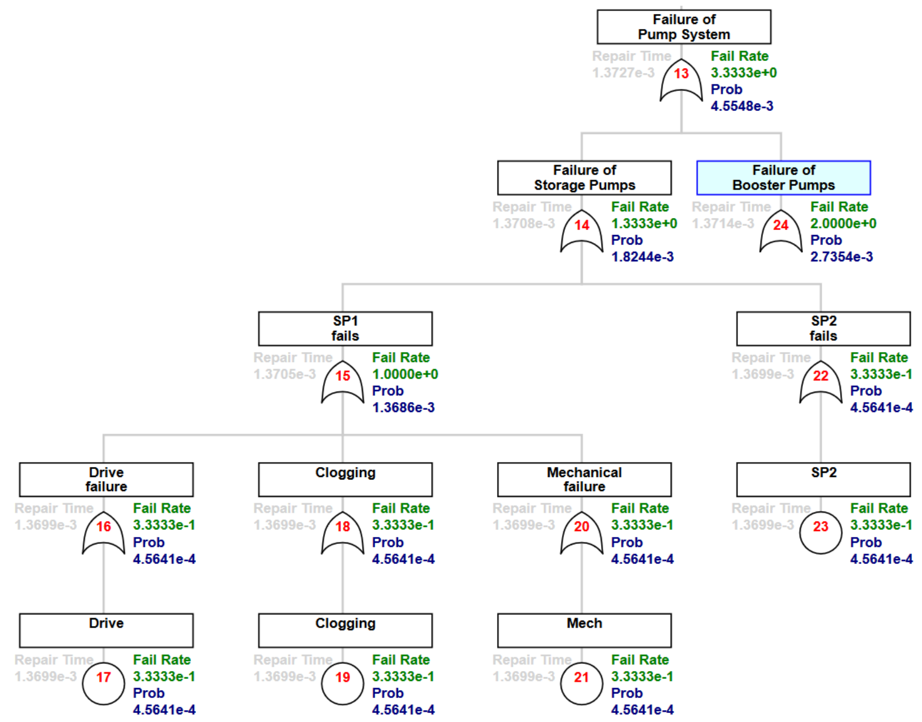


Figure 3.7: Fault Tree - Failure of Pump System

3.5.3 Herz model

Herz model is a semi-probabilistic model that has been used widely in deterioration prediction of water pipe [10, 9, 11]. Following formula describes formula to estimate the proportion or percentage of pipe (y_i) that remain in CS i at time x.

$$y_i(x) = \begin{cases} \frac{a+1}{a+e^{b(x-c)}} & x \geq c \\ 1, 0 & \text{Otherwise} \end{cases} \tag{3.7}$$

where

a	*Deterioration factor;*
b	*Transition parameter;*
c	*Resistance period.*

The percentage of CS i remains within a period x is analogy to reliability of the pipe staying in respective CS. The parameters a, b, and c are calibrated based on historical monitoring data. Thus, having historical data is pre-requisite for applying the model.

3.5.4 Weibull model

In hazard analysis, the deterioration of element is subjected to follow a stochastic process [16]. For binary state system, two condition level $0, 1$ are often used. When receiving a PI or CI, the CS from 1 must be changed into 0. In reliability study, this process is often regarded as renewal process. The renewal is carried out at alternative time t_k $(k = 0, 1, 2, ...)$. In this way, the next renewal time is denoted as $t = t_0 + \tau$, where τ indicating the elapsed time. The life span of an asset is expressed by a random variable ζ. The probability distribution and probability density function of the failure occurrence are $F(\zeta)$ and $f(\zeta)$ respectively. The domain of the random variable ζ is $[0, \infty]$. The living probability (hereafter named as survival probability) expressed by survival function $\tilde{F}(\tau)$ can be defined according to the value of failure probability $F(\tau)$ in the following equation:

$$\tilde{F}(\tau) = 1 - F(\tau). \tag{3.8}$$

The probability, at which the asset performs in good shape until time τ and break down for the first time during an interval of $\tau + \Delta\tau$ can be regarded as hazard rate and expressed in the following equation:

$$\lambda_i(\tau)\Delta\tau = \frac{f(\tau)\Delta\tau}{\tilde{F}(\tau)}, \tag{3.9}$$

where $\lambda(\tau)$ is the hazard function of the asset. In reality, the breakdown probability depends largely on the elapsed time of the asset since its beginning of operation. Thus, the hazard function should take into account the working duration of the asset (time-dependent). In another word, the memory of the system should be inherited. Weibull hazard function is satisfied in addressing the deterioration process [2, 15]:

$$\lambda(\tau) = \alpha m \tau^{m-1}, \tag{3.10}$$

where α is the parameter expressing the arrival density of the asset, and m is the acceleration or shape parameter. The probability density function $f(\tau)$ and survival function $\tilde{F}(\tau)$ in the form of Weibull hazard function can be further expressed in equation (3.11) and (3.12):

$$f(\tau) = \alpha m \tau^{m-1} \exp(-\alpha\tau^m), \tag{3.11}$$
$$\tilde{F}(\tau) = \exp(-\alpha\tau^m). \tag{3.12}$$

Estimation for Weibull's parameter is often with Maximum Likelihood Estimation (MLE) approach on historical data. Thus, the model's parameter is sensitive to how data behaves. We recommend to use this model only when there is sufficient data to be used.

An example of source code for education purpose is given in Github site of Nam Le [1]. The complete program is a copyright of Nam Le.

3.5.5 Markov model

The transition process among the condition states of an infrastructure component is uncertain. Therefore, future condition states cannot be forecasted deterministically. In this situation, Markov transition probability is employed to represent the uncertain transition pattern of the condition states during two time points. Markov transition probabilities can be defined for arbitrary time intervals.

For simplification, Markov transition probabilities can be defined and used to forecast the deterioration of a infrastructure component based on the information from periodical inspection scheme shown in Figure 3.4. The observed condition state of the component at time τ_A is expressed by using the state variable $h(\tau_A)$. If the condition state observed at time τ_A is i, then the state variable $h(\tau_A) = i$. A Markov transition probability, given a condition state $h(\tau_A) = i$ observed at time τ_A, defines the probability that the condition state at a future time (τ_B for example) will change to $h(\tau_B) = j$:

$$\text{Prob}[h(\tau_B) = j | h(\tau_A) = i] = \pi_{ij}. \tag{3.13}$$

The Markov transition probability matrix can be defined and rearranged by using the transition probabilities between each pair of condition states (i, j) as

$$\mathbf{\Pi} = \begin{pmatrix} \pi_{11} & \cdots & \pi_{1J} \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \pi_{JJ} \end{pmatrix}. \tag{3.14}$$

The Markov transition probability (3.13) shows the transition probability between the condition states at two given times τ_A and τ_B, therefore, it is straightforward that the values of a transition

[1] https://github.com/namkyodai/Models

probability will differ for different time intervals. Since deterioration continues as long as no repair is carried out $\pi_{ij} = 0$ $(i > j)$. From the definition of transition probability $\sum_{j=1}^{J} \pi_{ij} = 1$. Following conditions must be satisfied:

$$\left.\begin{array}{l} \pi_{ij} \geq 0 \\ \pi_{ij} = 0 \quad (\text{when } \ i > j) \\ \sum_{j=1}^{J} \pi_{ij} = 1 \end{array}\right\}. \tag{3.15}$$

The worse level of deterioration is expressed by the condition state J, which remains as an absorbing state in the Markov chain as long as no repair is carried out. In this case $\pi_{JJ} = 1$.

Markov transition probabilities are defined independently from the deterioration history. As shown in Figure 3.4, the condition state at the inspection time τ_A is i, however, the time, at which, condition state changed from $i-1$ to i is unobservable. In a Markov chain model, it is assumed that the transition probability between the inspection times τ_A and τ_B is only dependent on the condition state at time τ_A.

The Markov chain model is operative and widely applied in management of infrastructure system. Particularly, at management of network level, Markov chain model is used to define the average transition probability of the entire system, or a group of infrastructure components given two periodical inspection data.

Estimation for the Markov transition probability can be done by the MLE approach [16, 18] or Bayesian Estimation approach [12, 14] based on historical data. One advance of using the Markov model is that one time monitoring data can be used. A generic formula to estimate the transition probability is given in following Equations:

$$\pi_{ii} = \exp(-\theta_i Z), \tag{3.16-a}$$

$$\pi_{ii+1} = \frac{\theta_i}{\theta_i - \theta_{i+1}} \{-\exp(-\theta_i Z) + \exp(-\theta_{i+1} Z)\}, \tag{3.16-b}$$

$$\pi_{ij} = \sum_{k=i}^{j} \prod_{m=i}^{k-1} \frac{\theta_m}{\theta_m - \theta_k} \prod_{m=k}^{j-1} \frac{\theta_m}{\theta_{m+1} - \theta_k} \exp(-\theta_k Z), \tag{3.16-c}$$

$$\pi_{iJ} = 1 - \sum_{j=i}^{J-1} \pi_{ij}, \tag{3.16-d}$$

$$(i = 1, \cdots, J-1) \qquad (j = i, \cdots, J).$$

An example of source code for education purpose is given in Github site of Nam Le [2]. The complete program is a copyright of Nam Le.

3.6 Intervention Strategy (IS)

Intervention Strategy (IS) is at asset level (level 7). It is a collection of intervention type for component level (level 8). A collection of ISs will form an Intervention Program for (IP) the station. A collection of IPs will form a Work Program (WP) for network level intervention (e.g. a bid awarded for a designer/contractor can be a WP that consists of intervention program for one or more than one pump stations). Following generic IS is defined to guide the selection of IPs that will be details in the later part of the report.

For each type of asset, IS will be selected based on reliability study and consideration of cost. Further more, Employers inputs and requirements are also taken into account.

3.7 Determination of optimal intervention strategy

Following subsections briefly describe the model that can be used to determine optimal intervention strategy.

[2] https://github.com/namkyodai/Models

Table 3.3: Generic intervention strategy (IS).

IS	Definition	Remarks
1	Do Nothing	
2	Minor repair	Require minimal effort and can be done only for certain asset type
3	Major repair	Require extensive efforts to return the asset to likely new condition
4	Replacement/Renewal	Replacing assets or components of asset with identical one or with new model

3.7.1 Block Replacement Model

It is assumed that a PI is executed after a pre-defined time $n \cdot T$ $(n = 0, 1, 2, \cdots, N)$. Once the PI is executed, the functionality and serviceability of the asset could be the same or different from that of the asset before the intervention. In between the time Δt ($[0 \leq \Delta t \leq T]$), hazards could occur and cause the asset in worse CSs (hereafter denoted as i $(i = 1, \cdots, I)$), in which the asset is no longer providing an adequate level of services (LOS). In both cases, when the PI or CI is executed, there are impacts incurred by stakeholders s (e.g. the owner, the users, the public).

Following notations are used to describe the formulation of the model.

$\theta(\Delta t\vert t)$	Conditional failure rate i $(i = 1, \cdots, I)$ when the asset has been in service in an interval t after the PI
$\Psi(\cdot\vert t)$	Any conditional function Ψ given that a PI is executed by a unit of age t, where t is a random variable
$F(t)$	Cumulative distribution function (cdf) of age t of a unit for a PI at execution time
$w_p^s(t)$	Impacts incurred by stakeholder s due to the execution of PI
$w_c^s(t)$	Impacts incurred by stakeholder s due to the execution of CI
$w_o^s(\Delta t\vert t)$	Conditional impacts incurred by stakeholder s when the structure is remains in normal operation (*i.e.* providing an adequate LOS) during time interval Δt after a PI has been carried out and the asset has not entered failure state
ρ	discount factor
$p_l^k(t)$	probability of failure at time t of the affecting other assets k
$C_c^{s,k}$	Impacts incurred by stakeholder s due to the execution of an CI on other assets k
T	interval between the PIs
$T^\star$	Optimal interval time between PIs, which is the variable of the model
$\Omega_p(T,t)$	minimum expected total discounted impact for an infinite time span when the asset has been in service during an interval t after the execution of the PI and the asset has not entered failure state
$\Omega_c(T,t)$	minimum expected total discounted impact for an infinite time span when a CI has been executed, of the asset that has been in service during a time interval t after the execution of the PI and the asset has entered failure state

In the model, it is assumed that at each damage level i, there exists a corresponding well defined CI. Within an increment of time Δt, after the asset has been under the PI after time t, the total expected impacts due to the execution of CIs are:

$$v_c(\Delta t|t) = \sum_{s=1}^{S} \left[w_c^s(\Delta t) + \sum_{k=1}^{K} p_l^k \cdot C_c^{s,k} \right] \cdot \theta(\Delta t|t). \tag{3.17}$$

The total impacts due to the execution of PIs and the total impacts incurred by stakeholders during the service time of the asset are defined in Eq. (3.18) and Eq. (3.19), respectively.

$$v_p(t) = \sum_{s=1}^{S} w_p^s(t). \tag{3.18}$$

$$v_o(t) = \sum_{s=1}^{S} w_o^s(t). \tag{3.19}$$

According to the principle of optimality, which is described in [1, p. 15], the minimum expected total discounted impact $\Omega_c(T,t)$ for infinite time is formulated in following equation.

$$\Omega_c(T,t) = \int_0^{\infty} \left[v_c(\Delta t|t) + \Omega_p(T,\Delta t|t)\right] dF(t). \tag{3.20}$$

The minimum expected total discounted impact $\Omega_p(T,\Delta t|t)$, which appears inside Eq. (3.17), is obtained as follows

$$\Omega_p(T,\Delta t) = min\Gamma(\Delta t). \tag{3.21}$$

where $\Gamma(\Delta t)$ is defined as

$$\begin{aligned}\Gamma(\Delta t) = \int_0^{\infty} \Big[v_o \int_0^{dt} exp(-\rho\tau)d\tau + \{1-\theta(\Delta t|t)dt\} \cdot \Omega_p(T,\Delta t + dt|t) exp(-\rho dt) \\ +\theta(\Delta t|t)dt \cdot \Omega_c(T,\Delta t + dt|t) exp(-\rho dt) \Big] dF(t).\end{aligned} \tag{3.22}$$

According to [13], Eq. (3.22) is rewritten in following form

$$\begin{aligned}\Gamma(\Delta t) = \Omega_p(T,\Delta t) + \left[-\rho\Omega_p(T,\Delta t) + d\Omega_p(T,\Delta t)/dt\right] dt \\ + \int_0^{\infty} \left[v_o + v_c(\Delta t|t)\right] dF(t)dt.\end{aligned} \tag{3.23}$$

Thus, from $\Omega_p(T,\Delta t) = \Gamma(\Delta t)$ (Eq. (3.21)), the following equation can be derived:

$$\Omega_p(T,\Delta t) = exp(\rho\Delta t) \left[\Omega_p(T,0) - \int_0^{\infty} \int_0^{t} exp(-\rho\tau) \{v_o + v_c(\tau|t)\}\right] d\tau dF(t). \tag{3.24}$$

where,

$$\begin{aligned}\Omega_p(T,0) = \{1 - exp(-\rho T)\}^{-1} \int_0^{\infty} \Big[exp(-\rho T) \{v_p(T,t)\} \\ + \int_0^{T} exp(-\rho\Delta t) \{v_o(\Delta t|t) + v_c(\Delta t|t)\} dt \Big] dF(t).\end{aligned} \tag{3.25}$$

when T tends to infinity $T \to \infty$, Eq. (3.25) becomes

$$\Omega_p(\infty,0) = \int_0^{\infty} \int_0^{\infty} exp(-\rho t) \left[v_o + v_c(\Delta t|t)\right] dt dF(t). \tag{3.26}$$

Eqs. (3.25) and (3.26) are the explicit forms of the expected total discounted impact in infinite time horizon. This is the classical optimization problem. By differentiating the expected total discounted impact $\Omega_p(T,0)$ and $\Omega_p(\infty,0)$ and setting it equal to zero, the optimal time $T^\star$ can be obtained. The optimal time $T^\star$ for PI is the solution of the following system of equations:

$$\begin{cases} T^\star = \arg \min\limits_{T^\star \in [0,T]} \Theta_p(T,0) \\ T^\star = \arg \min\limits_{T^\star \in [0,\infty]} \Theta_p(\infty,0) \end{cases} \tag{3.27}$$

in which the differentiates of $\Theta_p(T,0)$ and $\Theta_p(\infty,0)$ are respectively:

$$\begin{aligned}\Theta_p(T,0) &= \frac{\delta(\Omega_p(T,0))}{\delta T} \\ &= [1 - exp(-\rho T)] \int_0^{\infty} \Big[-\rho v_p(T,t) \\ &\quad + d(v_p(T,t))/dT + v_o(T,t) + v_p(T,t) \Big] dF(t) \\ &\quad -\rho \int_0^{\infty} \Big[exp(-\rho T) \{v_p(T,t)\} \\ &\quad + \int_0^{T} exp(-\rho\Delta t) \{v_o(\Delta t|t) + v_c(\Delta t|t)\} dt \Big] dF(t).\end{aligned} \tag{3.28}$$

and

$$
\begin{aligned}
\Theta_p(\infty,0) &= \frac{\delta(\Omega_p(\infty,0))}{\delta T} \\
&= \int_0^\infty \left[-\rho\left\{v_p(\infty|t) + \int_0^\infty exp(-\rho t)\left\{v_o(\Delta t|t) + v_p(\Delta t|t)\right\}\right\}\right. \\
&\quad \left. + \lim_{T\to\infty} d(v_p(T,t))/dT + v_o(\infty|t) + v_p(\infty|t)\right] dF(t) \qquad (3.29)
\end{aligned}
$$

3.7.2 Time-dependent replacement model

Time-dependent replacement model (or Age replacement model) are the ones where the following conditions apply:

- the asset starts operating at $t = 0$, i.e. it is newly built or newly restored to a like new condition following an intervention;
- the probability of failure is described with $f(t)$ and $F(t)$, i.e. the lifetime density and the lifetime;
- if the asset fails on the interval $(0, T]$ a CI is executed;
- if the object does not fail on the interval $(0, T]$ the object is replaced at T, i.e. the PI replacement is executed, regardless if the object has failed and been restored in the time interval $(0, T]$;
- the execution of a PI restores the object to a like new condition;
- the execution of a CI restores the object to a like new condition.

3.7.2.1 Minimize impact

If an age replacement IS is followed the time to the first intervention, Z, is the minimum amount of the time to failure of the length of the renewal period:

$$Z = min(\tau, T) \qquad (3.30)$$

The expected, or mean, time to the first intervention is then determined by

$$E[Z = \int_0^T (1 - F(x))dx] \qquad (3.31)$$

The mean impact in one renewal period then equals the probability of failure on T multiplied by the impacts associated with the CI plus the probability that no failure occurs on T multiplied by the impacts associated with the PI:

$$F(T) \times I^{CI} + (1 - F(T)) \times I^{PI} \qquad (3.32)$$

The mean impacts per unit time, therefore, equal the mean cost in one renewal period divided by the length of the renewal period, i.e. the time to the first intervention.

$$\eta_{AC} = \frac{F(T) \times I^{CI} + (1 - F(T)) \times I^{PI}}{\int_0^T (1 - F(x))dx]} \qquad (3.33)$$

3.7.2.2 Maximize availability

If it is desired to determine the age replacement IS that maximizes availability the following is often assumed, additionally that:

- the PI replacement takes t^{PI};
- the PI takes t^{CI};

If the asset fails before T then the length of the renewal period will, therefore, be $X = t + t^{CI}$, which has the probability $f(t)dt$ of occurring, and if the object does not fail before T then the length of the renewal period will be $X = t + t^{PI}$, which has the probability $1 - F(T)$ of occurring.

In this case, the expected, or mean, renewal period length is:

$$E[X] = \int_0^T (1 - F(x))dx + t^{CI}F(T) + t^{PI}(1 - F(T)) \tag{3.34}$$

As the asset is operational on average $\int_0^T (1 - F(x))dx$ then the availability is given by:

$$\eta_{AA} = \frac{\int_0^T (1 - F(x))dx}{\int_0^T (1 - F(x))dx + t^{CI}F(T) + t^{PI}(1 - F(T))} \tag{3.35}$$

Chapter 4

Data and Analysis

4.1 Qualitative and Operational Analysis

4.1.1 Facts and Data

Summary of facts and data concerning operational and overall plan reliability is presented in this subsection.

4.1.1.1 Normal Operation Scenario

- 3 Booster pumps out of 4 are in operation to meet the 80psi discharge pressure;
- The 2 Supply pumps are not in operation.

4.1.1.2 High Demand Scenario

- If the pressure drops below 80 psi, one of the Supply Pumps is started to increase the discharge pressure above 80psi;
- Note that the current supply line pressure is at 4psi and future increase in demand (population growth), this will continue to drop causing more issues to the booster pumps.

4.1.1.3 Low Demand Scenario

- The one of the supply pumps is used to refill the supply tanks from 12mn until 5am;
- The pressure of the main supply line is only at 4psi and is not high enough to refill the supply tanks through the MOVs.

4.1.1.4 Spares Policy

- Booster pumps: There is no fixed schedule in switching the duty and the spare pumps. By "feel", the operators rotate the pumps as they see fit;
- Storage pumps: SP1 and SP2 are switched daily during the filling-up of the supply tanks.

4.1.1.5 Emergency Situation (loss of electrical power from Meralco)

- As soon as the power is cut, one of the 2 Gensets automatically start and makes electric power available for the booster and/or supply pumps. The operator resets all the pumps before restarting each manually. This may take between 60 seconds to 5 minutes before all the pumps provide enough pressure/flow to the system.

4.1.1.6 Maintenance

- There is no structured maintenance program in the facilities. The operator makes rounds of the pumps and if something unusual is observed, a text or email is sent to the Control Center for scheduling of maintenance check and repairs;
- There is also a maintenance team visiting the site regularly with specific lists of tasks and responsibilities.

4.1.1.7 Others

- BP3 is has just gone overhauling with impeller replacement as well as replacement of a damaged bearing. It was reported that this is the second bearing failure in 4 years.

4.1.2 Recommendations

In order to ensure the PS to provide adequate level of services around the clock, it is important to establish a good operational scheme that allows optimization of use of pumps to reduce breakdown and to conserve energy. A summary of major recommendations to be considered are

- Consider an additional booster pump to improve the reliability of the facility. With one pump undergoing major repairs, the arrangement does not allow for another pump to fail, otherwise, there will be a major loss of pressure with only 2 booster pumps running. The use of the other 2 storage pumps can only be done on short-term arrangement because the storage tank has a limited capacity plus the fact that during peak loads, the 4 pumps (2 BP + 2 SP) is not enough to sustain at least 80psi in the discharge line;
- Consider a dedicated duty and a dedicated spare set-up for the pumps. If this is not acceptable, then consider doing a much longer switch of the storage pumps. Currently, it is being switched daily to supply the storage tank between midnight and 5am. This allows for almost an equal rate of deterioration between the two pumps and if one pump fails due to age-related component failure, the other one is close to a similar failure which may occur before the first pump is fully repaired. It is suggested that the switch happen once a month or even every 3 months;
- In place of the longer switching cycle (e.g. every 3 months), there should be a corresponding maintenance program for the standby pump for both booster and storage;
- Develop a more structured discipline in applying routine maintenance work process to ensure that maintenance tasks are given the proper priority in terms of mitigation measures and avoid unplanned shutdown of critical pumps in operation.

Aside from the above recommendations, we also generate a list of recommendations based on the RCM methodology (refer to Appendix A). The list shall be considered as a living program, which requires continuously improvement as part of the total quality management system (refer to Deming cycle presented in GHD's technical proposal).

4.2 Pump discharge and suction pipe - thickness

4.2.1 Data and measurement

Thickness data on discharge and suction pipes of pumps is presented in Table 4.1 and Table 4.2 .

In the table, the positions and the distances for the Ultrasonic Thickness Gauging (UTG) are referred to Figure 4.1 and Figure 4.2.

4.2.2 Analysis

This section provides analysis/discussion on estimation of minimum allowable thickness of pipes and statistics around the measured data collected during inspection and testings.

Table 4.1: Thickness data - Booster Pumps (mm).

Asset	Position	Distance (m)						
		Suction				Discharge		
		2m	4m	5m	ELBOW	2.2 m	3.2 m	ELBOW
BP1	12	4.84	4.76	4.7	4.74	4.75	4.76	4.81
	3	4.77	4.74	4.76	4.86	4.71	4.75	4.63
	6	4.85	4.74	4.74	4.79	4.68	4.66	4.76
	9	4.84	4.77	4.69	-	4.77	4.7	-
BP2	12	4.84	4.84	4.93	5.02	4.76	4.76	4.68
	3	4.88	4.47	4.91	4.91	4.66	4.7	4.77
	6	4.83	4.94	4.84	5.04	4.65	4.57	4.77
	9	4.74	4.78	4.9	-	4.72	4.53	-
		2m	3m	ELBOW		2m	3m	ELBOW
BP3	12	4.74	4.75	4.67		4.66	4.75	4.66
	3	4.7	4.78	4.83		4.65	4.8	4.75
	6	4.81	4.76	4.75		4.76	4.73	4.77
	9	4.82	4.71	-		4.65	4.74	-
BP4	12	4.9	4.86	4.92		4.79	4.92	4.92
	3	4.79	4.89	4.75		4.86	4.96	4.69
	6	4.91	4.65	4.89		4.94	4.95	5.04
	9	4.65	4.7	-		4.96	4.96	-

Table 4.2: Thickness data - Storage Pumps (mm).

Asset	Position	Distance				
		Suction		Discharge		
		2m	ELBOW	2m	3m	ELBOW
SP1	12	4.64	4.68	4.69	4.64	4.39
	3	4.77	4.7	4.52	3.88	4.73
	6	4.76	4.69	4.05	4.62	4.74
	9	4.71	-	4.69	4.63	-
SP2	12	4.62	4.88	4.71	4.58	4.64
	3	4.76	4.8	4.63	4.62	4.79
	6	4.8	4.84	4.68	4.45	4.71
	9	4.67	-	4.69	4.72	-

4.2.2.1 Statistics

A summary on statistics regarding the measured thickness for booster pumps and storage pumps is presented in Table 4.3.

Table 4.3: Summary of statistics - thickness.

Statistics	Booster suction		Booster discharge		Storage suction		Storage discharge	
	Straight	Elbow	Straight	Elbow	Straight	Elbow	Straight	Elbow
Min	4.470	4.670	4.530	4.630	4.680	4.680	4.390	4.390
1st Qua.	4.740	4.750	4.675	4.688	4.693	4.693	4.658	4.658
Median	4.775	4.845	4.750	4.765	4.750	4.750	4.720	4.720
Mean	4.784	4.848	4.757	4.771	4.765	4.765	4.667	4.667
3rd Qua.	4.843	4.913	4.793	4.780	4.830	4.830	4.738	4.738
Max	4.940	5.040	4.960	5.040	4.880	4.880	4.790	4.790

Table 4.4 shows the summary of statistics for individual pump with extrados thickness calculated.

Figures 4.3 and 4.4 show comparative graphs of min, mean, and max values of thickness.

Followings are generic interpretation by examining the tables and graphs

- Mean value of thickness is above 4.6 mm;
- Mean and median values are close, inferring a confidence on having less heterogeneity, i.e. distribution of thickness around the pipe is more or less homogeneous;

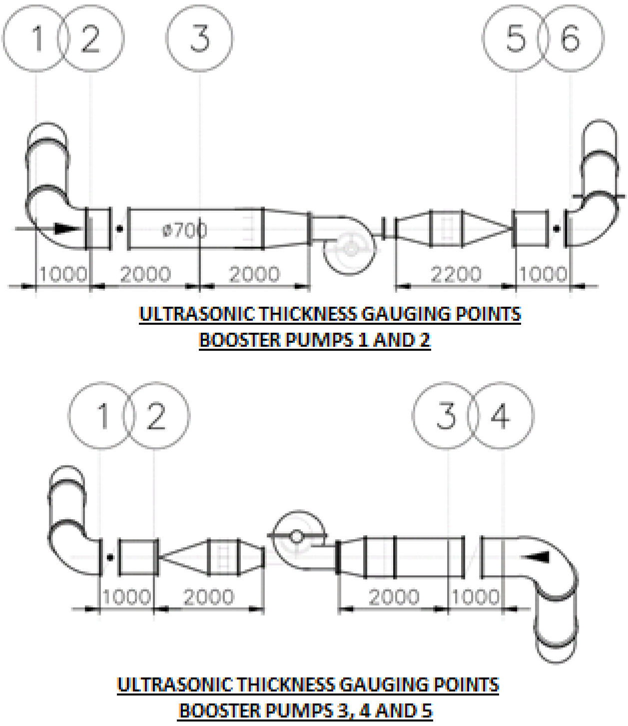


Figure 4.1: Positions and distances of UTG - Booster Pump

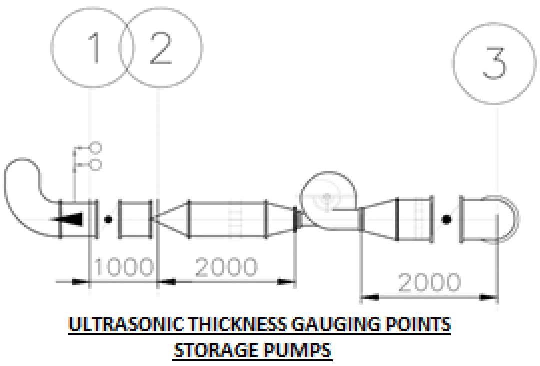


Figure 4.2: Positions and distances of UTG - Storage Pump

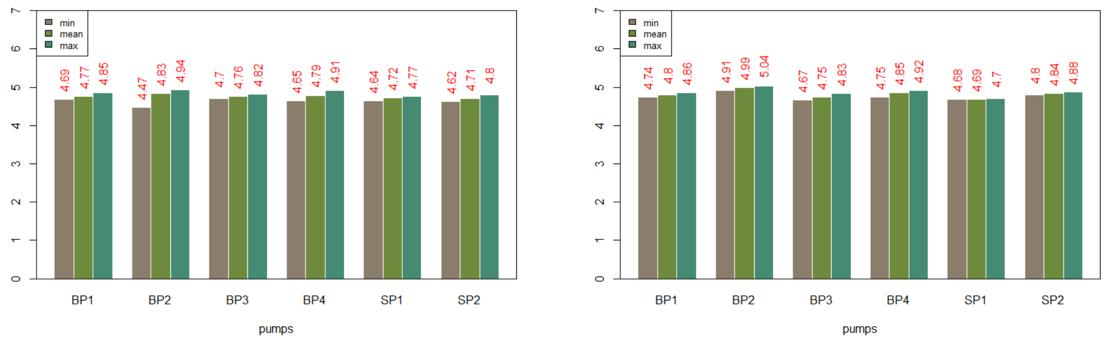
- Thickness at elbow is less than that of the straight line;
- THickness of storage line is likely to be higher than that of the discharge line;
- BP1 has a value of 3.92 as min at the elbow, which requires attention from time to time.

BP1

- Suction Piping System-This pump is observed to have low noise level during operation. The 4 m mark 3 and 6-o'clock positions have the thinner wall compared to other locations , this may due to the fact that water flows directly towards it. On the other hand, the 2 m mark has considerably small to no thinning;
- Discharge Piping System- As observed from the data gathered, the flow pattern based on thinning is higher in the lower half of the discharge pipe. It then enters the elbow and

Table 4.4: Summary of statistics - thickness (individual pump).

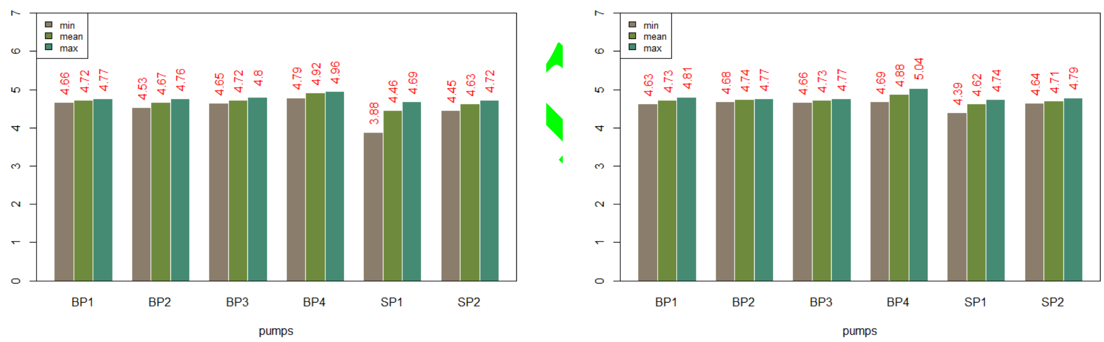
Assets	Suction (mm)				Discharge (mm)			
	Min	Mean	Extrados	Max	Min	Mean	Extrados	Max
BP1	4.690	4.773	4.770	4.860	4.630	4.725	4.740	4.810
BP2	4.470	4.858	4.950	5.040	4.530	4.688	4.750	4.770
BP3	4.670	4.755	4.750	4.830	4.650	4.720	4.730	4.800
BP4	4.650	4.801	4.860	4.920	4.690	4.908	4.890	5.040
SP1	4.640	4.707	4.690	4.770	3.880	4.507	4.630	4.740
SP2	4.620	4.767	4.840	4.880	4.450	4.656	4.680	4.790



a - Straight

b - Elbow

Figure 4.3: Suction line



a - Straight

b - Elbow

Figure 4.4: Discharge line

approaches towards the middle extrados (4.63 mm). The thickness of the discharge pipe is lower when compared to the suction pipe.

BP2

- Suction Piping System- It is observed to have considerably small or no thinning. However referring to 4m mark, 3-o'clock position where the flow seems to be directed to this area, the thickness has a difference of 0.3mm to 0.4 mm from the rest of the readings. This is possible due to the high velocity of water entering at high momentum. Also possibility that needs to be validated is that abrasions increase the effect of erosions due to sediments making contact in the wall;
- Discharge Piping System- The thickness gathered is lower compared to the suction line of the same pipeline. This means that the thinning rate at the discharge line is higher. This

could be possible due to the cavitation carried out to the discharge side of the pump. The flow pattern is that it enters the elbow having the lower half of the pipe a higher velocity approach. It can also be observed that the thinning occurs greatly at the entrance of the elbow and decreases at the exit of the elbow bend.

BP3

- Suction Piping System- Upon inspection, this pipe was observed to emit certain water flow sound and crackling sounds. Referring to data, the water flow contacts higher at the exit extrados area and swirls at the 3 and 6-o'clock positions of the 3m mark. It is also seen to have a high backflow rate creating eddies at the 12 and 9-o'clock orientations, thus having a possibility of turbulency. Moreover, 2 m away from the pump, the water tends to swirl from the left side to the right side of the pipe;
- Discharge Piping System- The data gathered may indicate that cavitation is carried over the discharge side of the pump. The cavitation occurs at the upper half of the pipe. This extends to the elbow's extrados.

BP4

- Suction Piping System- This suction pipe inhibits localized wall thinning at the exit elbow extrados. Backflow is also present at the elbow as indicated by the thinning in the intrados area of the bend;
- Discharge Piping System- Localized wall thinning is not present except in the middle extrados are of the elbow. This thinning indicates that the flow approaches directly in the middle extrados of the elbow and then exits the elbow with less turbulent phase. .

SP1

- Suction Piping System- The suction line of the SP's are vertical and not inclined like the setups in the BP's. The thickness confirmed to have a direct flow contacting the extrados surface from the entrance up to the elbow exit. This extends to the 12-o'clock position at the 2m mark. The 2m mark is also near at the elbow. No high backflow rate has been observed;
- Discharge Piping System- localized wall thinning occurs at the bottom part of the pipe as it is next to a concentric reducers that concentrates the flow. It then continues by swirling to one side of the pipe before entering the elbow. The flow then extends the swirling from the side to the extrados bend entry.

SP2

- Suction Piping System- In this pipeline, the water flow contacted towards the 2m mark and less contacting the entrance elbow part. The thinning data also describes the water pattern of most pattern which travels at the higher half and then flows below half of pipe;
- Discharge Piping System-Based on the measurements, the discharge side of the pump indicates that low cavitation may be carried out. The flow enters and is concentrated in the lower half of the pipe and swirls to the extrados entry of the pipe. It indicates a backflow at the bend intrados extending to the extrados exit of the bend.

4.2.2.2 Assumptions

Following assumptions are used in calculating the required thickness of pipe

- Maximum Working Head – based on the design drawings and pump nameplate;
- Pipe Material – assume pipe material is ASTM A570 Grade 33 (market available material for spiral welded pipe);

- Design Guide – basis used for the simulated calculation is AWWA Manual M11 – Steel Pipe, A Guide for Design and Installation, 4th Edition. Statement for corrosion allowance is located at Chapter 4, which states *"At one time, it was a general practice to add a fixed, rule-of-thumb thickness to the pipe wall as a corrosion allowance. This was not an applicable solution in the water work field, where standard for coating and lining materials and procedures exists. The design shall be made for the required wall-thickness pipe as determined by the loads imposed, then linings, coatings, and cathodic protection selected to provide the necessary corrosion protection"*;
- Thickness calculation will be based on the internal pressure. External pressure will not be considered because much of the discharge line is not buried;
- Surge Pressure was not considered since there are surge protection along the line.;
- This document will only consider the calculation of the minimum thickness along the discharge line since this is the part of the system where maximum pressure is experience.

4.2.2.3 Limitations

As confirmed by Maynilad, there is no available data regarding the design report. Design assumptions herein may be different from what was used by the designer/contractor of this station.

This document will not be able to provide the corrosion/degradation factor of the pipe since there is no available historical data on the thickness of the pipe.

4.2.2.4 Parameter values for thickness estimation

In order to estimate the minimum allowance thickness for pipes in straight line considering material handling (t_{mh}) and maximum internal pressure based on AWWA M11 (t_{sph}), following equations are used, respectively:

$$t_{mh} = \frac{\Phi}{\delta} \tag{4.1}$$

$$t_{sp} = \frac{\epsilon \times P_{max} \times \Phi}{2 \times S_e} \tag{4.2}$$

where P_{max} is maximum internal pressure

$$P_{max} = \frac{\rho_{H_2O} \times g \times H_{max}}{1000} \tag{4.3}$$

In order to estimate the minimum allowance thickness for pipes at elbows (Miter Bend), only maximum internal pressure is considered:

$$t_{mb} = \frac{P_{max} \times \Phi}{2 \times S_e} \times \left[1 + \frac{\Phi}{(3 \times R) - (1.5 \times \Phi_d)}\right] \times \epsilon \tag{4.4}$$

Parameter values used for computation are given in Table 4.5

4.2.2.5 Required thickness

Results of computation for minimum allowable thickness for booster pumps and storage pumps are given in Table 4.6 and Table 4.7.

If comparing these values with the measured values of thickness shown in subsection 4.2.2.1, it can be concluded that current thickness of pipes at both suction and discharge still provide adequate level of services.

Table 4.5: Parameter values for thickness estimation.

Parameters	Symbol	Unit	Pumps		Remarks
			Booster	Storage	
Discharge diameter	Φ_d	mm	600	600	
Hydro test pressure	H_max	m	105.6	105.6	
Max flow rate	Q_max	m^3/s	0.671	0.231	
Max pump head	H_max	m	50	60	based on name plate
Yield strength of material	S_y	MPa	227.5	227.5	ASTM A570 Grade 33, spiral welded pipe based on AWWA C200
Allowable stress	S_e	MPa	113.75	113.75	
Density of water	ρ_{H_2O}	kg/m^3	1000	1000	
Gravity constant	g	m/s^2	9.81	9.81	
Safety factor	ϵ		1.5	1.5	
Bulk modulus of compressibility of liquid	k	Pa	2.1E+09	2.1E+09	
Young's modulus of elasticity of pipe wall	E	Pa	2.1E+11	2.1E+11	
Radius of Elbow	R	mm	800	800	
Empirical constant	δ		288	288	

Table 4.6: Minimum thickness allowance based on pump head.

Pumps	Internal pressure (Mpa)	Minimum allowable thickness (mm)		
	P_{max}	t_{mh}	t_{sp}	t_{mb}
Booster	0.491	2.08	2.59	3.62
Storage	0.589	1.74	2.59	3.37

4.2.2.6 Deterioration

Given the lack of design data, precise design thickness is unknown, following assumptions are made

- Maximum measured thickness is considered to be the design thickness;
- Pipe has been in operation for 9 years since 2010;
- Deterioration rate is to follow linear function.

4.2.2.7 Recommendations

Given the current thickness of pipe the lack of design information, it is advisable to

- Not perform any major intervention on the pipes;
- Keep regular testing on exact locations using the same type of UTG device. It is important for Maynilad to establish a testing regime for obtaining thickness at exact same location over time (e.g. every year). Information obtained from testing will be then used to compute deterioration rate based on thickness value;
- Establish an approach to inspect/test the thickness of underground pipe, which is considered to be more vulnerable to leakage and corrosion on external wall;
- The elbows in the suction and the discharge piping systems must be monitored regularly;
- It is recommended to have a profiling of the piping systems above and below the ground in order to have a baseline in the analysis of the Maynilad Piping System. In order to have a profiling of pipe thickness at differential time T, additional measurement at similar locations shall be conducted periodically, behavior can then be monitored;
- Perform coating regularly of the pipe to prevent possible corrosion/erosion and damage that cause by external factors and surrounding condition;

Table 4.7: Minimum thickness allowance based hydro test pressure.

Pumps	Internal pressure (Mpa)	Minimum allowable thickness (mm)		
	P_{max}	t_{mh}	t_{sp}	t_{mb}
Booster	0.491	2.08	4.10	5.74
Storage	0.589	1.74	3.42	4.45

4.3 Visual Inspection on Pipe, valves, fittings, supports, expansions, and appurtenances

4.3.1 Highlights

Visual inspection data on pipes, valves, fittings, supports, expansions, and appurtenances is highlighted in Table 4.8.

Table 4.8: Highlights of visual inspection

No.	Items	Remarks
1	Modified pipe design to fit space limitations	Limitation in space prompted compromise in pipe design and not did not follow recommended piping arrangements and instead may promote turbulent flow profiles at pump suction and discharge that can accelerate pump and fittings wear
2	Type of pipe and fitting support	Anchor type piping support makes pipe system rigid.
3	Paint and protective coating of outdoor pipe	Portion of pipe extending outside of pump house and are experiencing surface deterioration. Protective coating and paint falling off exposing some bare metal which are already display corrosion.
4	Local corrosion on indoor pipes	Some indoor pipes have torn paint films and exposed bare metals which display corrosion
5	Valve Leaks	Minor leaks that still contributes to deterioration of parts due to corrosion
6	Pressure gauges	Discrepant measurements between dial and digital gauges up to 10 psi Deterioration of information tags making them unreadable Superimposed tags which make it obscure
7	Motion actuated lighting	Interview with the maintenance team revealed that the motion actuated lighting sometimes causes slight nausea due to dim lighting when repair. The minute motions of repair are sometimes not enough to actuate the lights and thus interrupt the work

Visual inspections are supported with the photos taken at particular locations/positions in questions.

Relative to the station desired capacity and reservoir size, the space allotted for the pump house is limited. Vertical split case pumps were chosen to fit more pumps and pipe design was modified to fit the working space. Straight pipe provisions were cut short to fit in various valves, expansion joints and reducers and T-type branch take-offs are used.

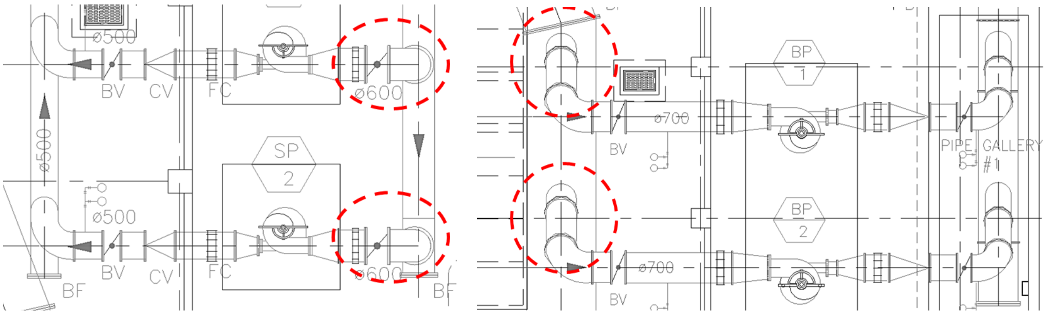
The suction pipe design for the SPs resemble that of double elbow at two perpendicular planes and immediately connect to the pump intake via a concentric reducer.

The suction pipe design for the BPs resembles that of double elbow at two separate planes. The second elbow branches of the header at 45 degrees followed by a short straight pipe then connecting to the pump intake via a concentric reducer (refer to Figure 4.5-a and Figure 4.5-b).

Hydraulic design considerations for pump suction piping would recommend at least 5 to 10 diameters of straight pipe leading to the pump intake to minimize swirls or turbulent flow and facilitate better pumping action. The pipe design then has no provisions for flow measurement for conventional meters such as mechanical meters, weigh tanks and ultrasonic/Doppler flow meters, magnetic flow meters. All of these depend on some provisions of straight pipe with relatively developed flow or require space for installation of monitoring devices.

Furthermore, common practice to avoid air pockets building up at the suction side of the pump is to use flat-on-top eccentric reducer before the pump suction (Figure 4.18). This is applicable for piping coming from below or straight ahead.

Supports for pipes and valves can fall on three general categories according to the manner of support they provide. Supports can either function simply as rests, as guides or as anchors. Installation of expansion joints would indicate a provision for minute pipe expansion when



a - suction pipe (01)   b - suction pipe (02)

Figure 4.5: Piping design and alignment

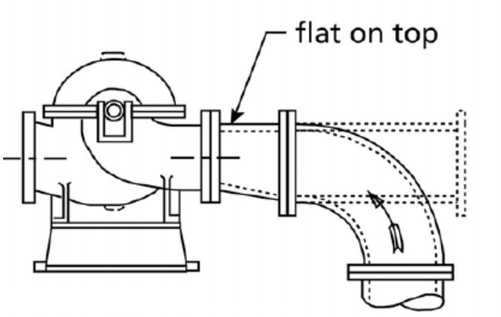
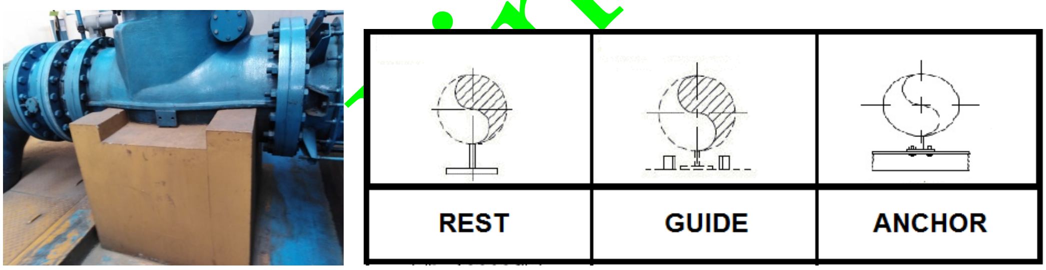


Figure 4.6: Eccentric reducer

flow is high and fluid momentum is great. However, from the visual inspection of the concrete support for check valves and how the valve seats on it, the supports function like anchors (fixed).



a - concrete support   b - type of supports

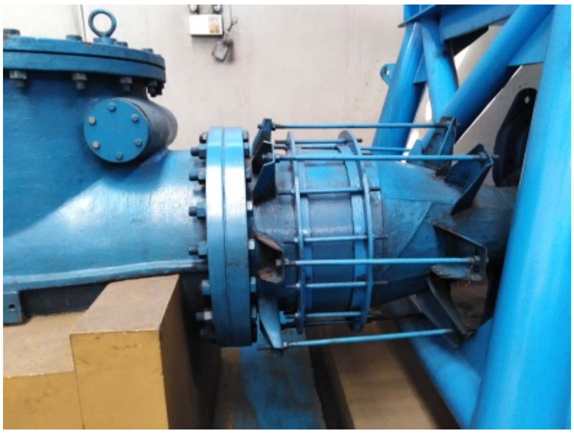
Figure 4.7: Piping support

The position of the check valve becomes fixed and the expansion joint will have to expand to the direction of the pump casing, which may promote misalignment of pump and motor. However, the expansion joint is observed to be short circuited by another set of outer stud rods where they are tightened fixed with inner and outer nuts. The pipe system ends up rigid (Figure 4.8-a).

A similar situation for the SP suction pipe could occur. Pipe penetrating the ground will fix the elbow and the expansion will be to the direction of the pump casing promoting misalignment of pump and motor (Figure 4.8-b).

The protective coating and paint of the outdoor pipes on the side of the pumping station facing the golf course have severely deteriorated. The finishing paint has become brittle and the protective layer has cracked. Some portions of the pipe particularly at the elbow, have the bare metal exposed and has corroded for some time (Figure 4.9-a).

Several dial pressure gauges were not functioning. Operating conditions sometimes reach negative suction pressures. Some suction pressure gauges do not have a vacuum range for negative suction pressures. A discrepancy between the dial and digital gauges is observed to be up to 10 psi like the gauges seen for BP4 discharge (Figure 4.9-b).



a - outer stud rods

b - Concrete penetration

Figure 4.8: Piping support

a - Outer deterioration

b - Gauge not provide adequate LOS

Figure 4.9: Piping support

During inspection, it was found that there are water leaks in the engineering room during rainstorms.

4.3.2 Visual inspection data

Visual inspection data on assets are summarized in tables of this section.

Table 4.9: Visual inspection data - BP1 and BP2

No.	Items	CS	Remarks
1	SE	1	Elbow surface is good, paint is consistent
2	SBV	1	Mitered elbows were used (not radius elbows)
3	STR	1	No leaks, cracks, deterioration or corrosion
4	AV	1	Air valve installed to release trapped air during operation
5	CS1	2	Cracks propagating, very small gap observed between pipe and saddle rest
6	CCR	3	Should be replaced with eccentric reducer to avoid formation of air pockets
7	EJ	2	Check locking nuts on outer and inner stud bolts, some are bolted on both sides of plate making joint fixed
8	CCD	1	Used as necessary
9	EJ	2	Check locking nuts on outer and inner stud bolts, some are bolted on both sides of plate making joint fixed
10	CV	1	Used as necessary, almost no leaks
11	CS2	3	May need redesign as it holds valve fixed
12	DBV	1	Used as necessary
13	DE	2	Have portions where surface paint is brittle and some areas where bare metal is exposed to corrosion

Table 4.10: Visual inspection data - BP3 and BP4

No.	Items	CS	Remarks
1	SE	2	Exposure to outdoor conditions cause pipe coating to deteriorate; protective coat torn with cracks and finishing paint brittle; bare metal exposed on some portions and already showing corrosion
2	SBV	1	Mitered elbows were used (not radius elbows)
3	STR	1	No leaks, cracks, deterioration or corrosion
4	AV	1	Air valve installed to release trapped air during operation
5	CS1	2	Cracks propagating, very small gap observed between pipe and saddle rest
6	CCR	3	Should be replaced with eccentric reducer to avoid formation of air pockets
7	EJ	2	Check locking nuts on outer and inner stud bolts, some are bolted on both sides of plate making joint fixed
8	CCD	1	Used as necessary
9	EJ	2	Check locking nuts on outer and inner stud bolts, some are bolted on both sides of plate making joint fixed
10	CV	1	Used as necessary, almost no leaks
11	CS2	3	May need redesign as it holds valve fixed
12	DBV	1	Used as necessary
13	DE	2	Have portions where surface paint is brittle and some areas where bare metal is exposed to corrosion

Table 4.11: Visual inspection data - BP5 and BP6

No.	Items	CS	Remarks
1	SE	2	Exposure to outdoor conditions cause pipe coating to deteriorate; protective coat torn with cracks and finishing paint brittle; bare metal exposed on some portions and already showing corrosion
2	SBV	1	Mitered elbows were used (not radius elbows)
3	STR	1	Not yet in use
4	AV	1	Services empty pipe
5	CS1	1	Supports empty pipe

Table 4.12: Visual inspection data - SP1 and SP2

No.	Items	CS	Remarks
1	SE	2	Could be replaced with a Y-type branch take off but with space constraints a replacement of long radius type might not be physically possible
2	SBV	1	Used as necessary
3	EJ	2	Check locking nuts on outer and inner stud bolts, some are bolted on both sides of plate making joint fixed
4	CCR	1	Used as necessary
5	CCD	1	Used as necessary
6	EJ	2	Check locking nuts on outer and inner stud bolts, some are bolted on both sides of plate making joint fixed
7	CV	1	Used as necessary
8	AV	1	Used as necessary
9	DBV	1	Used as necessary
10	DE	1	Follows 45 degree entry into discharge header which better facilitates water flow
11	CS	3	May need redesign as it holds valve fixed

4.3.3 Observation and recommendations

- Pumps have little to no isolation from hydrodynamic forces. Strain due to movement at the inlet and outlet pipe sections are directly transmitted to pump casings. Hydrodynamic forces, along with the static weight of said pipe sections, including the weights of the flexible couplings and the water contained therein, are transmitted to the pump casing due to lack of proper piping support upstream or downstream of the pumps.

  Recommendations

  ✓ Install proper isolation and support of pipe sections upstream and downstream of the pumps.

- The welded tubular frame supports employed in this station are less rigid than traditional base plates. Such construction results in mounting surfaces that are not necessarily coplanar or parallel to each other. Moreover, the vertical design raises the centerline of rotation relative to the floor line, leading to a less stable installation. Thus, PSR motor-pump units are deemed vulnerable to misalignment "creep" during operation.

Recommendations

✓ Conduct regular vibration analysis to assess extent of misalignment and/or its effects on the bearings.

4.4 Pump efficiency

Data on flow and head were measured for each pump. However, there was no measured data of motor/pump assembly regarding power ratings of all pumps as of this writing since the GHD/APSI testing for the station is yet to be conducted. Thus, assumptions will be made for the computations of the power ratings of the Pump and Motor.

4.4.1 Unit flow measurement

Data on measured flow (Q) was recorded with min and max values is shown in Table 4.13 for each pumps.

Table 4.13: Unit flow measurement (cubic meter per second - cms).

Assets	Φ (mm)	Flow Q (cms)				Remarks
		Design	Measure			
			Min	Max	Ave.	
BP1	700	0.6713	0.4858	0.4984	0.4921	
BP2	700	0.6713	0.4858	0.4984	0.4921	
BP4	700	0.6713	0.5110	0.5615	0.5363	
SP1	500	0.2315	0.3584	0.3659	0.3622	
SP2	500	0.2315	0.3584	0.3659	0.3622	

4.4.2 Pressure measurement

Data on measured flow (Q) was recorded with min and max values is shown in Table 4.14 for each pumps.

Table 4.14: Head (mH_2O).

Assets	Head (H - mH_2O)			Remarks
	Design	Discharge	Suction	
BP1	50	47.0766	-3.4429	
BP2	50	48.4819	-3.0916	
BP4	50	49.1845	-3.0916	
SP1	60	48.4819	0.5621	
SP2	60	48.4819	0	

4.4.3 Efficiency

Pump efficiency is computed based on the flow/head measurement and the assumed value of power rating (Table 4.15).

It is important to note that the values of input power is an assumed values which might not perfectly reflect the actual value in actual situation. This assumption is a limitation of the study, particularly for this station, since the electrical audit is yet to be conducted. The design pump efficiencies are taken from the test report of Kubota Corporation [**Kubota2010**].

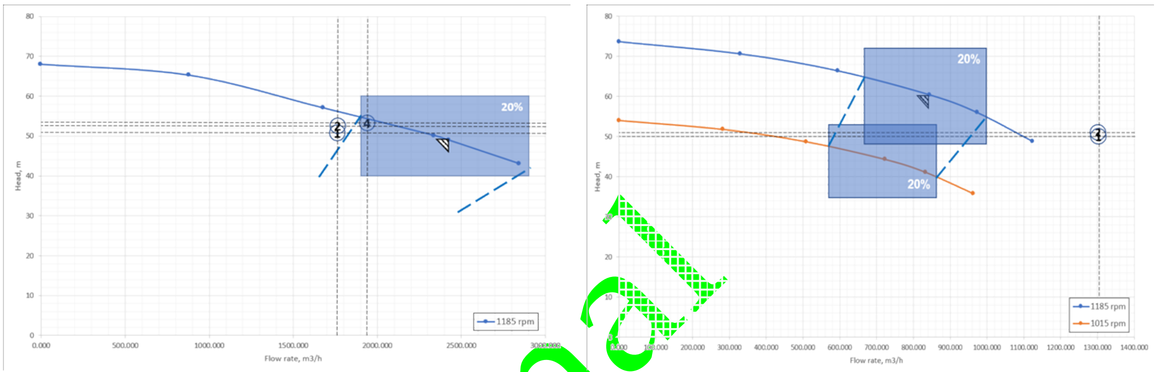
In Table 4.15, efficiencies for SP1 and SP2 were not estimated due to the fact that the measured flow are beyond the maximum allowable flow of the pumps. These might infers that the

Table 4.15: Pump efficiency (%).

Assets	Flow	Head	Input Power	Water Power	Efficiency (%)		
	m^3/s	mH_2O	kW	kW	Tested	Design	Diff.
BP1	0.492	51.581	385	249	64.54	80	-15.46
BP2	0.492	52.635	385	254	65.86	80	-14.14
BP4	0.536	53.338	385	280	72.73	80	-7.27
SP1	0.362	50.364	200	179	-	83.2	-
SP2	0.362	50.926	200	181	-	83.2	-

pumps have been operated inappropriately pursuant to their design specifications, a case that could be associated to VFD operated pumps, aside from the fact that the viable measuring points of the flow is near the elbow at the discharge side. With that, the operation of the pumps might not be the optimum and as a result incurred more power than they should be.

Figure 4.10-a, and 4.10-b presents the efficiency curves for booster pumps and storage pumps, respectively. The curves are created based on the recorded data provided in the test record of Kubota Corporation [**Kubota2010**].



a - Booster pumps

b -Storage Pumps

Figure 4.10: Efficiency curves

Figure 4.10-a

As shown in Figure 4.10-b, the storage pumps operate at an overflow condition and are beyond the tolerance of 20% Best Efficiency Point (BEP). Both pumps only run at 1015 rpm at the time of testing, but delivers an overflow and so deviate greatly from the curve. In this operating conditions, the pump might incurs higher power consumption aside from the increase of deterioration rate of its components. Specifically, it will produce high cavitation and high vibration thus associated to the so called operate-to-destruction. This is similar to underflow as it will increase the temperature rise rate and produce noisy operations, cavitation surge and even high vibration scenarios.

<u>Recommendations</u>

- Proper operating condition shall be established for the VFD pumps in a given time to avoid them operating beyond their BEP for a long period of time. Also include optimization of the proper combinations of running pumps in a given time.
- Regular pump performance monitoring and analysis shall be conducted to have a profiling of pump in relation to actual operating conditions, a major tool for pump performance optimization. In addition, multiple tests and conditions shall be implemented during testing to have a holistic approach on the pump assessment.
- Provision for installation of testing points in measuring pump performance, such as thermodynamic method, shall also be included in the modifications (refer to the conceptual design in Chapter 5).

4.5 Vibration and structural assessment

4.5.1 Measurement and spectrum reading

Rotating equipment generate vibration waveforms that are mathematical functions of machine dynamics, such as speed, alignment, and rotor balance, among others. Vibration analysis entails measurement and analysis of the amplitude of vibration at certain frequencies to gather useful information relating to the accuracy of shaft alignment and balance, the physical condition of bearings, and the possible effects of structural issues; in the case of Maynilad, the problem of impeller possible cavitation is an added and serious concern.

Three main parameters are measured to determine the severity or amplitude of vibration; namely: displacement, velocity and acceleration. Along with temperature, the vibration level is a primary indicator of the physical condition of a machine. As a generally rule, higher vibration levels indicate greater defects.

Rotating speeds below 600 rpm (10 Hz) generate minimal acceleration, moderate velocity, but relatively high displacement. Hence, shaft displacement is a critical parameter for slow speed rotors, such as steam turbines. Between 600 – 60000 rpm (10 - 1000 Hz) velocity and acceleration levels provide useful indications of the severity of defects. While velocity as a parameter may indicate the presence or relative magnitude of a problem, it makes no distinction as to the source or cause. This is where an FFT vibration analyzer comes in. A fast Fourier transform algorithm converts acceleration waveforms into functions of frequency in a way suitable-trained humans can distinguish the component sources or causes of the vibration.

By means of a OneProd Falcon high-resolution FFT analyzer equipped with tri-axial accelerometer with a linear frequency range of 2Hz-30kHz, vibration spectral readings were taken from four bearing locations in each motor-pump unit.

Analysis and results are summarized as follows:

4.5.2 Data and analysis

Raw data of vibration measurement is provided in separately digital format. The raw data of each pump is used to generate a set of graphs provided in Appendix B.

Analytical results on vibration are with the Appendix B. A summary of grading for each pump is given in Table 4.16.

Table 4.16: Pump vibration condition state.

Assets	Operational issues detected	Condition	
		Motor	Pump
BP1	impeller cavitation minor looseness on motor base bolts and/or minor shaft misalignment	2	3
BP2	impeller cavitation	2	3
BP3	no reading; under repair during time of testing	-	-
BP4	impeller cavitation shaft misalignment	3	3
SP1	early stage motor drive-end (DE) bearing defect	3	2
SP2	early stage motor drive-end bearing (DE) defect	3	2

It is note that the CS 2, and 3 shown in Table 4.16 infers good and fair, respectively [1].

It can be concluded from the results of vibration study that there is no negative impact of the structural foundation and pads of pumps.

4.5.3 Recommendations

Pumping station comprising two vertical supply pumps and four vertical booster pumps were constructed with extremely short inlet and outlet pipe sections, leading to inefficient, if not incorrect, operation regimes. Increased power consumption and recurrent damage to impellers

[1] The CS is slightly different from that defines in Table 3.1

and bearings are natural consequences of the said design. From the analysis of vibration spectra, there is a high probability that cavitation has been with the three booster pump units in operation.

Recommendations are shown in Table 4.17 and Table 4.18, which describes the permissible misalignment.

Table 4.17: Recommendation to reduce vibration.

Assets	Condition		Recommendations	IT
	Motor	Pump		
BP1	2	3	Check motor-pump alignment conditions Mitigate or rectify cavitation ASAP Follow manufacturer-prescribed dynamic operation to prevent impeller damage Schedule pump-DE bearing for replacement.	2
BP2	2	3	Mitigate or rectify impeller cavitation ASAP Follow manufacturer-prescribed dynamic operation to prevent impeller damage Schedule pump-DE bearing for replacement	2
BP3	-	-	no reading; dismantled under repair	NA
BP4	3	3	Align motor and pump shafts per manufacturer's specifications or Table for permissible shaft alignments for machines Rectify cavitation ASAP; schedule pump reconditioning to allow inspection of impeller and wear ring for damages Replace pump-DE bearing	2
SP1	3	2	Refresh bearing grease regularly Monitor to assess vibration trend	2
SP2	3	2	Refresh bearing grease regularly Monitor vibration regularly to assess trend	2

4.6 Energy management audit

4.6.1 Production and power data

Production data for this station has been recorded in excel files. Each file represents a month with 24 hours of daily records. Maynilad provided this set of data from 2014 to 2018 per GHD' request. Initial verification on this set was conducted with following conclusions

- The structure of data is not homogeneous with many numerical errors. This problem is due to the fact that excel file is not suitable for recording a large volume of data, particularly cells are not set up to reject string and value outside the lower and upper bounds. content.

In order to compile such a huge data set, it is not possible with manual inputting, instead, GHD has developed a hybrid program consisting of Visual Basic (VBA) Code and MySQL code for fast compilation. VBA code is used to add header, fill up missing information in excel file, and ignore rows and columns that should not exist with regard to database structure. MySQL codes are used to eliminate measurement errors and bring together all individual files to one file that allows statistical analysis with R.

4.6.2 Measurement errors

Following measurement errors are with the provided excel files

- String/text values are found numerous in columns that shall be only numerical values;
- Extreme values are found numerous;
- Negative values are found in many places that shall only be positive

Table 4.18: Generic table for permissible misalignment

Parameter	RPM	Tolerances mm	
		Good tolerances	Acceptable tolerances
Parallel errors between axles/couplings	**0-1,000**	0.07	0.13
	1,000-2,000	0.05	0.10
	2,000-3,000	0.03	0.07
	3,000-4,000	0.02	0.04
	4,000-5,000	0.01	0.03
	5,000-6,000	<0.01	<0.03
	RPM	mm/100mm	mm/100mm
Angular errors between axles/couplings	**0-1,000**	0.06	0.1
	1,000-2,000	0.05	0.08
	2,000-3,000	0.04	0.07
	3,000-4,000	0.03	0.06
	4,000-5,000	0.02	0.05
	5,000-6,000	0.01	<0.04

4.6.3 Data compilation for analysis

Out of all recorded attributes, useful attributes that can be used for energy audit are total production per hour and total power consumption per hour. There is no record on production and power consumption for individual pump.

After data filtering, data correction, and compilation, the obtained set of data includes 43,740 records (equivalent to 1458 days in total 5 years). Final data set is saved in MySQL server.

4.6.4 Analysis

As a matter of fact, power consumption of a PS is mostly contributed by the operation of pumps. Thus, the audit has been centralized on

- Analyzing given production and power consumption data to understand the trend and establish a benchmark ratio of production vs power for future audit and management;
- Evaluating other part of the audit such as pump efficiency and reliability in order to derive better intervention program that will eventually beneficial to the Client to maintain a benchmark level of power consumption against the production.

Figure 4.11 shows the statistical correlation between production and power. It can be seen from the correlation graph and correlation value that there is relatively strong correlation among these two values (coefficient is 0.63). This infers more or less that there is less breakdown of components of this station. This conclusion is also supported by the fact that there has been little historical record on both preventive and corrective intervention of this station.

Figure 4.12 shows a trend in time series production since 2014. It can be seen from the graph that the production has kept decreasing slightly over the year.

Figure 4.13 shows a trend in time series power consumption since 2014. It can be seen from the graph that the power has kept increasing over the year.

Figure 4.14 shows time series of ratio between power and production. As the production decreases and power increase, the ratio keeps increasing over time.

Interpretation from these graphs can be summarized as follows

- There is a relatively strong correlation between the production and power, inferring that there has been less breakdown in this station;

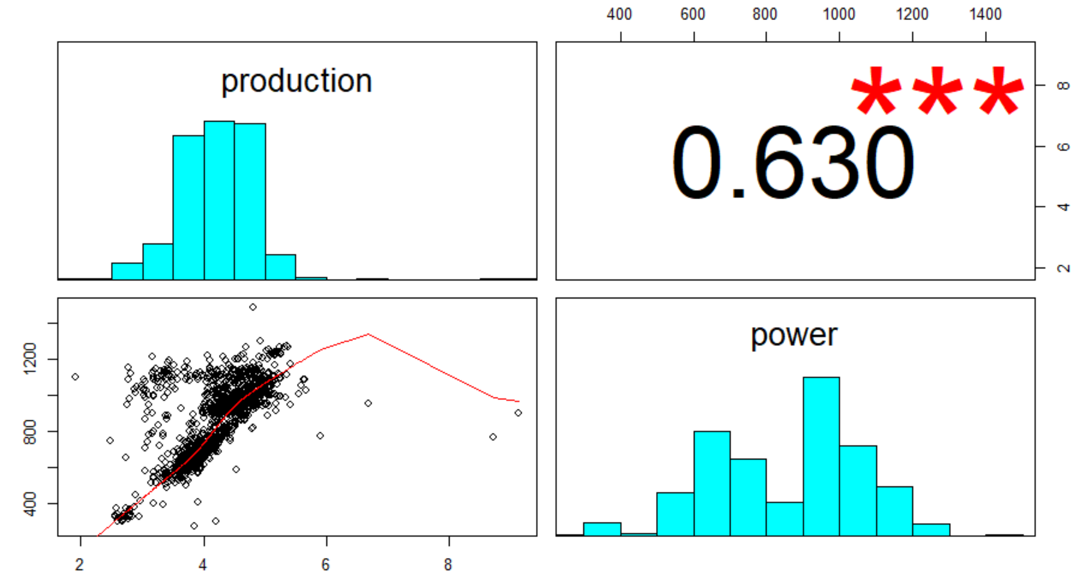


Figure 4.11: Correlation between production and power consumption

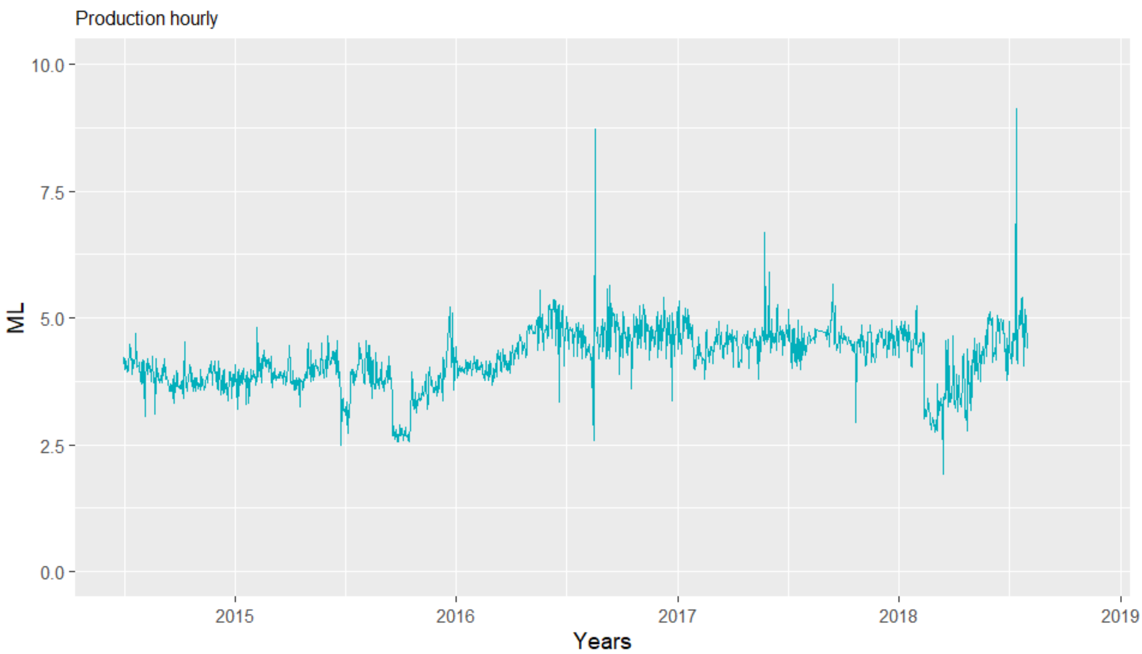


Figure 4.12: Time series production/hour

- There has been a few number of peaks at which the ratio between power and production were significantly high compared to average value. These peaks seem to be repeated at least one in a year. The reason causing that peaks are unknown;
- There are a number of outliners which should not be an actual cases;
- There was a high peak in ratio in the first quarter of 2018. The ratio has reached between 300 and 400 for 3 months period, inferring an abnormal operation.

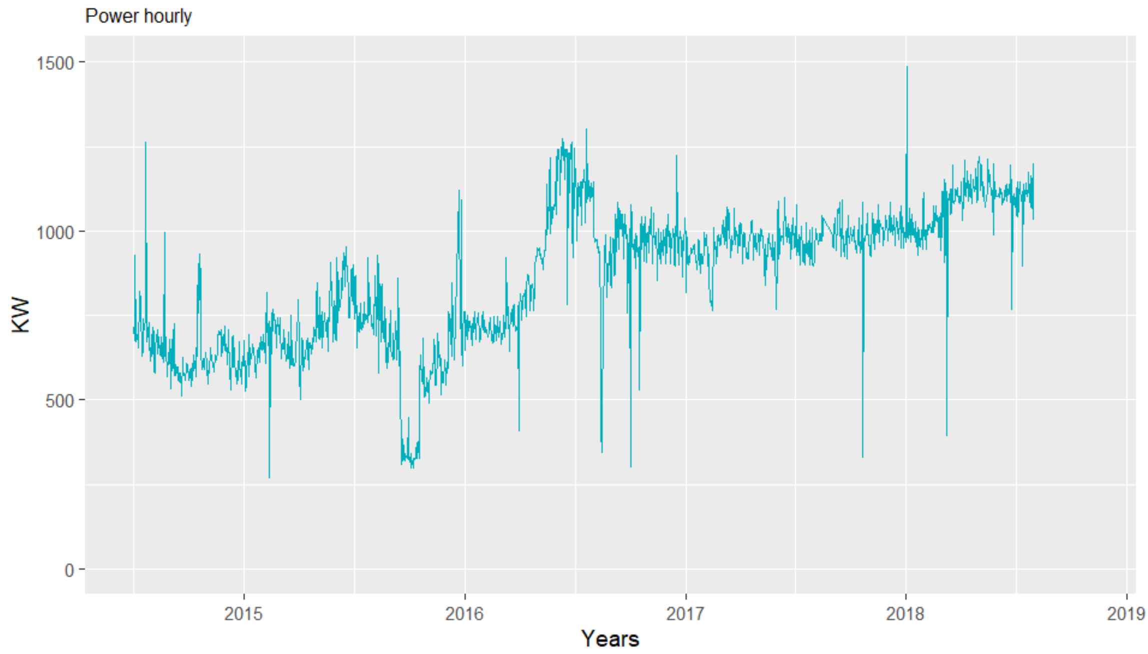


Figure 4.13: Time series power/hour

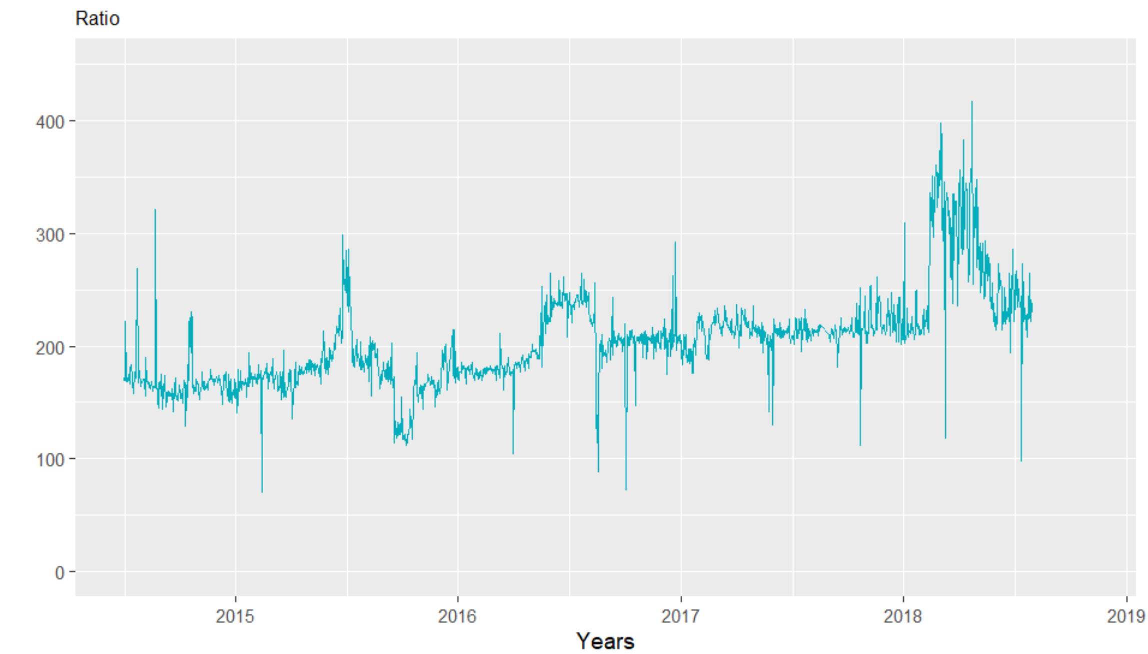


Figure 4.14: Time series ratio between production and power

4.6.5 Recommendation

In order to operate the PS in a manner that is energy efficient, it is advisable to

- Establish an optimal operation scheme;
- Establish a benchmark energy efficiency ratio for continuous monitoring and reporting. This ratio shall become a Key Performance Indicator (KPI) used for managerial purpose. GHD suggests to establish a benchmark ratio at an optimal value below 200.

4.7 Workplace environment management

4.7.1 Temperature and relative humidity

4.7.1.1 Data

Data concerning the temperature and relative humidity is presented in Table 4.19. Data was measured at targeted points shown in Figure 2.16. Raw data is with the site inspection reports, which will be provided to the Client separately. Persuant to ASHRAE standard, the recommended ranges for temperature and humidity are [72 - 80 $^{\circ}F$] and [45 - 60 %], respectively.

4.7.1.2 Data and Analysis

Table 4.19: Temperature and Relative Humidity.

Points	Description of points	Temperature (F)		Humidity (%)	
		Actual	Range	Actual	Range
	A. Inside pump house (outside office)				
1	Between BP2 and BP1	95.36	72 - 80	50.6	45 - 60
2	Between BP1 and SP2	93.74	72 - 80	53.3	45 - 60
3	Between SP2 and SP1	91.40	72 - 80	56.9	45 - 60
4	Near the Roll Up Door	89.60	72 - 80	61.2	45 - 60
5	Near the Office Door	89.60	72 - 80	61.5	45 - 60
6	Near at the Operators' Office Window	87.98	72 - 80	62.4	45 - 60
7	Near BP3 and along the Roll Up Door	88.70	72 - 80	64.7	45 - 60
8	Between BP3 and BP4	93.02	72 - 80	56	45 - 60
9	Between BP4 and Spare 1	93.74	72 - 80	55.1	45 - 60
10	Between two Spares	93.38	72 - 80	56.9	45 - 60
11	Between Suction Pipes of BP3 and BP4	93.412	72 - 80	53.5	45 - 60
12	Between Suction Pipes of Spares	93.74	72 - 80	57.6	45 - 60
	Average	91.97	72 - 80	57.5	45 - 60
13	B. Office	80.96	72 - 80	52.2	45 - 60
	C. Outside pump house				
14	Guard House	89.80	72 - 80	55.8	45 - 60
15	At the back of the station	93.74	72 - 80	53.1	45 - 60
16	Near Substation Gate	95.8	72 - 80	50.6	45 - 60

Inside office registered a reading of approximately 81 F near the upper limit of the standard. As for the RH, the reading registered 52.2 % and is close to the range average. Note that Air Conditioning System is installed inside the Office thus the temperature can still be vary based on the thermal comfort needed by the Operators.

As can be seen from Table 4.19, it is the temperatures inside the pump house at every measurement points are significant higher than the maximum value of the recommended range (80 F). The average value is 94.16 F. The higher values of temperature compared to the range have also been observed for points outside the pump house, in the vicinity, and inside the office.

As a matter of fact, temperature and humidity is highly correlated and as per ASHRAE standard 55 under summer comfort zone, the recommended combination of temperature and humidity shall be within the comfortable zone as shown in Figure 4.15.

4.7.1.3 Recommendations

In order to reduce the negative impacts from high temperature, particularly inside the pump house, the Client shall consider

- Establishing a good daily monitoring, exercise, and management considering ergonomic and health and occupational activities (e.g. appropriate time window for break in designated resting area);

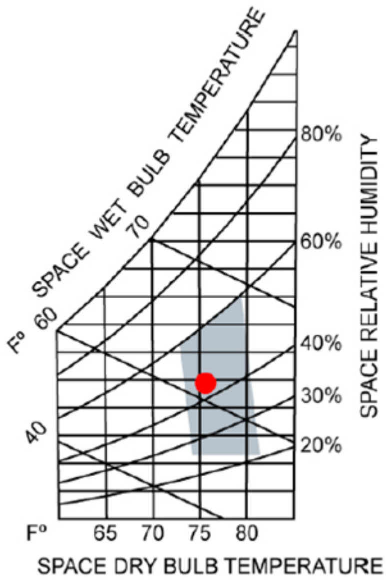


Figure 4.15: ASHRAE standard 55 : Summer Comfort Zone

- Execute physical intervention to reduce temperature can be with improving ventilation system by natural mean (e.g. installation of weather proofed louvers). This will be reflected in the conceptual design in Chapter 5.

4.7.2 Air quality

4.7.2.1 Data and analysis

Data concerning the air quality is presented in 4.20 with value of PM2.5 measured in ppm. Data was measured at targeted points shown in 2.16. Raw data is with the site inspection reports, which will be provided to the Client separately. Pursuant to currently applied standard, the recommended safe range for PM2.5 is in [0-35].

Table 4.20: Air Quality - PM2.5

Point	Description of the Point Location	PM2.5
	A. Inside pump house (outside office)	
1	Between BP2 and BP1	35
2	Between BP1 and SP2	33
3	Between SP2 and SP1	30
4	Near the Roll Up Door	26
5	Near the Office Door	24
6	Near at the Operators' Office Window	24
7	Near BP3 and along the Roll Up Door	19
8	Between BP3 and BP4	23
9	Between BP4 and Spare 1	20
10	Between two Spares	24
11	Between Suction Pipes of BP3 and BP4	13
12	Between Suction Pipes of Spares	17
	Average	24
13	B. Office	16
	C. Outside pump house	
14	Guard House *	18
15	At the back of the station	18
16	Near Substation Gate*	23

* Varies along skyway

The average reading inside and outside the vicinity of the Pump Stations and Reservoir as well as the Office is from 13 to 35 and falls under the Excellent Air Quality Level Range. Values of PM2.5 are all within the range of acceptance, inferring no issue with the quality of air.

4.7.2.2 Recommendations

Though there is no issue with the air quality, it is anticipated that future problem can incur with a certain low probability, a better management approach is to ensure that all activities/tasks to be executed within the premise of the PS to follow strictly safety and environmental regulation. For example, all employees and staff to wear appropriate dust-proofed masks when working with activities that potentially incurs dusts or other harmful particles.

4.7.3 Illumination

4.7.3.1 Data and analysis

Data concerning the illumination is presented in Table 4.21 with the LUX value. Data was measured at targeted points shown in Figure 2.16. Raw data is with the site inspection reports, which will be provided to the Client separately. Persuant to RULE 1075.4 of DOLE-OSH standard [3], the recommended minimum for LUX is in 100.

Table 4.21: Illumination.

Point	Description of the points	Trials			Ave.
		1	2	3	
	A. Inside pump house (outside office - x10)				
1	Between BP2 and BP1	45.9	49.3	59.8	51.67
2	Between BP1 and SP2	44.5	54.7	74.8	58.00
3	Between SP2 and SP1	50.4	64.1	72	62.17
4	Near the Roll Up Door	56.7	69.2	65.9	63.93
5	Near the Office Door	43	46.1	41.6	43.57
6	Near at the Operators' Office Window	55.8	53.8	57	55.53
7	Near BP3 and along the Roll Up Door	47	46.3	44.7	46.00
8	Between BP3 and BP4	70.2	72.4	68.8	70.47
9	Between BP4 and Spare 1	79.3	82.4	86.3	82.67
10	Between two Spares	73.7	76.9	76	75.53
11	Between Suction Pipes of BP3 and BP4	138.6	135.2	134.7	136.17
12	Between Suction Pipes of Spares	140.7	145.9	148.6	145.07
	Average				74.23
13	B. Office (x10)	109.8	110.2	110.8	110.27
	C. Outside pump house (x100)				
14	Guard House *	180.2	178.4	177.2	178.60
15	At the back of the station	220	225	223	222.67
16	Near Substation Gate*	270	285	294	283.00

The illumination of the pump is well above the standard minimum. Illumination is provided by natural means through the Skylights and is augmented by Motion-activated Lighting Systems. At night time, the light provided by Lighting System is for a particular zone only or place where there are motions.

4.7.3.2 Recommendations

- Use artificial lighting equipment when accessing and conducting activities requiring detailed output at darker specific areas especially at night because the existing lighting systems cannot provide adequate lighting or when deemed necessary.
- Such artificial supplementary lightings shall be especially designed for the specific tasks and provided with shading or diffusing devices to prevent glare.
- Periodic cleaning of Skylights and glass windows should be implemented to ensure they are kept clean at all times

4.7.4 Industrial ventilation

4.7.4.1 Data and analysis

Natural ventilation through Door 1 and Door 2 is not sufficient to attain the minimum Air Changes requirement of the Pump House and so Mechanical Ventilation is utilized most of the time.

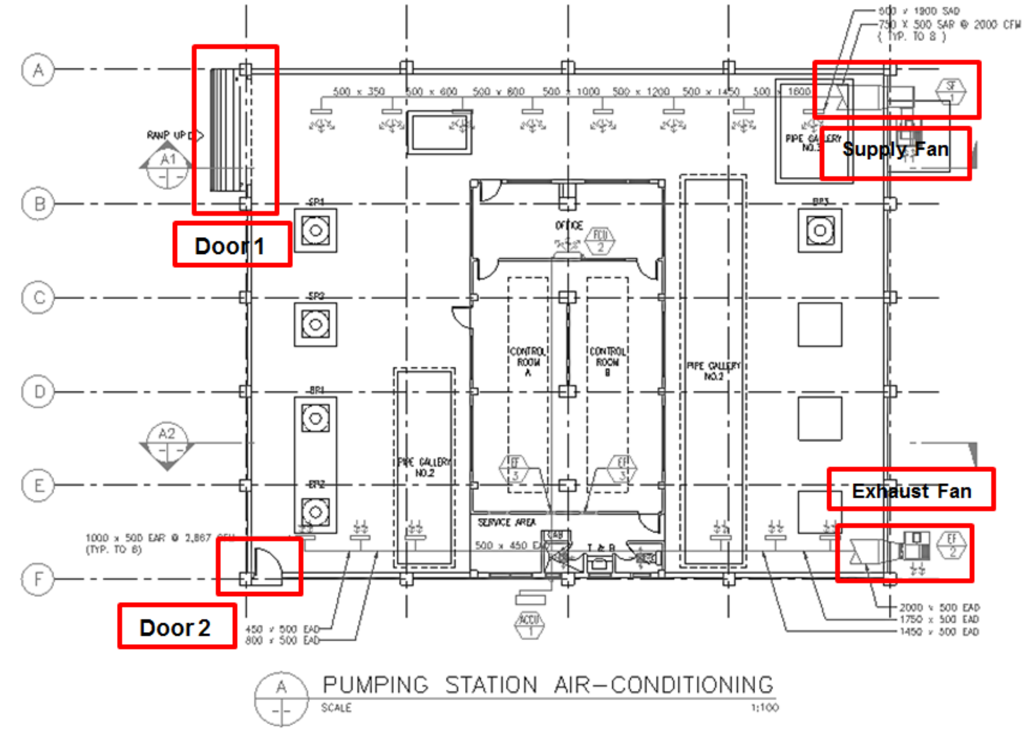


Figure 4.16: Existing ventilation layout

4.7.4.2 Recommendations

- Install weather-proof louver at the Pump House. This is to increase the air change inside the pump house by natural ventilation. The purpose is to utilize the Natural wind around the area and at the same time, lessen the Power Consumption of the Supply and Exhaust Fan.

If the PS is rehabilitated with the recommendation, eventually, it will contribute to the reduction of hazards associated with air quality and energy/heat. The recommendation is also reflected in the conceptual design provided in later chapter.

4.7.5 Housekeeping

4.7.5.1 Documentation

Following problems are the facts:

- Current documentation practice is heavily dominated with paper based system, which follows the current practice in Maynilad. There is a large amount/collection of papers that recorded past activities but is of no use and beneficial if data cannot be transformed into digital format for time series analysis, which is an essential part of asset management practice;
- No proper filing/library system with standardized coding rule that will provide convenience for operators/users to timely find appropriate documents;

- Daily operation data is crucial information for future analysis but it is recorded in excel based file without relational tables, which makes it from hard to impossible for data compilation, filtering, and mining. Many past data has been recorded with outliers and incorrect data types.

4.7.5.2 Waste management and environmental control

There is no issue with regard to waste management and environmental control as confirmed by the checklist shown in Table 4.23

Table 4.22: Housekeeping

Description	Status	CS	IT	Remarks
- Sufficient waste segregation assets	yes	1	1	
- waste segregation policy	yes	1	1	
- Signage	yes	1	1	
- Genset emission control	yes		1	

4.7.5.3 Office arrangement and ergonomic

Table 4.23 shows the data concerning parameters associated with office arrangement and ergonomic considerations.

Table 4.23: Housekeeping

Description	Status	CS	IT	Remarks
- Sufficient waste segregation assets	yes	1	1	
- waste segregation policy	yes	1	1	
- Signage	yes	1	1	
- Genset emission control	yes		1	

4.7.5.4 Recommendations

Followings are recommendations

- Development of a web-based database management system, with appropriate set of relational data tables to record operational data, power consumption data, and intervention data;
- Development of documentation code and naming for appropriate filing and library/referencing;
- Applying best practices with regard to ergonomic in combination with interior design and arrangement of office space.

4.7.6 Noise

4.7.6.1 Data and analysis

Data concerning the noise is presented in 4.24.Data was measured at targeted points shown in Figure 2.18. Raw data is with the site inspection reports, which will be provided to the Client separately.

Regular operation at 2 Booster and 2 Storage Pumps running (BP3 at breakdown) was considered during the Sound Level Testing and so the reading closely represents the normal daily noise level inside the Plant. The average sound level inside the Pump House is 90.4 dBA, a little more than the 90 dbA treshhold.

The sound level at pump station vicinity and inside the office are within safe values.

Table 4.24: Noise.

Point	Desc. of the point location Location	Trials									
		1			2			3			
		Min	Ave.	max	Min	Ave.	Max	Min	Ave.	Max	Ave.
	A. Inside pump house (outside office)										
1	Between BP2 and BP1	91.3	93.4	95.5	91.2	93.4	95.6	91.5	93.55	95.6	93.45
2	Between BP1 and SP2	91.1	93.05	95	90.8	92.75	94.7	90.6	92.8	95	92.87
3	Between SP2 and SP1	89.5	91.65	93.8	89.5	91.65	93.8	89.7	91.8	93.9	91.70
4	Near the Roll Up Door	88.5	89.1	89.7	88.3	88.9	89.5	88.4	88.7	89	88.90
5	Near the Office Door	87.9	88.45	89	87.7	88.35	89	87.9	88.5	89.1	88.43
6	Near the Operator's Room Window	88.1	88.5	88.9	88.1	88.65	89.2	88.5	89	89.5	88.72
7	Near BP3 and along the Roll Up Door	88.5	89.05	89.6	x	88.7	89.1	88.3	88.85	89.4	88.87
8	Between BP3 and BP4	92	93.8	95.6	89.2	91.05	92.9	89	91.55	94.1	92.13
9	Between BP4 and Spare 1	88.8	91.75	94.7	88.7	89.1	89.5	88.7	89.2	89.7	90.02
10	Between two Spares	88	88.65	89.3	87.9	88.55	89.2	88.3	88.6	88.9	88.60
	Average		90.74			90.11			90.26		90.37
	B. Vicinity										
11	Between Suction Pipes of BP3 and BP4	65.8	66.7	67.6	67.3	67.8	68.3	65.1	66.65	68.2	67.05
12	Between Suction Pipes of Spares	60.2	63.85	67.5	59.1	62.2	65.3	60.6	63	65.4	63.02
13	C. Office	65.4	68.5	71.6	66.4	69.35	72.3	65.8	68.5	71.2	68.78

4.7.6.2 Recommendations

- Use protective hearing equipment when working inside the Pump House and have a scheduled break/rest at designated location. Shall not be exposed at such noise beyond 5 hours in a day.
- Designate location inside the Plant with the minimum noise level - can be the Office, Inside Pump Station and Reservoir, and Outside the Vicinity of Pump Station, if below is not possible.
- Install Sound Attenuation Device (such as sound-absorbing wall panels and door seals) at the Office to reduce the current 69 dBA to ideal Office level of 50-55 dBA.
- Purchase a sufficient numbers of electronic noise canceling earphones.

4.8 Fire protection and safety (FDAS) audit

4.8.1 Fire alarm and detection system

4.8.1.1 Data and analysis

Summary of data and information from FDAS audit is presented in Table 4.25 with visual images on as-found devices and panels (Figure 4.17).

4.8.1.2 Recommendations

The findings/facts and results of the audit are presented in Table 4.27. Visual images of assets are shown in Figure 4.20.

Highlights are

Table 4.25: FDAS data highlights 01.

No.	Assets	Status	Remarks
A	Visual check of the fire alarm control panel	0	No panel
1	Panel Status, installed and location area	0	No panel
2	Power indicator lamp operational	0	No panel
3	Devices properly indicated and marked	0	No panel
4	Panel clear from trouble indicators	0	No panel
5	Lamp test indicator operational	0	No panel
6	Zones properly indicated and marked	0	No panel
7	Check if it's connected to sprinkler system	0	No panel
B	Checking of installed devices		
1	Check floor plan lay-out and location of the device if accessible/easy to access	0	No as-built plan
2	Heat detectors and / or smoke detectors indicator lamp functioning	0	No indicator lamp for battery operated device
3	Heat detectors and / or smoke detectors indicator lamp functioning	0	No final test
4	Pull station locations acceptable	1	Accessible
5	Bells and buzzers operated correctly	0	For verification
6	Bells and buzzers audibility	0	For verification
7	Strobe lights locations are acceptable	0	No strobe lights
8	Strobe light operated correctly	0	No device
9	Are Fire alarm zones (areas) clearly marked	0	N/A
10	Is there a maintenance and service contract for the fire alarm system	0	N/A
11	Does the Fire Alarm System smoke detector, heat detector, manual call point , horn and strobe light working and have a current inspection tag	1	MCP and bell have inspection tags
12	Is the fire alarm system if full working order	0	No FACP panel

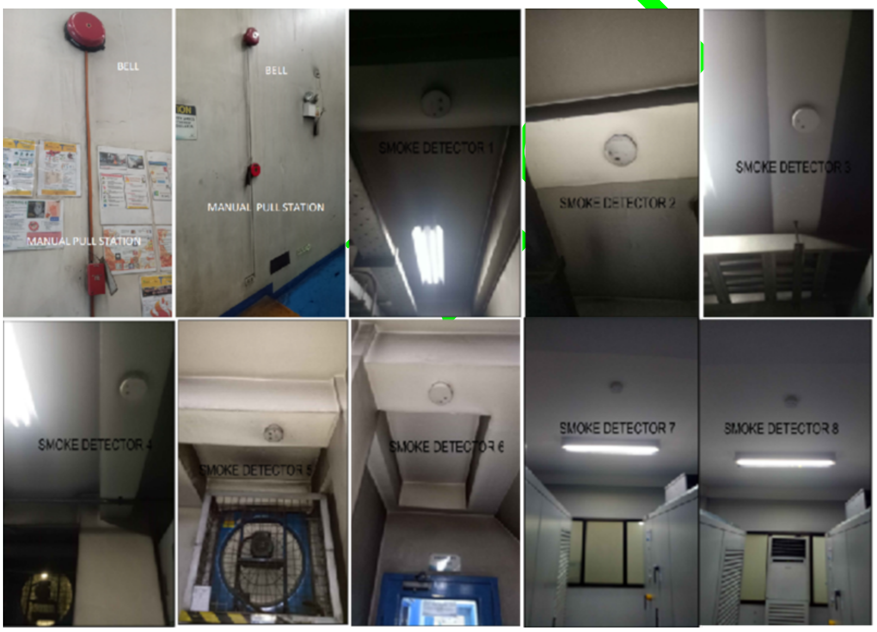
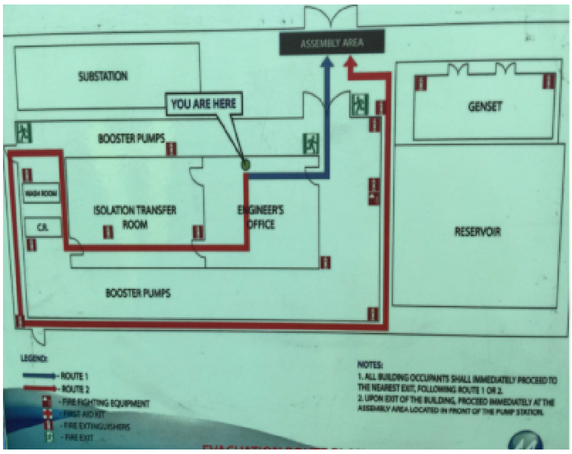


Figure 4.17: As-found devices and panels

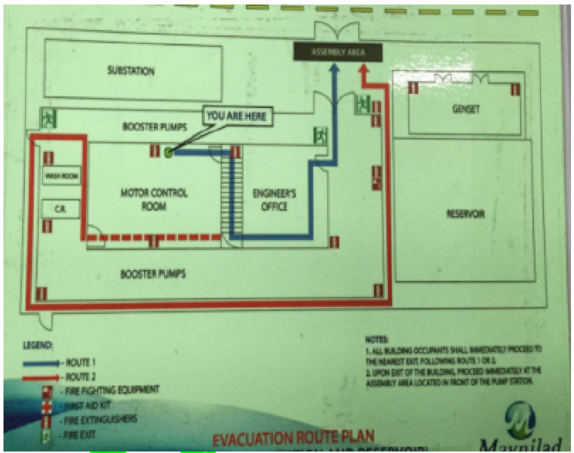
- **Smoke Detectors 01/02/04/05/06/07/08:** Battery operated smoke detector should have audible chirping sound to indicate that device needs battery replacement. However, since there was no response from SD to the tests conducted, this means that the battery is already drained. Removal of device from base for cleaning did not show any improvement on the device. Hence device is declared not functioning;
- **Manual Call Point 01:** Manual call point should have an audible alarm response after pulling the cover. Hence this device is declared functioning;
- **Manual Call Point 02:** Manual call point did not respond with an audible alarm after

Table 4.26: FDAS data highlights 02.

No.	Assets/Description	Status	Remarks
1	Evacuation plan	1	Ground floor and 2nd floor
2	Fire extinguishers	1	Green (HCFC); Red (Dry Chemical); FEX signages without FEX. As per plan total of 16
3	Fire exits	1	Indicated
4	Fire hose cabine	1	with inspection tag 8/3/2018
5	Fire sprinkler system	1	no
6	Fire sprinkler tank	1	3 units as per inspection
7	Emergency exit signages	1	BIGLITE brand, signages no power supply
8	Emergency lights	1	FIREFLY brand, last inspection 8/30/2-18
9	PPE cabinet	1	with inspection tag



(a - 1st floor)



(b -2nd floor)

(c -Genset room)

Figure 4.18: Existing evacuation plan

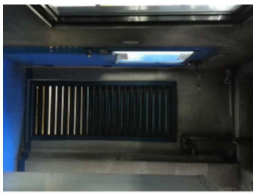
pushing the button. Hence this device is declared not functioning;

- **Bell 01:** Bell #01 responded to MCP01 with an audible alarm after pulling the cover. Hence this device is declared functioning;
- **Bell 02:** Bell 02 did not responded to MCP2 with an audible alarm after pushing the button. Hence this device is declared not functioning.

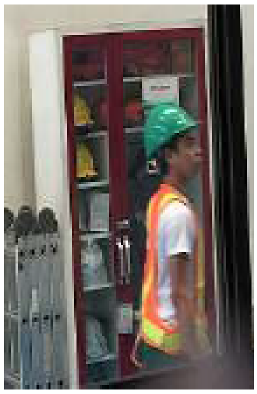
In brief, FDAS of the station is not provide adequate level of services mainly due to:

- Most of the smoke detector devices, manual call point, buzzer and the FACP were not functioning. These were established during the conducted testing of FDAS and devices;

(a - Emergency light)



(b-Exit door)



(c- Cabinet)

(d - Fire hose)

(e - HFCF FEX)

(f-Dry chemical FEX)

(g - Exit signage)

Figure 4.19: Existing safety devices

Table 4.27: FDAS analysis.

No.	Assets	CS	IT	Facts	Remarks
1	SM 01	0	4	dust inside and outside no chirping sound indicating that the battery does not provide adequate LOS Perform push and hold to test Spray Max 3 times	No response to push and hold test Repeat clean After 3x sprays, still no response
2	SM 02	0	4	Same as SM01	Same as SM 01
3	SM 03	1	1	dust inside and outside With chirping sound. This indicates that battery needs replacement Perform push and hold to test Spray Max 3 times	With audible alarm response to Push and hold test Repeat clean 3X Repeat spray with audible alarm response in the device
4	SM 04	0	4	Same as SM01	Same as SM 01
4	SM 05	0	4	Same as SM01	Same as SM 01
6	SM 06	0	4	Same as SM01	Same as SM 01
7	SM 07	0	4	Same as SM01 (No light signal indication (orange color maintained light)	Same as SM01
8	SM 08	0	4	Same as SM01 (No light signal indication (orange color maintained light)	Same as SM01
7	MCP 01	1	1	Pull the MCP cover	Alarm response audible after pulling the cover
8	MCP 02	0	4	Push the MCP button	No response after pushing the button
9	Bell 01	0	4	Pull cover of MCP#1	With response/audible sound activated on Manual call point (MCP)#1
10	Bell 02	0	4	push button of MCP#2	No response or activation on Manual call point (MCP) #2

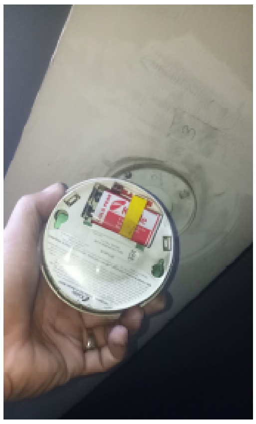
<u>Short term recommendations</u>

- Test the batteries for voltage output;

a - Smoker detector 01

b - Smoker detector 02

c - Smoker detector 03



d - Smoker detector 04

e - Smoker detector 05

f - Smoker detector 06

f - Smoker detector 07

f - Smoker detector 08

g - Manual call point 01

h - Manual call point 02

i - bell 01

j - bell 02

Figure 4.20: FDAS assets

- Replace existing batteries for smoke detectors that are not functioning with fresh 9V Battery super heavy duty (Carbon-zinc type or Alkaline) with 0% Mercury;
- After replacement of battery, push test/ "hush" button. This will decrease the sensitivity for approximately 8 minutes. During this time, the RED LED will flush every 10 seconds. This will indicate that the device is functioning;
- Dust can clog your smoke alarms. Battery-powered smoke alarms should be cleaned by opening the cover of the alarm and gently vacuuming the inside with a soft bristle brush;
- Maintain smoke detectors by testing and manual push to ascertain functionality every week as per instruction on the device by the manufacturer.

Long term recommendations

- ✓ Replace the system with newer and addressable type FACP to determine exact location of fire as it happens;
- ✓ Additional smoke detector devices are required in engineer's office, guardhouse, pump area;
- ✓ Additional heat detector devices are required in pantry, genset room, substation room;
- ✓ Additional strobe with sounder and call point at the genset and substation room since these rooms are located in separate buildings and for safety reasons for sounding alarm at the instant that there is fire;
- ✓ Annual Inspection, Testing and Maintenance;
- ✓ Replace existing bell to strobe light with sounder and call point at the booster pump area and additional strobe light with sounder and call point at genset room. Genset room is located in separate building and for safety reasons for sounding alarm at the instant that there is fire;

Note that the FACP will no longer communicate with existing bell and is not compatible

System Testing

FDAS shall be subjected to the following tests conforming to the Philippine Electronics Code of 2014 and Philippine Electrical Code of 2017

- ✓ Testing of insulation resistance and continuity of wires;
- ✓ Verification of installed devices;
- ✓ Operation and response of FDAS;
- ✓ Testing the operation of initiating devices;
- ✓ Measuring sound pressure level generated by notification devices;

Records

Every FDAS system shall keep the following documentations

- ✓ A complete set of operation and maintenance manuals of the manufacturer covering all equipment used in the system;
- ✓ A complete set of as-built drawings;
- ✓ A written sequence of operation;
- ✓ Record of completion and results of every inspection, testing and maintenance;
- ✓ Record of components within the database.

4.8.2 Lighting protection system

4.8.2.1 Data and analysis

No lightning protection was installed for this PS.

4.8.2.2 Recommendations

Refer to the conceptual design in Chapter 5

Short term Recommendations

Plan for the installation of a new lightning protection system

- ✓ the LPS conforms to the design and is based on the standard;
- ✓ all components of the LPS are in good condition and capable of performing their designed functions, and that there is no corrosion.

Long term Recommendations

Plan for the installation of a new lightning protection system

- ✓ According to the standard, an inspection should be undertaken during the construction of the structure, after the installation, after alterations or repairs, and when it is known that the structure has been struck by lightning;
- ✓ It is also recommended that inspections take place "periodically at such intervals as determined with regard to the nature of the structure to be protected", taking into account the local environment, such as corrosive soils and corrosive atmospheric conditions and the type of protection measures employed;
- ✓ The inspection comprises checking the technical documentation, visual inspections and test measurements;
- ✓ Prepare an inspection guide to facilitate the inspection process containing sufficient information on the installation and its components, tests methods and previous inspection/test data;
- ✓ During the visual inspection, the following should be checked;
  - the deterioration and corrosion of air-termination elements, conductors and connections
  - the corrosion of earth electrodes
  - the earthing resistance value for the earth-termination system
  - the condition of connections, equipotential bonding and fixings.
- ✓ For those parts of an earthing system and bonding network not visible for inspection, tests of electrical continuity should be performed;
- ✓ An inspection report should be prepared detailing the status of the system, any deviations from the technical documentation and the results of any measurements undertaken. Any obvious faults should also be reported.

No lightning protection system is 100% effective. A system designed in compliance with the standard does not guarantee immunity from damage. Lightning protection is an issue of statistical probabilities and risk management. A system designed in compliance with the standard should statistically reduce the risk to below a pre-determined threshold. The IEC 62305-2 risk management process provides a framework for this analysis. An effective lightning protection system needs to control a variety of risks. While the current of the lightning flash creates a number of electrical hazards, thermal and mechanical hazards also need to be addressed.

Risk to persons (and animals) include:

- Direct flash;
- Step potential ;
- Touch potential ;
- Side flash ;
- Secondary effects
  - asphyxiation from smoke or injury due to fire
  - structural dangers such as falling masonry from point of strike

- unsafe conditions such as water ingress from roof penetrations causing electrical or other hazards, failure or malfunction of processes, equipment and safety systems

Risk to structures & internal equipment include:

- Fire and/or explosion triggered by heat of lightning flash, its attachment point or electrical arcing of lightning current within structures ;
- Fire and/or explosion triggered by ohmic heating of conductors or arcing due to melted conductors;
- Punctures of structure roofing due to plasma heat at lightning point of strike ;
- Failure of internal electrical and electronic systems ;
- Mechanical damage including dislodged materials at point of strike.

4.8.3 Ground-Fault circuit interrupter (GFCI) or electric leakage circuit breaker (ELCB) or Residual circuit devices (RCD)

4.8.3.1 Data and analysis

No ground fault circuit interrupter (GFCI) or earth leakage Circuit breaker (ELCB) protection was installed in the panel for FDAS for this PS.

4.8.3.2 Recommendations

Refer to the conceptual design in Chapter 5

4.8.4 Electrical safety and protective devices

4.8.4.1 Data and analysis

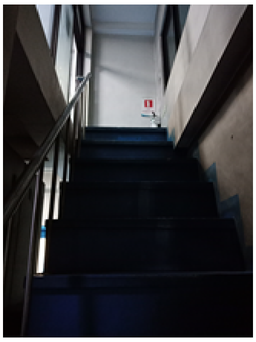
Facts obtained from inspection are presented in Table 4.28 with indicative figures for each devices presented in Figure 4.21.

4.8.4.2 Recommendations

Based on the status of devices, recommendations are with intervention types shown in Table 4.28. Chapter 5 further illustrates the recommendation with the conceptual design.

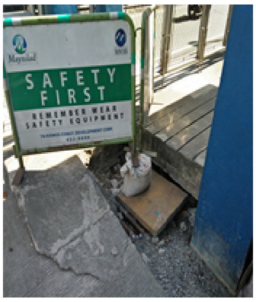
Table 4.28: Protective devices.

No.	Assets	CS	IT	Facts	Remarks
1	Stairway going to 2nd floor	0	4	No adequate illumination Steep stairway	Unsafe May cause tripping and downfall
2	Stairway going to rooftop	0	4	Safety Cage shield for climbing is too high. It do not protect personnel on the onset of climbing after 6 feet. Safety cage should start at 6 feet	Unsafe May cause fall
3	Construction near entrance	0	4	Unfinished construction left unattended and without restoring pathway	Unsafe May cause tripping if unnoticed
4	Fire Extinguisher at the entrance	0	4	Fire extinguisher placed beside an obstruction	Not readily accessible Fire Extinguisher partly hidden by boxes
5	Emergency Light-Ground floor	0	4	Green indicator Without inspection tag	Emergency Light does not show when was the last inspection due to lost tag
6	Fire Extinguisher - ground floor tag 01	0	4	No updated Last update is 30/Aug/2018	Unsafe Failure to inspect can make it ineffective
7	Fire Extinguisher - ground floor tag 02	0	4	No tag	FEX workability/functionality should be determined
8	Fire Extinguisher - Pump Area	0	4	No tag	FEX workability/functionality should be determined
9	Cooking pot-Pump Area	0	4	Cooking activity being done in Pump Area	Unsafe Cooking activity should be done in designated Area like pantry
10	Isolation Transfer Room - Ground floor	0	4	Chair obstruction in front of Switchgear	Unsafe Switchgear shall be free from all obstruction.
11	Chairs stores at the back of MCC	0	4	Chair obstruction on the rear of the Motor control Starter	Unsafe Switchgear shall be free from all obstruction
12	Emergency Light - Pump Area	0	4	With Power indicator Not charging	Inspection tag says EL is ok
13	First Aid Kit- Engineer's Area	0	4	First Aid kit not found only with signage	Unsafe Area should be dedicated to First Aid Alone and not to mix with other office materials



a - stairway going to 2nd floor

b - stairway going to rooftop of Building



c - Construction near entrance gate

d - Fire Extinguisher at the entrance

e - Emergency light ground floor

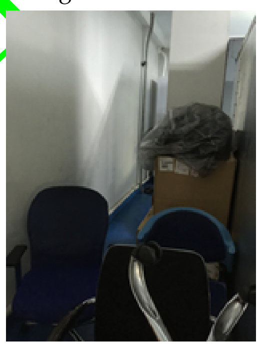
f - Fire Extinguisher – ground floor 01

g - Fire Extinguisher – ground floor 02

h - Fire Extinguisher – pump area

i - Cooking pot

j - Isolation transfer room



k - Chair at the back of the MCC

l - emergency light - pump area

m - First aid kid

Figure 4.21: Protective devices.

Chapter 5

Conceptual Design and Reliability Study

5.1 Basis of Design

5.1.1 As-built drawings

A collection of as-built drawings are given in A3 print out with electronic files saved both in PDF and CAD formats.

5.1.2 Mechanical design

As set of conceptual drawings is given in Appendix

5.1.3 FDAS design

5.1.3.1 Fire alarm and detection system

Design criteria

The conceptual design for FDAS has been developed based on findings/results of the audit (refer to subsections 4.8, design criteria including required code of practice, and the required level of services.

- Individual components shall be compatible with each other and shall be approved and listed by institutions recognized by the relevant authority
- The FDAS designer shall have the experience in the proper design, application, installation and testing of FDAS
- If the total floor area is more than 8000m2, a semi-addressable system shall be used, otherwise, a conventional system maybe used.
- Automatic detection shall have a complete indoor coverage of building or facilities including all rooms, halls, etc.
- For smoke detectors, the performance characteristics of the detector and the area shall be taken into account when selecting smoke detectors. Smoke detectors shall not be installed in rooms with temperature below 5 degree centigrade, above 45 degree centigrade and with relative humidity above 93%.
- For heat detectors, temperature rating shall be set at least 11 degree centigrade above maximum expected temperature and is spaces not more than 7.5meters. It shall not be installed in locations where relative humidity is above 93 % and if the ceiling is more than 4 meters.
- Beam-type smoke detector shall be used if ceilings are more than 6m in height and shall be kept clear of opaque obstacles at all times

- Manual detection is achieved through the manual activation of fire push or pull stations installed at a height of 1.4meters above floor and shall be easily seen and is accessible. It is usually colored red.
- Alarm shall be clearly audible throughout the floor and or/or building where they are installed. It shall have a minimum of 65 dbA or 10db higher than ambient room noise and a maximum of 115 dbA.
- Visual notification shall be used along with audible notification for areas where hearing protection is worn.

Design

5.1.3.2 Lighting protection system

Requirements

The design of a lightning protection system needs to: Intercept lightning flash (i.e. create a preferred point of strike) Conduct the lightning current to earth Dissipate current into the earth Create an equipotential bond to prevent hazardous potential differences between LPS, structure and internal elements/circuits

Following points shall be considered

- The lightning protection design shall be in accordance with the requirements of Article 2.90 Protection against Lightning , Philippine Electrical Code 2017 and NFPA 780, standard for the installation of lightning protection systems;
- The building lightning protection system shall include
  - Roof mounted copper air terminals;
  - Ground rods of lightning protection shall shall be metal clad steel with a diameter of 20mm by 3 meters long connected triangularly with equal distances of 3 meters between two ground rods;
  - Down conductor, 50mm2 Bare copper wire and shall be placed in protective conduit (PVC);
  - Lightning protection shall have electronically controlled mechanical register which activates registration for every discharge;
  - clamps, conduits and auxiliary equipment as required for complete and operational lightning protection system. Materials shall be resistant or protected against corrosion.
- The company providing the design should have a minimum of 5 years experience and be well versed with Article 2.90 Protection against Lightning , Philippine Electrical Code 2017 and NFPA 780;
- Lightning protection systems are designed specifically for the building or structures they are intended to protect;
- The design is not only impacted by the shape and size, but also by building systems and structural components.

Installation

The installation shall be in accordance with the requirements set forth in Article 2.90 Protection against Lightning and NFPA 780 and installed in a neat and workmanlike manner

5.1.3.3 Ground Electrode Installation and Common Bonding

Ground electrode installation and common building

- Ground electrodes shall be installed in accordance with NFPA 780 and Article 2.90 of PEC 2017.
- Common bonding between all building electrode systems shall be installed in accordance with NFPA 780 and PEC 2017
- Maintain horizontal or vertical runs of ground wires and ensures that all bends have at least 200 mm radius and angle of any bend shall not be less than 90 degrees.
- Lightning carrier cable and down conductor shall be supported every 1.50 meters on center using fabricated copper clamps, bolted to roof slab with plastic expansion sleeves.
- Ground rods should be driven far enough away from the footing and drain tile and also past the roof's drip edge.
- Ground rods shall be installed into undisturbed soil.
- If it is not practical to install ground rods outside of the building, the ground rods should be installed as close to the building's walls as practical without damaging the footing.
- The correct ground rod driver adapter should be used to avoid mushrooming or damaging the end of the ground rod.
- If the damage to the ground rod is to severe, the top of the rod may need to be cut off so that the ground rod clamp or exothermic connection can be properly made
- For testing and maintenance, access of each ground electrode should be available.

Ground ring electrode installation

- If required, a ground ring electrode for the lightning protection system shall be installed at least 460mm (18 inches) below earth unless prohibited by ground conditions;
- A ground ring electrode installed for the purposes of electrical grounding shall be installed to a depth of at least 765 mm (30 inches);
- Ground ring electrodes shall be continuous around the structure and connected to all down conductors. The ground ring electrode shall be installed below the line.

field test

Test the grounding system to assure the continuity and that the resistance to ground is not excessive.

5.2 Bill of Materials

Based on the recommendations and conceptual design, a high level Bill of Quantity (BOQ) can be generated . The BOQ table includes the condition states and intervention types respectively.

5.3 Determination of optimal intervention strategies

This section focuses on determination of intervention strategies for pumps or components of pumps in the station. Other assets such as electrical assets and other assets belong to FDAS system are not part of the analysis because they are utmost critical assets that require to provide adequate level of services at all time. Intervention strategies for electrical assets and FDAS assets are suggested to follow replacement schedule defined by the manufacturers.

5.3.1 Reliability

With the historical data given, it is not possible to precisely quantify the reliability for each pump or even each components of pumps. Thus, In order to more or less estimate the reliability, obtaining knowledge and experience of the end-users becomes important.

We assume reliability of an asset to follow a Weibull function. The Weibull function is suitable function to be used in survival/reliability analysis since it considers the memory of assets, i.e. past failure probability will be considered with duration of failure (refer to subsection 3.5.4 for further description on Weibull model).

Table 5.1 shows the assumed values used for model's parameters.

Table 5.1: Weibull parameters.

Assets	Weibull parameters		Remarks
	α	β	
BP1	6,966	2.174	
BP2	7,308	2.576	
BP3	7,092	2.573	
BP4	7,710	2.987	
SP1	6,458	2.983	
SP2	6,048	2.636	

Using the parameter values in Table 5.1, reliability curves for respective pumps can be drawn (Figure 5.1.

5.3.2 Impacts

Impacts are costs or loss of benefits incurred to the Client and users. Impacts are incurred by execution of PI or CI and by disruption to the operation of the PS.

Impacts incurred by execution of PI can be estimated based on, for example, conceptual design with the ballpark estimate. However, impacts incurred by execution of a CI is not easy to obtain due to lack of historical data. This is similar to the estimation of impacts such as loss in revenue, reputation, and regulatory.

Fortunately, from mathematical view point, the optimization model presented in subsection 3.7.1 will be only dependent on the ratio between CI and PI. This means that we can make assumption on the ratio between PI and CI based on holistic approach. For example, if the PI is 10 millions PHP and CI is 20 million, the ratio would be PI/CI =0.5, and the model will determine the optimal time window (T) to execute the PI. This time window T will not change as long as the ratio between CI/PI is the same.

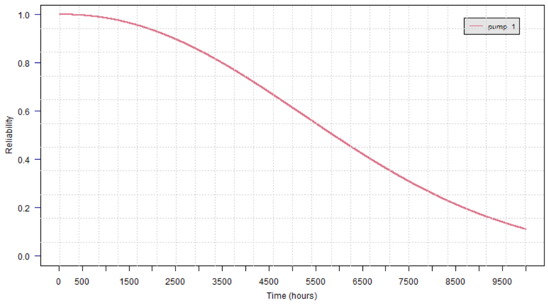
Table 5.2 shows the assumption on impacts incurred by execution of PI and CI as well the the impacts incurred considering the 3Rs (revenue, reputation, and regulatory).

Table 5.2: Impact values (mus).

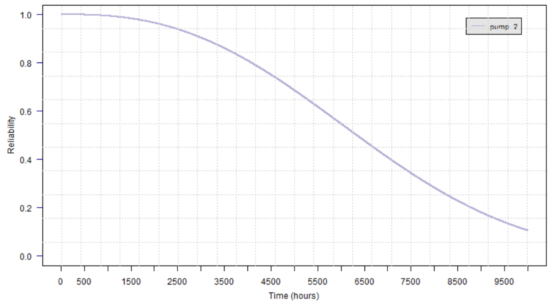
Assets	Weibull parameters		Impacts	Discount (%)	Remarks
	α	β	PI/CI	ρ	
BP1	6,966	2.174	0.1072	8.5	
BP2	7,308	2.576	0.4244	8.5	
BP3	7,092	2.573	0.2583	8.5	
BP4	7,710	2.987	0.3061	8.5	
SP1	6,458	2.983	0.3086	8.5	
SP2	6,048	2.636	0.2031	8.5	

Note: R1, R2, R3 are revenue, reputation and regulatory, respectively.

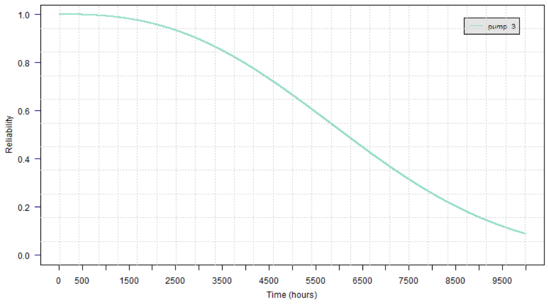
Values of revenues incurred by execution on respective pumps shall be calculated based on assumption on maintainability (e.g. duration of CI execution to fix the pump). Reputation and regulatory are not straightforward to estimate in monetary units, however, they can be assumed to be measured by "Willingness to Pay".



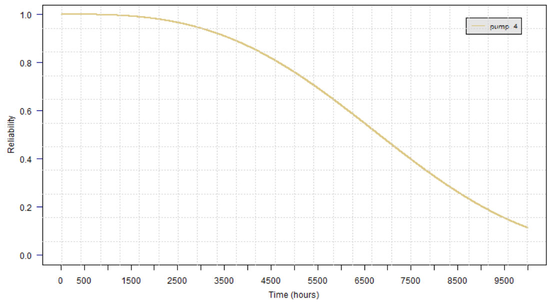
a - BP#1



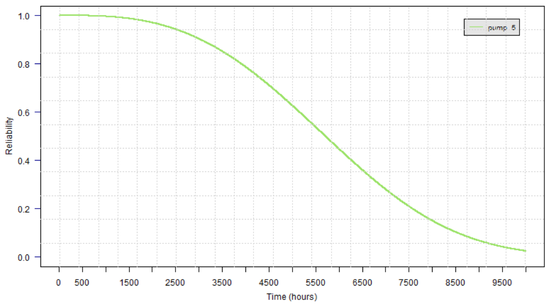
b - BP#2



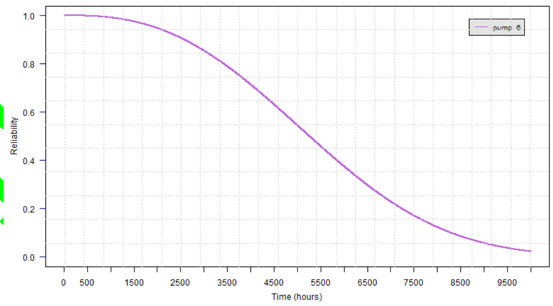
c - BP#3



d - BP#4



g - SP#1



h - SP#2

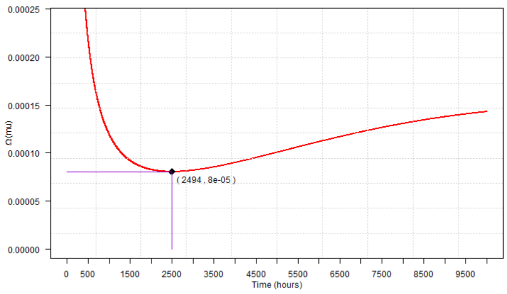
Figure 5.1: Reliability

5.3.3 Optimal Time Window and Impacts

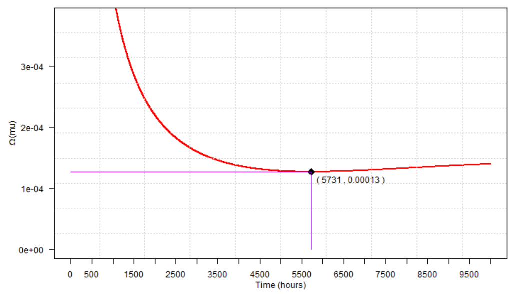
Figure 5.2 presents a collection of curves representing Optimal Time Window (OTW) and impacts incurred by executing PIs on respective pumps.

The curves are with parabolic shapes, with a minimal point representing the optimal point obtained by the model. Shapes of the curves prove following important conclusions

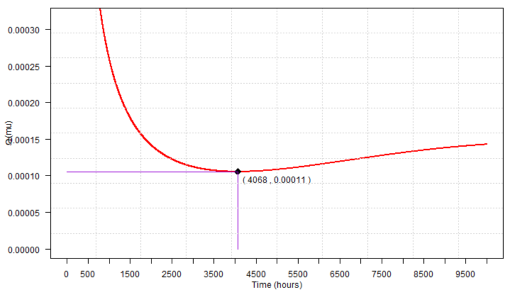
- If a PI is executed too often, the failure probability will be decreased, however, at the same time, more money is to spend on intervention activities. It will be a waste of resources to follow a program that triggers PIs;
- The impact will decrease as the OTW increases to the optimal point and then go upward indicating that if a PI is executed beyond a certain reliability threshold, failure probability will increase, leading to more sudden failures that require to execute CIs and higher loss (e.g. the 3 Rs).



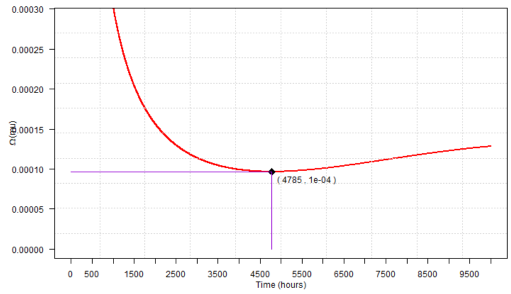
a - BP#1



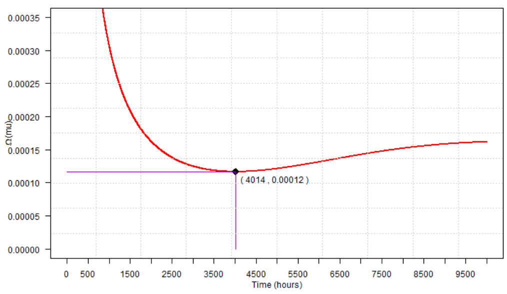
b - BP#2



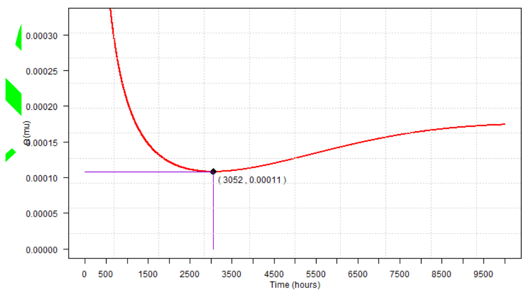
c - BP#3



d - BP#4



g - SP#1



h - SP#2

Figure 5.2: Impact curves

5.3.4 Sensitivity analysis

As a matter of fact, results of the optimization model are subjected to uncertainties with model's parameters and variables. Model's parameters are deterioration parameters η and β and impacts that should be obtained from historical data.

This subsection provides results of sensitivity analysis (SA) conducted on Weibull parameters η and β and the ratio between CI and PI. A SA was conducted by running the targeted parameter in a pre-defined range while keeping other parameters constant.

Results of the SA on parameter η are shown in Figure 5.3, with following discussion points.

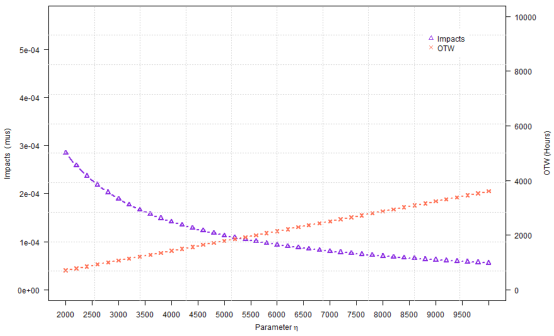
- Values of OTW follow either exponential function or log-normal function with decreasing trend and be converged to a minimum year. This is logic as the smaller value of α is, the less failure probability, and therefore the OTW will be deferred longer;
- Values of impact follow a monotonic increasing function. This is also logic as the higher failure probability infers more CIs to be executed.

Results of the SA on parameter β are shown in Figure 5.4, with following discussion points.

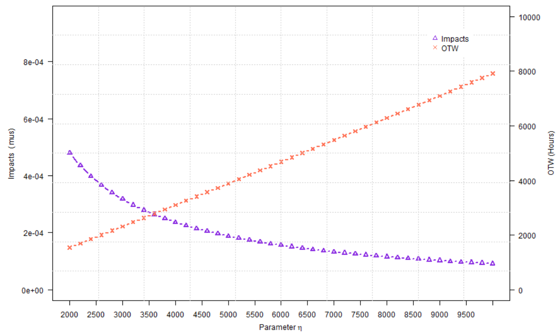
Table 5.3: Impact values (mus).

Assets	OTW (hours)	Minimum Impact (mus)
BP1	2,494	8.04E-05
BP2	5,731	1.27E-04
BP3	4,068	1.06E-04
BP4	4,785	9.66E-05
SP1	4,014	1.17E-04
SP2	3,052	1.08E-04

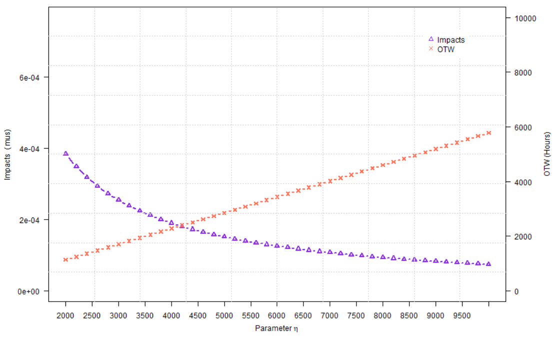
Note: OTW stands for Optimal Time Window to execute an PI.



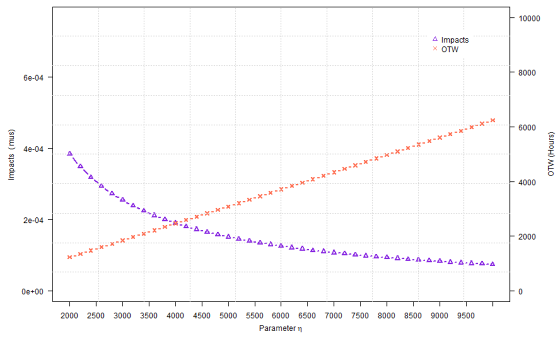
a - BP#1



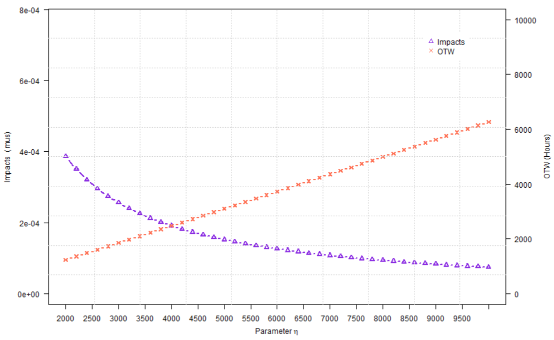
b - BP#2



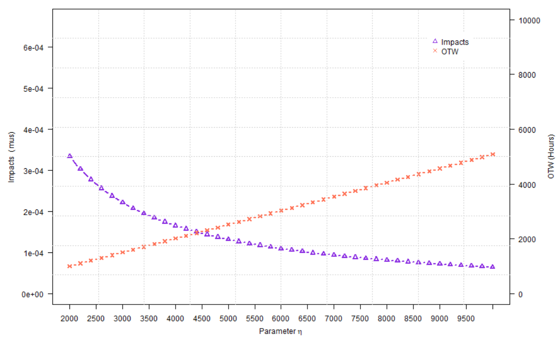
c - BP#3



d - BP#4



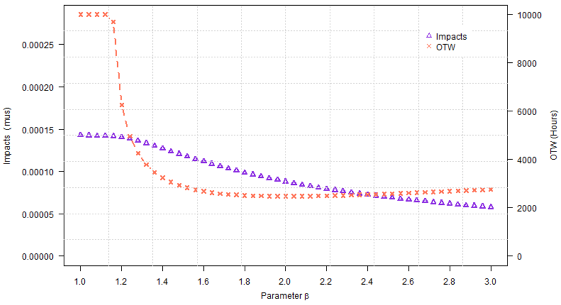
g - SP#1



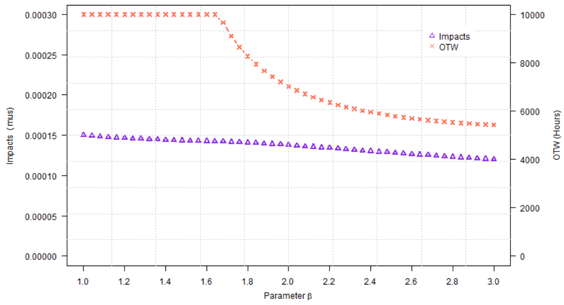
h - SP#2

Figure 5.3: Sensitivity Analysis (η)

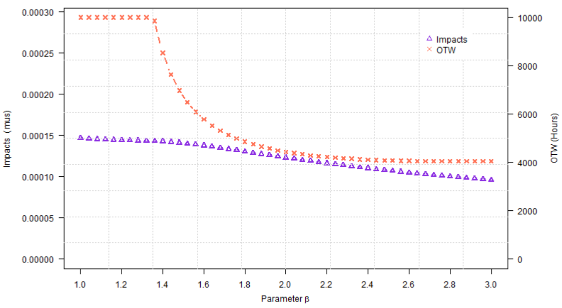
- Values of OTW follow an exponential function function with decreasing trend and be converged to a minimum year. This is logic as the smaller value of β is, the less failure probability, and therefore the OTW will be deferred longer;
- Values of impact follow a monotonic increasing function. This is also logic as the higher



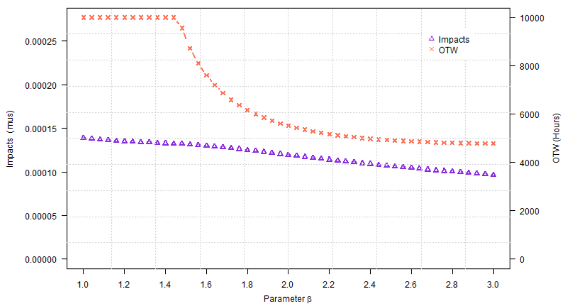
a - BP#1



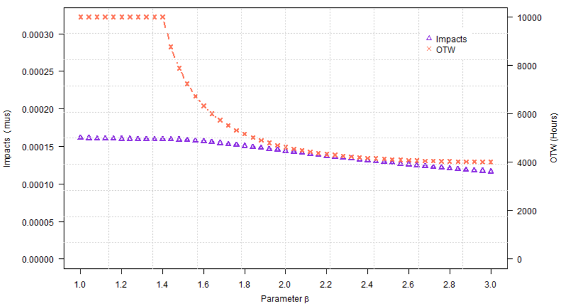
b - BP#2



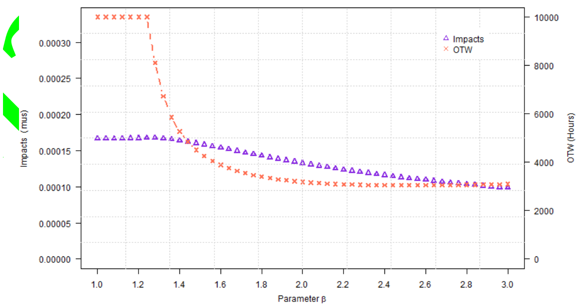
c - BP#3



d - BP#4



g - SP#1



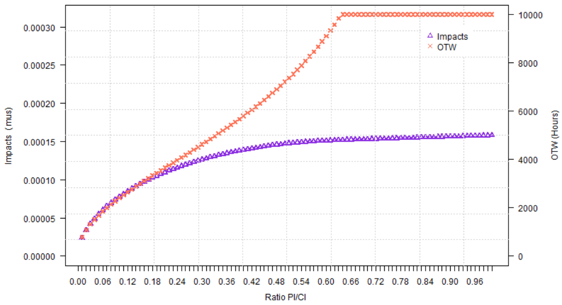
h - SP#2

Figure 5.4: Sensitivity Analysis (β)

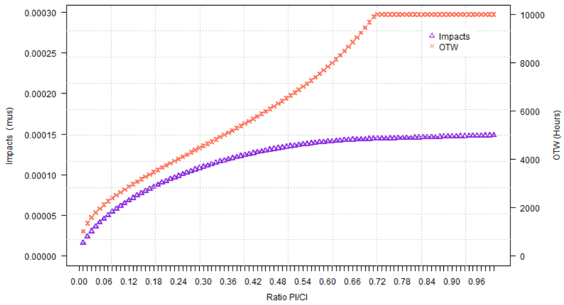
failure probability infers more CIs to be executed.

Results of the SA on the ratio PI/CI are shown in Figure 5.5, with following discussion points.

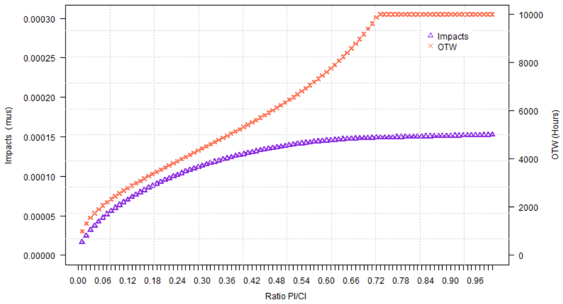
- Values of OTW follow an exponential function function with decreasing trend and be converged to a minimum year. This is logic as if the value of CI is not much different from PI, there is no need to perform PI often, the operators can just execute a CI when pumps fail. However, if the ratio is high, it means it will be very costly to let the system fails, hence it is advisable to shorten the time window to execute PIs to prevent possible failures from happening;
- Values of impact follow a monotonic increasing function. This is also logic as the higher ratio of CI/PI, the more impacts will be incurred with CI and therefore the annual cost will increase.



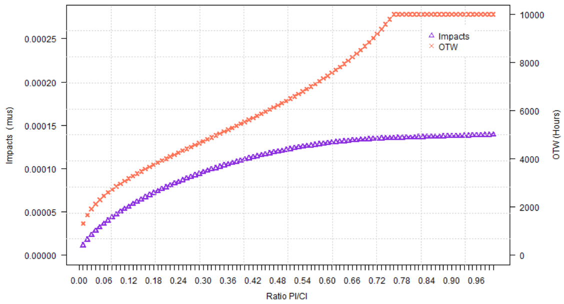
a - BP#1



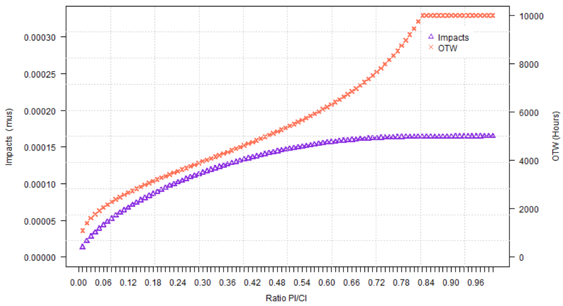
b - BP#2



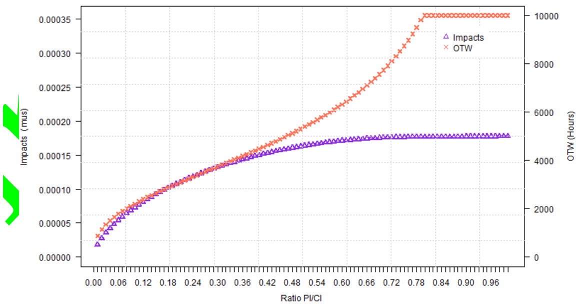
c - BP#3



d - BP#4



g - SP#1



h - SP#2

Figure 5.5: Sensitivity Analysis (PI/CI)

5.4 Return on Investment

It is important to note that in asset management context, the Return on Investment (ROI) is understood different from the ROI used for CAPEX projects. In CAPEX project, ROI is a ratio between the Net Present Value (NPV) of benefits (e.g. positive sum of cash flow) incurred over a pre-defined life cycle of a project (e.g. 20 or 30 years), at which there is a salvage value of the facility.

In asset management context, the ROI encompasses the ROI used in CAPEX project. This can be obviously seen in the impact curves shown in Figure 5.2. If the owner follows the optimal time window defined to execute a PI on any individual pump, the return on investment compared to other strategy that follow different time window is the difference of the impacts.

Chapter 6

Conclusions and Recommendations

Conclusions and recommendations have already presented in Chapter 4 for individual assets under investigation. This section is hence only to provide a high level conclusions and recommendations.

6.1 Conclusions

- Pumps have been operated in non-optimal control approach that might lead to higher failure probability of total system failure in a long run;
- Daily data on operation and power consumption is poorly recorded in non-relational table structure that is of little use for data analysis, especially when considering the huge amount of data recorded over time. This data shall be considered a very important part of management as it shall be used for energy audit and investigation on reliability of pumps and the system;
- No real time measurement of production and power consumption per pump. This leads to the impossibility of calculating the reliability of pump over time;
- No systematic inspection/testing strategy;
- Piping supports suffer significant deterioration and wear out;
- Existing FDAS system is not provide adequate level of services;
- No lighting and grounding protection system in place.

6.2 Recommendations

- Establishment of control philosophy to optimally operate pumps in a manner to protect pumps from being failed;
- Establishment of a good asset management practice (see recommendation in the Appendix);
- Establishment of a benchmark value for monitoring energy efficiency;
- Hiring an asset management expert/specialist to help the IAM to design a good platform to record data concerning daily production and power consumption via web-based system. Note that this is different platform from the current CMMS program. (Hiring a specialist to work with the IAM will eventually save cost for Maynilad in a long run. This can be contracted to individual expert);
- Establishment of a optimal inspection/testing regime for all assets. This testing regime shall be developed using the concept of optimality based on a solid mathematical modeling approach and best practices learnt from the industry (e.g. case based reasoning methodology);

- Redesign the FDAS system, lighting and grounding system. This shall be an immediate action to be executed prior to next raining season;
- Installation of flow meters and power meters to all pumps. This will allow having records on daily production and power per pump. This will enable prediction and detection of abnormal behavior of pump, thus providing background for failure prediction;
- Upgrade entirely the SCADA system to be fully automated. This is toward the industrial revolution 4.0 which is now a reality. By doing so, energy management statistic can be a real time monitoring system, which eventually supports Maynilad to detect the errors and improve the operation to minimize the energy consumption while still providing adequate level of services.

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Appendix A

Recommended Maintenance Program

Code	Name	Station ID	Asset Description	Component	Failure Mode	Criticality	Failure Pattern	Task	Frequency	Done by	Comments
WSO-VIMPR-0011	Storage Pump SP1	VIL	Horizontal pump between bearings	Bearings	Loss of lubrication	High	Age-related	Scheduled greasing	Weekly	Maintenance contractor	Avoid overgreasing. Use correct grease as stipulated by bearing manufacturer.
WSO-VIMPR-0011	Storage Pump SP1	VIL	Horizontal pump between bearings	Bearings	High vibration due to cavitation	High	Random	Monitor suction pressure not to go below xx head (set by client) (set by client).	Every hour	Operator	Refer to pump specifications on minimum NPSH requirements. Follow company policy in dealing with cavitation issues (e.g. call MCC to increase suction pressure and/or shutdown pumps)
WSO-VIMPR-0011	Storage Pump SP1	VIL	Horizontal pump between bearings	Bearings	High vibration due to bearing failure (e.g. foreign materials in lubrication)	High	Random	Vibration monitoring	2-weekly (every 2 weeks)	Maintenance contractor	Use trained contractor for the appropriate vibration monitoring device. Report findings every month.
WSO-VIMPR-0011	Storage Pump SP1	VIL	Horizontal pump between bearings	Packing	Excessive leaks	Medium	Age-related	Tighten packing bolts	2-weekly (every 2 weeks)	Maintenance contractor	Avoid overtightening of packing bolts.
WSO-VIMPR-0011	Storage Pump SP1	VIL	Horizontal pump between bearings	Motor	Motor trip due to overloading	High	Random	Motor (skin) temperature measurement	Every hour	Operator	Refer to motor specifications on maximum allowable surface temperature.
WSO-VIMPR-0011	Storage Pump SP1	VIL	Horizontal pump between bearings	Motor	Motor burns due to failure of winding insulation	Low	Age-related	Inspect motor winding insulation	Annually	Maintenance contractor	Use qualified maintenance contractor.
WSO-VIMPR-0011	Storage Pump SP1	VIL	Horizontal pump between bearings	Suction isolating valve	Valve passing (leaks)	Medium	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve may cause problems during maintenance of pump/motor.
WSO-VIMPR-0011	Storage Pump SP1	VIL	Horizontal pump between bearings	Discharge isolating valve	Valve passing (leaks)	Low	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve is not critical as long as the check valve is working.
WSO-VIMPR-0011	Storage Pump SP1	VIL	Horizontal pump between bearings	Pressure gauge (suction & discharge)	Pressure gauge reading is wrong due to wear	Low	Age-related	Replace pressure gauge	Annually	Maintenance contractor	Replace with calibrated pressure gauge. Mark with acceptable operating range. Criticality is low if the online pressure sensors are still functioning properly.
WSO-VIMPR-0011	Storage Pump SP1	VIL	Horizontal pump between bearings	Pressure sensors (suction & discharge)	Pressure reading is erroneous	High	Random	Calibrate pressure sensors	Semi-annually (every 6 months)	Maintenance contractor	Use qualified maintenance contractor.
WSO-VIMPR-0011	Storage Pump SP1	VIL	Horizontal pump between bearings	Flange	Leaks due to loose bolts and/or gasket failure	Medium	Age-related	Re-tighten bolts using specified torque values	Annually	Maintenance contractor	Use proper bolt tightening methods (e.g. manual, hydraulic, pneumatic, tensioning, etc.) Apply required bolt torque values.
WSO-VIMPR-0011	Storage Pump SP1	VIL	Horizontal pump between bearings	Vibration dampers	Leaks due to deteriorated materials caused by fatigue	Medium	Age-related	Replace vibration dampers based on recommended life	Every 10 years	Maintenance contractor	Refer to recommended life of dampers by manufacturer. Otherwise, purchase spare damper before its recommended life to ensure availability when needed.
WSO-VIMPR-0011	Storage Pump SP1	VIL	Horizontal pump between bearings	System	General system leaks	Low	Random	Inspect system for leaks	Shift	Operator	Report excessive leaks for scheduled repairs.
WSO-VIMPR-0011	Storage Pump SP1	VIL	Horizontal pump between bearings	Impeller	Impeller wear	Low	Age-related	-Replace impeller -Inspect and measure clearances after every	-10 years -Annually	Maintenance contractor	Inspect during annual overhauls.
WSO-VIMPR-0011	Storage Pump SP1	VIL	Horizontal pump between bearings	Suction strainer	Blockage	Medium	Age-related	Clean strainer	Annually	Maintenance contractor	During annual overhauls.
WSO-VIMPR-0018	Storage Pump SP2	VIL	Horizontal pump between bearings	Bearings	Loss of lubrication	High	Age-related	Scheduled greasing	Weekly	Maintenance contractor	Avoid overgreasing. Use correct grease as stipulated by bearing manufacturer.
WSO-VIMPR-0018	Storage Pump SP2	VIL	Horizontal pump between bearings	Bearings	High vibration due to cavitation	High	Random	Monitor suction pressure not to go below xx head (set by client) (set by client).	Every hour	Operator	Refer to pump specifications on minimum NPSH requirements. Follow company policy in dealing with cavitation issues (e.g. call MCC to increase suction pressure and/or shutdown pumps)
WSO-VIMPR-0018	Storage Pump SP2	VIL	Horizontal pump between bearings	Bearings	High vibration due to bearing failure (e.g. foreign materials in lubrication)	High	Random	Vibration monitoring	2-weekly (every 2 weeks)	Maintenance contractor	Use trained contractor for the appropriate vibration monitoring device. Report findings every month.
WSO-VIMPR-0018	Storage Pump SP2	VIL	Horizontal pump between bearings	Packing	Excessive leaks	Medium	Age-related	Tighten packing bolts	2-weekly (every 2 weeks)	Maintenance contractor	Avoid overtightening of packing bolts.
WSO-VIMPR-0018	Storage Pump SP2	VIL	Horizontal pump between bearings	Motor	Motor trip due to overloading	High	Random	Motor (skin) temperature measurement	Every hour	Operator	Refer to motor specifications on maximum allowable surface temperature.
WSO-VIMPR-0018	Storage Pump SP2	VIL	Horizontal pump between bearings	Motor	Motor burns due to failure of winding insulation	Low	Age-related	Inspect motor winding insulation	Annually	Maintenance contractor	Use qualified maintenance contractor.
WSO-VIMPR-0018	Storage Pump SP2	VIL	Horizontal pump between bearings	Suction isolating valve	Valve passing (leaks)	Medium	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve may cause problems during maintenance of pump/motor.
WSO-VIMPR-0018	Storage Pump SP2	VIL	Horizontal pump between bearings	Discharge isolating valve	Valve passing (leaks)	Low	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve is not critical as long as the check valve is working.
WSO-VIMPR-0018	Storage Pump SP2	VIL	Horizontal pump between bearings	Pressure gauge (suction & discharge)	Pressure gauge reading is wrong due to wear	Low	Age-related	Replace pressure gauge	Annually	Maintenance contractor	Replace with calibrated pressure gauge. Mark with acceptable operating range. Criticality is low if the online pressure sensors are still functioning properly.

Code	Name	Station ID	Asset Description	Component	Failure Mode	Criticality	Failure Pattern	Task	Frequency	Done by	Comments
WSO-VIMPR-0018	Storage Pump SP2	VIL	Horizontal pump between bearings	Pressure sensors (suction & discharge)	Pressure reading is erroneous	High	Random	Calibrate pressure sensors	Semi-annually (every 6 months)	Maintenance contractor	Use qualified maintenance contractor.
WSO-VIMPR-0018	Storage Pump SP2	VIL	Horizontal pump between bearings	Flange	Leaks due to loose bolts and/or gasket failure	Medium	Age-related	Re-tighten bolts using specified torque values	Annually	Maintenance contractor	Use proper bolt tightening methods (e.g. manual, hydraulic, pneumatic, tensioning, etc.) Apply required bolt torque values.
WSO-VIMPR-0018	Storage Pump SP2	VIL	Horizontal pump between bearings	Vibration dampers	Leaks due to deteriorated materials caused by fatigue	Medium	Age-related	Replace vibration dampers based on recommended life	Every 10 years	Maintenance contractor	Refer to recommended life of dampers by manufacturer. Otherwise, purchase spare damper before its recommended life to ensure availability when needed.
WSO-VIMPR-0018	Storage Pump SP2	VIL	Horizontal pump between bearings	System	General system leaks	Low	Random	Inspect system for leaks	Shift	Operator	Report excessive leaks for scheduled repairs.
WSO-VIMPR-0018	Storage Pump SP2	VIL	Horizontal pump between bearings	Impeller	Impeller wear	Low	Age-related	-Replace impeller -Inspect and measure clearances after every	-10 years -Annually	Maintenance contractor	Inspect during annual overhauls.
WSO-VIMPR-0018	Storage Pump SP2	VIL	Horizontal pump between bearings	Suction strainer	Blockage	Medium	Age-related	Clean strainer	Annually	Maintenance contractor	During annual overhauls.
WSO-VIMPR-0029	Booster Pump BP1	VIL	Horizontal pump between bearings	Bearings	Loss of lubrication	High	Age-related	Scheduled greasing	Weekly	Maintenance contractor	Avoid overgreasing. Use correct grease as stipulated by bearing manufacturer.
WSO-VIMPR-0029	Booster Pump BP1	VIL	Horizontal pump between bearings	Bearings	High vibration due to cavitation	High	Random	Monitor suction pressure not to go below xx head (set by client) (set by client).	Every hour	Operator	Refer to pump specifications on minimum NPSH requirements. Follow company policy in dealing with cavitation issues (e.g. call MCC to increase suction pressure and/or shutdown pumps)
WSO-VIMPR-0029	Booster Pump BP1	VIL	Horizontal pump between bearings	Bearings	High vibration due to bearing failure (e.g. foreign materials in lubrication)	High	Random	Vibration monitoring	2-weekly (every 2 weeks)	Maintenance contractor	Use trained contractor for the appropriate vibration monitoring device. Report findings every month.
WSO-VIMPR-0029	Booster Pump BP1	VIL	Horizontal pump between bearings	Packing	Excessive leaks	Medium	Age-related	Tighten packing bolts	2-weekly (every 2 weeks)	Maintenance contractor	Avoid overtightening of packing bolts.
WSO-VIMPR-0029	Booster Pump BP1	VIL	Horizontal pump between bearings	Motor	Motor trip due to overloading	High	Random	Motor (skin) temperature measurement	Every hour	Operator	Refer to motor specifications on maximum allowable surface temperature.
WSO-VIMPR-0029	Booster Pump BP1	VIL	Horizontal pump between bearings	Motor	Motor burns due to failure of winding insulation	Low	Age-related	Inspect motor winding insulation	Annually	Maintenance contractor	Use qualified maintenance contractor.
WSO-VIMPR-0029	Booster Pump BP1	VIL	Horizontal pump between bearings	Suction isolating valve	Valve passing (leaks)	Medium	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve may cause problems during maintenance of pump/motor.
WSO-VIMPR-0029	Booster Pump BP1	VIL	Horizontal pump between bearings	Discharge isolating valve	Valve passing (leaks)	Low	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve is not critical as long as the check valve is working.
WSO-VIMPR-0029	Booster Pump BP1	VIL	Horizontal pump between bearings	Pressure gauge (suction & discharge)	Pressure gauge reading is wrong due to wear	Low	Age-related	Replace pressure gauge	Annually	Maintenance contractor	Replace with calibrated pressure gauge. Mark with acceptable operating range. Criticality is low if the online pressure sensors are still functioning properly.
WSO-VIMPR-0029	Booster Pump BP1	VIL	Horizontal pump between bearings	Pressure sensors (suction & discharge)	Pressure reading is erroneous	High	Random	Calibrate pressure sensors	Semi-annually (every 6 months)	Maintenance contractor	Use qualified maintenance contractor.
WSO-VIMPR-0029	Booster Pump BP1	VIL	Horizontal pump between bearings	Flange	Leaks due to loose bolts and/or gasket failure	Medium	Age-related	Re-tighten bolts using specified torque values	Annually	Maintenance contractor	Use proper bolt tightening methods (e.g. manual, hydraulic, pneumatic, tensioning, etc.) Apply required bolt torque values.
WSO-VIMPR-0029	Booster Pump BP1	VIL	Horizontal pump between bearings	Vibration dampers	Leaks due to deteriorated materials caused by fatigue	Medium	Age-related	Replace vibration dampers based on recommended life	Every 10 years	Maintenance contractor	Refer to recommended life of dampers by manufacturer. Otherwise, purchase spare damper before its recommended life to ensure availability when needed.
WSO-VIMPR-0029	Booster Pump BP1	VIL	Horizontal pump between bearings	System	General system leaks	Low	Random	Inspect system for leaks	Shift	Operator	Report excessive leaks for scheduled repairs.
WSO-VIMPR-0029	Booster Pump BP1	VIL	Horizontal pump between bearings	Impeller	Impeller wear	Low	Age-related	-Replace impeller -Inspect and measure clearances after every	-10 years -Annually	Maintenance contractor	Inspect during annual overhauls.
WSO-VIMPR-0029	Booster Pump BP1	VIL	Horizontal pump between bearings	Suction strainer	Blockage	Medium	Age-related	Clean strainer	Annually	Maintenance contractor	During annual overhauls.
WSO-VIMPR-0036	Booster Pump BP2	VIL	Horizontal pump between bearings	Bearings	Loss of lubrication	High	Age-related	Scheduled greasing	Weekly	Maintenance contractor	Avoid overgreasing. Use correct grease as stipulated by bearing manufacturer.
WSO-VIMPR-0036	Booster Pump BP2	VIL	Horizontal pump between bearings	Bearings	High vibration due to cavitation	High	Random	Monitor suction pressure not to go below xx head (set by client) (set by client).	Every hour	Operator	Refer to pump specifications on minimum NPSH requirements. Follow company policy in dealing with cavitation issues (e.g. call MCC to increase suction pressure and/or shutdown pumps)

Code	Name	Station ID	Asset Description	Component	Failure Mode	Criticality	Failure Pattern	Task	Frequency	Done by	Comments
WSO-VIMPR-0036	Booster Pump BP2	VIL	Horizontal pump between bearings	Bearings	High vibration due to bearing failure (e.g. foreign materials in lubrication)	High	Random	Vibration monitoring	2-weekly (every 2 weeks)	Maintenance contractor	Use trained contractor for the appropriate vibration monitoring device. Report findings every month.
WSO-VIMPR-0036	Booster Pump BP2	VIL	Horizontal pump between bearings	Packing	Excessive leaks	Medium	Age-related	Tighten packing bolts	2-weekly (every 2 weeks)	Maintenance contractor	Avoid overtightening of packing bolts.
WSO-VIMPR-0036	Booster Pump BP2	VIL	Horizontal pump between bearings	Motor	Motor trip due to overloading	High	Random	Motor (skin) temperature measurement	Every hour	Operator	Refer to motor specifications on maximum allowable surface temperature.
WSO-VIMPR-0036	Booster Pump BP2	VIL	Horizontal pump between bearings	Motor	Motor burns due to failure of winding insulation	Low	Age-related	Inspect motor winding insulation	Annually	Maintenance contractor	Use qualified maintenance contractor.
WSO-VIMPR-0036	Booster Pump BP2	VIL	Horizontal pump between bearings	Suction isolating valve	Valve passing (leaks)	Medium	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve may cause problems during maintenance of pump/motor.
WSO-VIMPR-0036	Booster Pump BP2	VIL	Horizontal pump between bearings	Discharge isolating valve	Valve passing (leaks)	Low	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve is not critical as long as the check valve is working.
WSO-VIMPR-0036	Booster Pump BP2	VIL	Horizontal pump between bearings	Pressure gauge (suction & discharge)	Pressure gauge reading is wrong due to wear	Low	Age-related	Replace pressure gauge	Annually	Maintenance contractor	Replace with calibrated pressure gauge. Mark with acceptable operating range. Criticality is low if the online pressure sensors are still functioning properly.
WSO-VIMPR-0036	Booster Pump BP2	VIL	Horizontal pump between bearings	Pressure sensors (suction & discharge)	Pressure reading is erroneous	High	Random	Calibrate pressure sensors	Semi-annually (every 6 months)	Maintenance contractor	Use qualified maintenance contractor.
WSO-VIMPR-0036	Booster Pump BP2	VIL	Horizontal pump between bearings	Flange	Leaks due to loose bolts and/or gasket failure	Medium	Age-related	Re-tighten bolts using specified torque values	Annually	Maintenance contractor	Use proper bolt tightening methods (e.g. manual, hydraulic, pneumatic, tensioning, etc.) Apply required bolt torque values.
WSO-VIMPR-0036	Booster Pump BP2	VIL	Horizontal pump between bearings	Vibration dampers	Leaks due to deteriorated material caused by fatigue	Medium	Age-related	Replace vibration dampers based on recommended life	Every 10 years	Maintenance contractor	Refer to recommended life of dampers by manufacturer. Otherwise, purchase spare damper before its recommended life to ensure availability when needed.
WSO-VIMPR-0036	Booster Pump BP2	VIL	Horizontal pump between bearings	System	General system leaks	Low	Random	Inspect system for leaks	Shift	Operator	Report excessive leaks for scheduled repairs.
WSO-VIMPR-0036	Booster Pump BP2	VIL	Horizontal pump between bearings	Impeller	Impeller wear	Low	Age-related	-Replace impeller -Inspect and measure clearances after every	-10 years -Annually	Maintenance contractor	Inspect during annual overhauls.
WSO-VIMPR-0036	Booster Pump BP2	VIL	Horizontal pump between bearings	Suction strainer	Blockage	Medium	Age-related	Clean strainer	Annually	Maintenance contractor	During annual overhauls.
WSO-VIMPR-0043	Booster Pump BP3	VIL	Vertical pump	Bearings	Loss of lubrication	High	Age-related	Scheduled greasing	Weekly	Maintenance contractor	Avoid overgreasing. Use correct grease as stipulated by bearing manufacturer.
WSO-VIMPR-0043	Booster Pump BP3	VIL	Vertical pump	Bearings	High vibration due to cavitation	High	Random	Monitor suction pressure not to go below xx head (set by client) (set by client).	Every hour	Operator	Refer to pump specifications on minimum NPSH requirements. Follow company policy in dealing with cavitation issues (e.g. call MCC to increase suction pressure and/or shutdown pumps)
WSO-VIMPR-0043	Booster Pump BP3	VIL	Vertical pump	Bearings	High vibration due to bearing failure (e.g. foreign materials in lubrication)	High	Random	Vibration monitoring	2-weekly (every 2 weeks)	Maintenance contractor	Use trained contractor for the appropriate vibration monitoring device. Report findings every month.
WSO-VIMPR-0043	Booster Pump BP3	VIL	Vertical pump	Packing	Excessive leaks	Medium	Age-related	Tighten packing bolts	2-weekly (every 2 weeks)	Maintenance contractor	Avoid overtightening of packing bolts.
WSO-VIMPR-0043	Booster Pump BP3	VIL	Vertical pump	Motor	Motor trip due to overloading	High	Random	Motor (skin) temperature measurement	Every hour	Operator	Refer to motor specifications on maximum allowable surface temperature.
WSO-VIMPR-0043	Booster Pump BP3	VIL	Vertical pump	Motor	Motor burns due to failure of winding insulation	Low	Age-related	Inspect motor winding insulation	Annually	Maintenance contractor	Use qualified maintenance contractor.
WSO-VIMPR-0043	Booster Pump BP3	VIL	Vertical pump	Suction isolating valve	Valve passing (leaks)	Medium	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve may cause problems during maintenance of pump/motor.
WSO-VIMPR-0043	Booster Pump BP3	VIL	Vertical pump	Discharge isolating valve	Valve passing (leaks)	Low	Age-related	Test valve integrity	Annually	Maintenance contractor	Use qualified maintenance contractor. Failure of this valve is not critical as long as the check valve is working.
WSO-VIMPR-0043	Booster Pump BP3	VIL	Vertical pump	Pressure gauge (suction & discharge)	Pressure gauge reading is wrong due to wear	Low	Age-related	Replace pressure gauge	Annually	Maintenance contractor	Replace with calibrated pressure gauge. Mark with acceptable operating range. Criticality is low if the online pressure sensors are still functioning properly.
WSO-VIMPR-0043	Booster Pump BP3	VIL	Vertical pump	Pressure sensors (suction & discharge)	Pressure reading is erroneous	High	Random	Calibrate pressure sensors	Semi-annually (every 6 months)	Maintenance contractor	Use qualified maintenance contractor.
WSO-VIMPR-0043	Booster Pump BP3	VIL	Vertical pump	Flange	Leaks due to loose bolts and/or gasket failure	Medium	Age-related	Re-tighten bolts using specified torque values	Annually	Maintenance contractor	Use proper bolt tightening methods (e.g. manual, hydraulic, pneumatic, tensioning, etc.) Apply required bolt torque values.

Appendix B

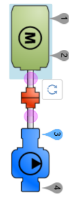
Vibration Data

Expertise Report

Filter: Equipment name (+) \ Tree order (+)

Location	VILLAMOR\	Fixed speed
Designation		
Equipment	BOOSTER PUMP#1	
Designation		
Abbreviation	BP#1	
Serial No		
Model		
Periodicity (d)	Normal 60 Alarm 15	

Previous Advice	Condition	Rotation Speed



Date 15/11/2018 12:34:45	FAIR *Health is not acceptable for a long time service.*	Speed	19.8 Hz / 1185 rpm
Condition DfCnd		Author	u1
		System - Serial	FALCON - 11407
		Sensor	
		Connector	

Diagnosis & Recommendation

Parameters sheet

Diagnosis

Pump Cavitation

Good overall state for component 'Electric motor'.
Overall Vibration levels are tolerable at 2.79mm/s though there were minor pedestal looseness on Motor holding base bolts or Minor Misalignment that being reflected in FFT at Motor DE Vertical.

Fair state for the component 'Pump'.
Highest vibrations measured at Pump IB Bearing Vertical with Overall Velocity of 5.53mm/s and dominant peak at 1x Blade Passing Frequency (119.25Hz) caused by Pump Cavitation.

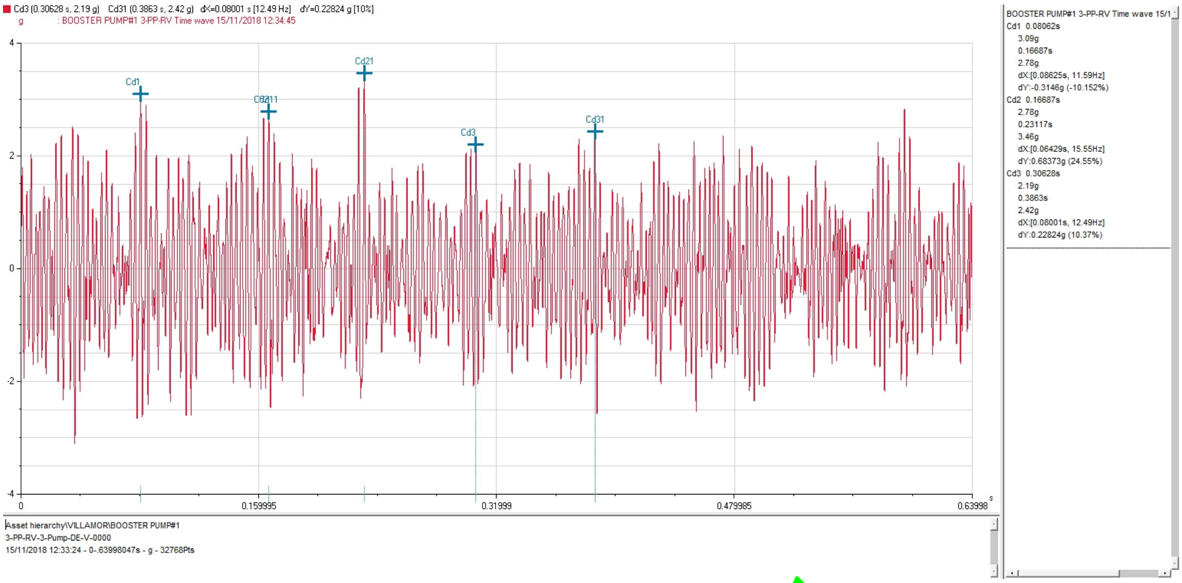
Recommendations

Cavitation to be corrected

Double check alignment conditions using Precision laser alignment tool.
Cavitation to be corrected: process control and action as soon as possible. Follow the dynamic behavior of the pump to prevent impeller damage.
☐Location "3-Pump-DE" to be corrected
☐Location "4-Pump-NDE" to be watched
Continue monitor periodically to further trend the vibrations from pump cavitations.

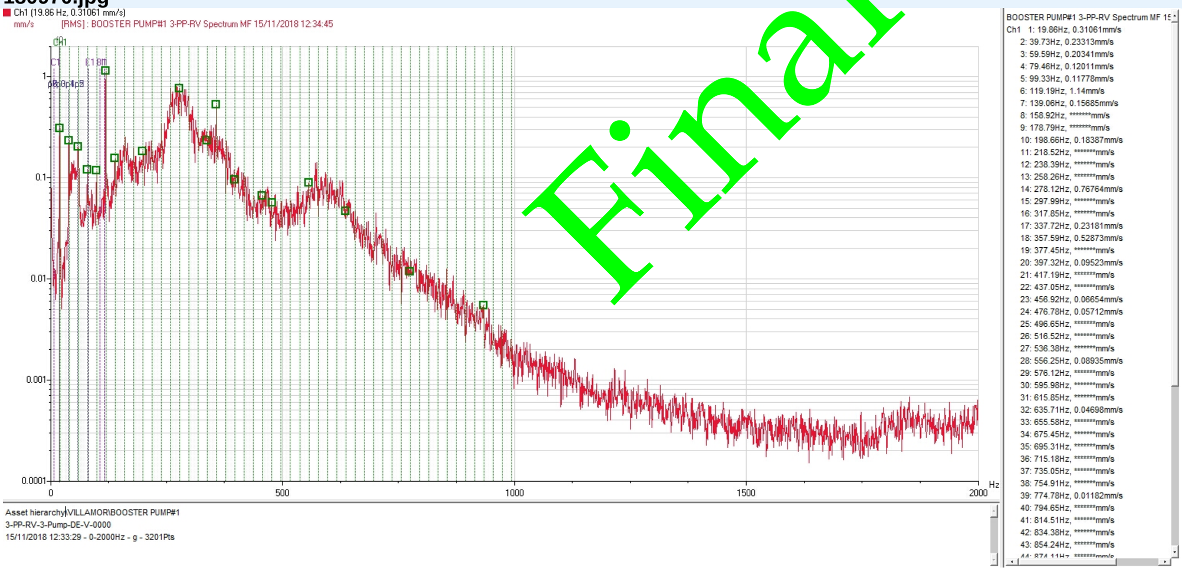
280aba.jpg

Final



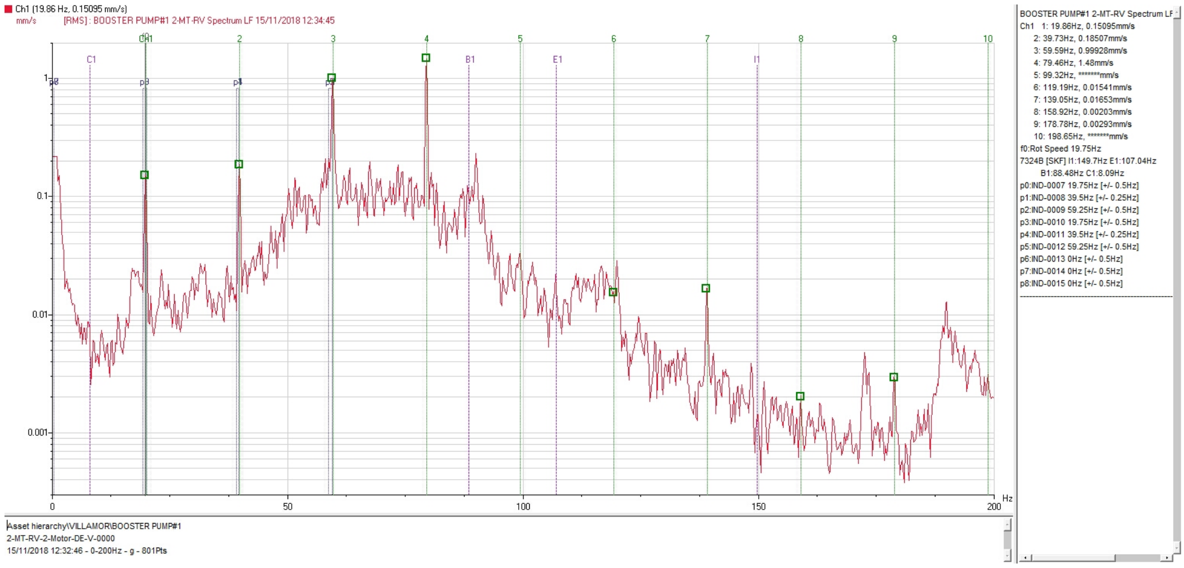
Non-periodic pulsation due to pump cavitations

180970.jpg



FFT clearly shows haystack/humps or elevated base at high frequencies and 1x peak at Blade Passing Frequency - an indication of induced Pump Cavitations

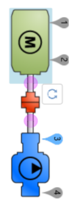
b09a0.jpg



Pedestal Looseness at 1x, 2x, 3x, 4x peak

Location	**VILLAMOR**
Designation	
Equipment	**BOOSTER PUMP#2**
Designation	
Abbreviation	**BP#2**
Serial No	
Model	
Periodicity (d)	*Normal* **60** *Alarm* **15**

Fixed speed



Previous Advice	***Condition***	***Rotation Speed***

Date **15/11/2018 12:40:21**	**FAIR**	*Speed*	**19.8 Hz / 1185 rpm**
Condition **DfCnd**	***Health is not acceptable for a long time service.***	*Author*	**u1**
		System - Serial	**FALCON - 11407**
		Sensor	
		Connector	

Diagnosis & Recommendation

Parameters sheet

Diagnosis

Pump Cavitation

Good overall state for component 'Electric motor'.

Fair state for the component 'Pump'.

Highest vibrations measured at Pump IB Bearing Vertical with Overall Velocity of 5.17mm/s and dominant peak at 1x Blade Passing Frequency (119.25Hz) caused by Pump Cavitation.

Recommendations

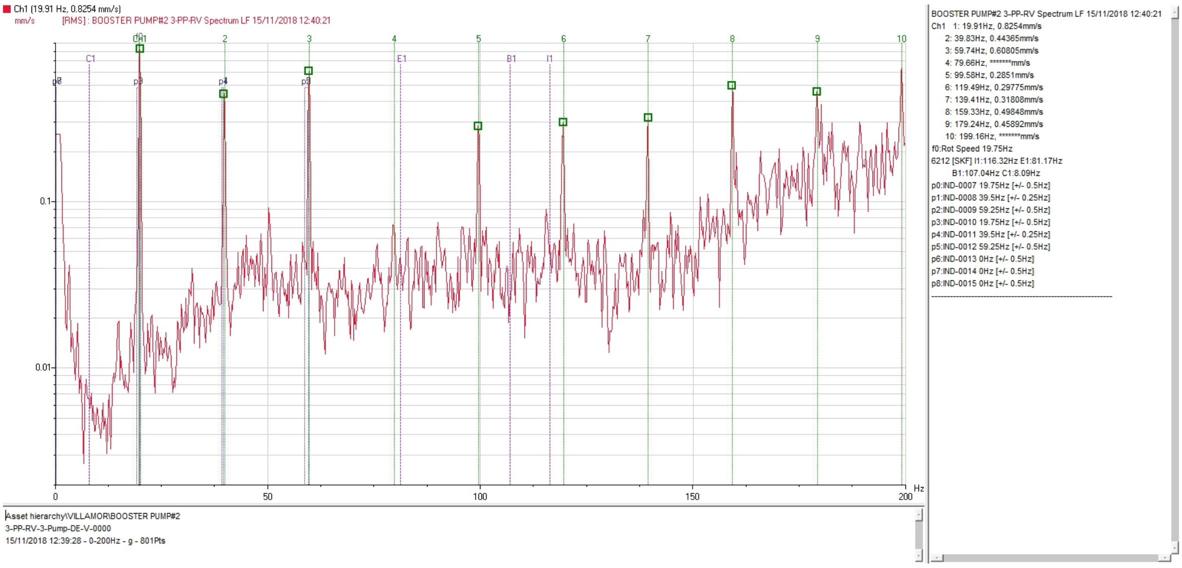
Cavitation to be corrected

Cavitation to be corrected: process control and action as soon as possible. Follow the dynamic behavior of the pump to prevent impeller damage.

☐Location "3-Pump-DE" to be corrected

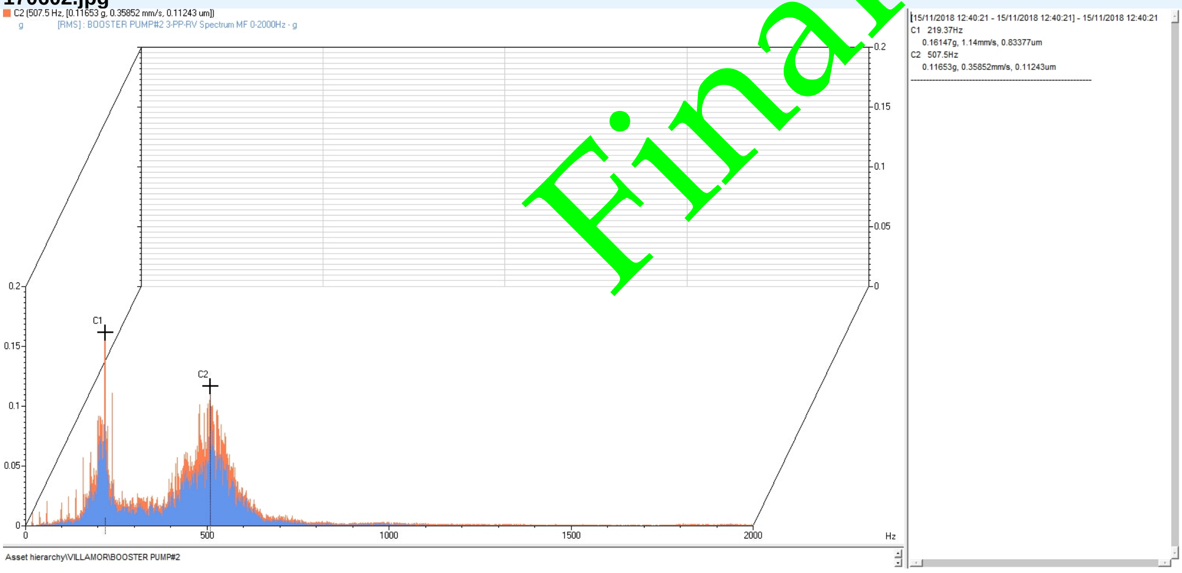
☐Location "4-Pump-NDE" to be watched

140abe.jpg



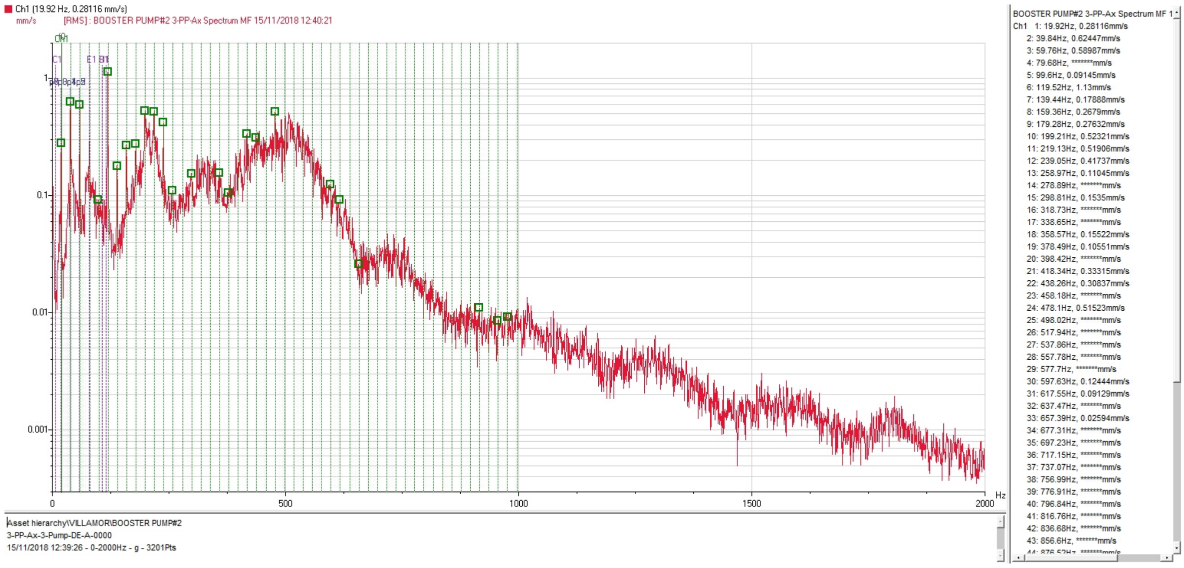
Highest vibrations measured at Pump IB Bearing Vertical with Overall Velocity of [illegible]17mm/s and dominant peak at 1x Blade Passing Frequency (119.25Hz) caused by Pump Cavitation.

170602.jpg



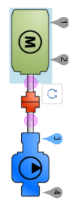
Elevated Base of Spectrum at high frequency range is an indication of Pump Cavitations

b0648.jpg



Location	VILLAMOR\	
Designation		
Equipment	BOOSTER PUMP#4	
Designation		
Abbreviation	BP#4	Fixed speed
Serial No		
Model		
Periodicity (d)	*Normal* **60** *Alarm* **15**	

Previous Advice	*Condition*	*Rotation Speed*



Date 15/11/2018 12:50:45	**FAIR** *Health is not acceptable for a long time service.*	*Speed* **19.9 Hz / 1194 rpm**
Condition **DfCnd**		*Author* **u1** *System - Serial* **FALCON - 11407** *Sensor* *Connector*

Diagnosis & Recommendation

Parameters sheet

Diagnosis

Pump Cavitations, Misalignment

Fair State for the component 'Electric motor'.
Highest vibrations measured Motor NDE Bearing Axial with Overall velocity of 4.16mm/s and dominant peak of 1x Motor RPM caused by Misalignment and alarmed Motor NDE Bearing Fault - Outer Race

Fair state for the component 'Pump'.
Highest vibrations measured at Pump IB Bearing Axial with Overall velocity of 5.76mm/s and dominant peak at 1x Motor RPM and 1x Blade passing Freq caused by Severe Pump Cavitations and Misalignment

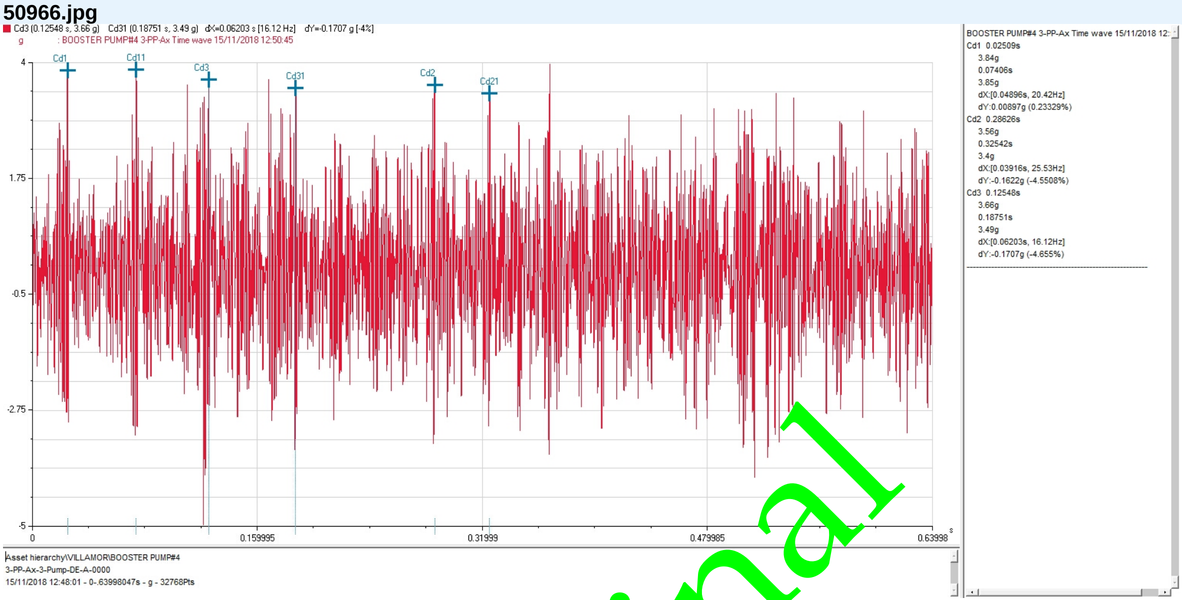
Recommendations

Realign coupling, Recondition Pump

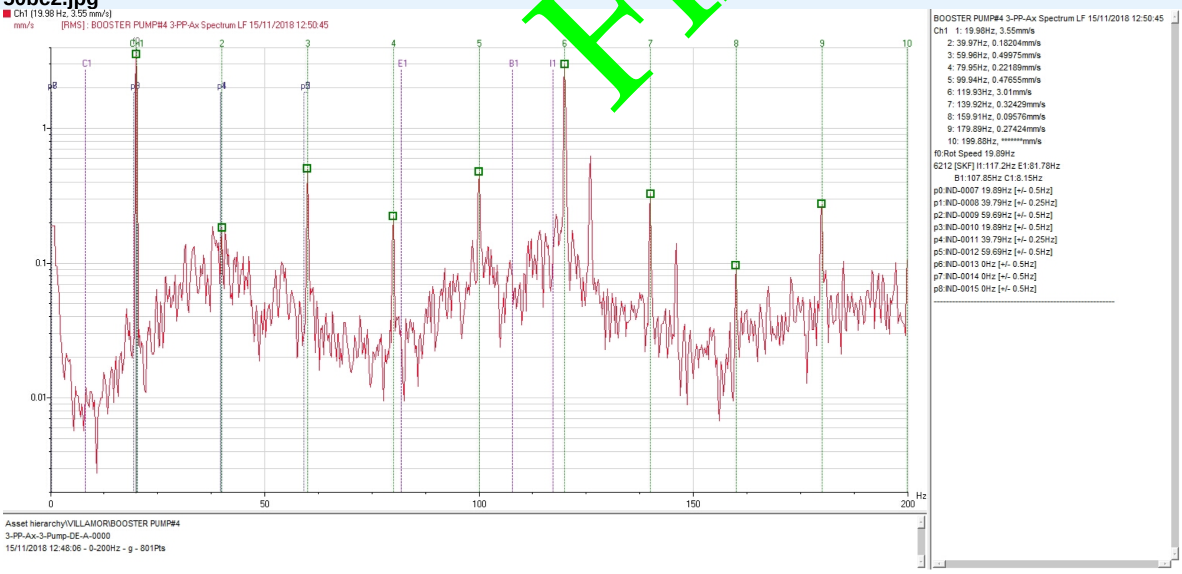
Realign motor and pump shaft or coupling using precision laser alignment tool.

Cavitation to be corrected: process control and action as soon as possible. Follow the dynamic behavior of the pump to prevent impeller damage.
☐Location "3-Pump-DE" to be corrected
☐Location "4-Pump-NDE" to be corrected
Schedule Pump reconditioning to visualize Pump Impeller blades profile and pitch for damages. Check as well its wear ring clearances

50966.jpg

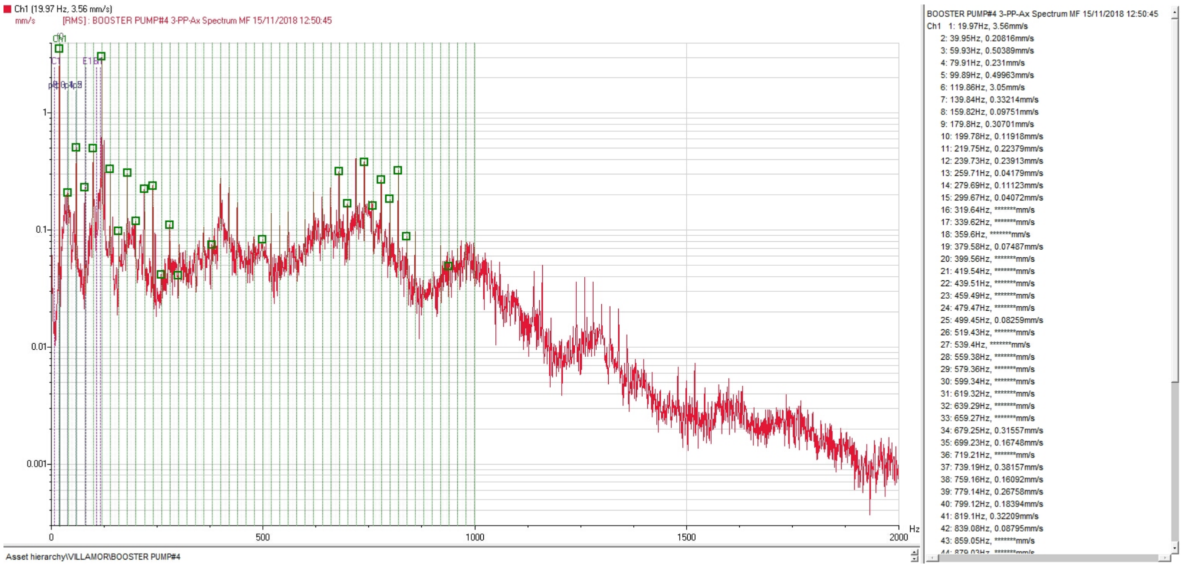


50bc2.jpg



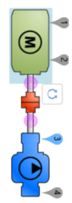
1x RPM peak and 1x Blade Passing - an indications of Misalignment and Cavitations

70648.jpg



Location	**VILLAMOR**
Designation	
Equipment	**STORAGE PUMP#1**
Designation	
Abbreviation	**SP#1**
Serial No	
Model	
Periodicity (d)	*Normal* **60** *Alarm* **15**

Fixed speed



Previous Advice	***Condition***	***Rotation Speed***

Date **15/11/2018 12:55:28**	**FAIR** *Health is not acceptable for a long time service.*	*Speed*	**17 Hz / 1022 rpm**
Condition **DfCnd**		*Author*	**u1**
		System - Serial	**FALCON - 11407**
		Sensor	
		Connector	

Diagnosis & Recommendation

Parameters sheet

Diagnosis

Early Stage Motor Bearing DE Defect

Fair state for component 'Electric motor'.

Early Stage Motor Bearing DE Defect - Inner Race

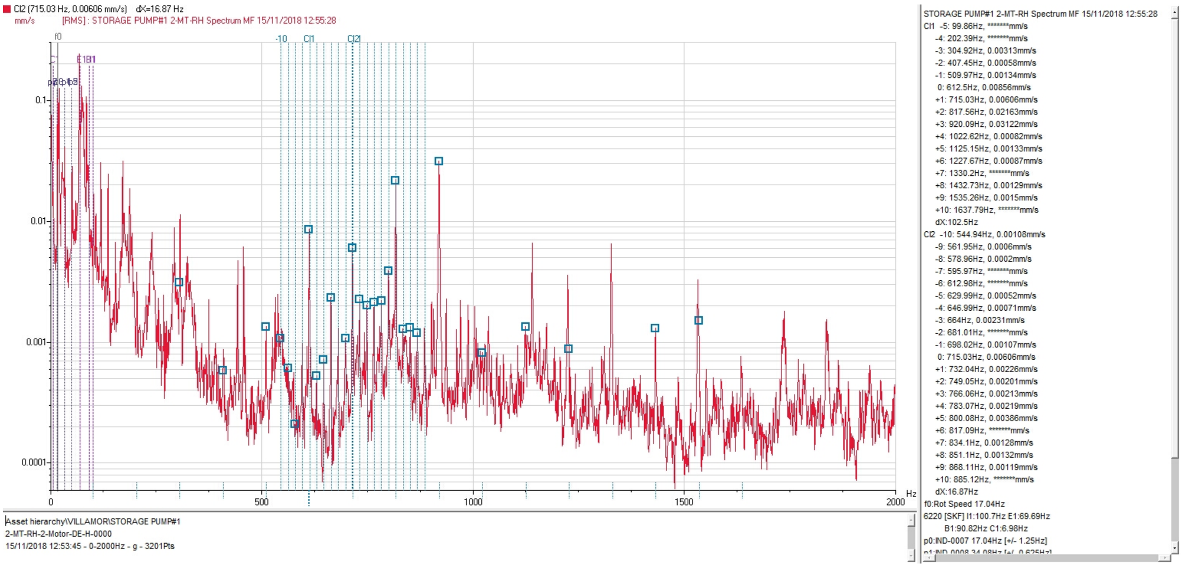
Good overall state for component 'Pump'.

Recommendations

Regrease bearings periodically.

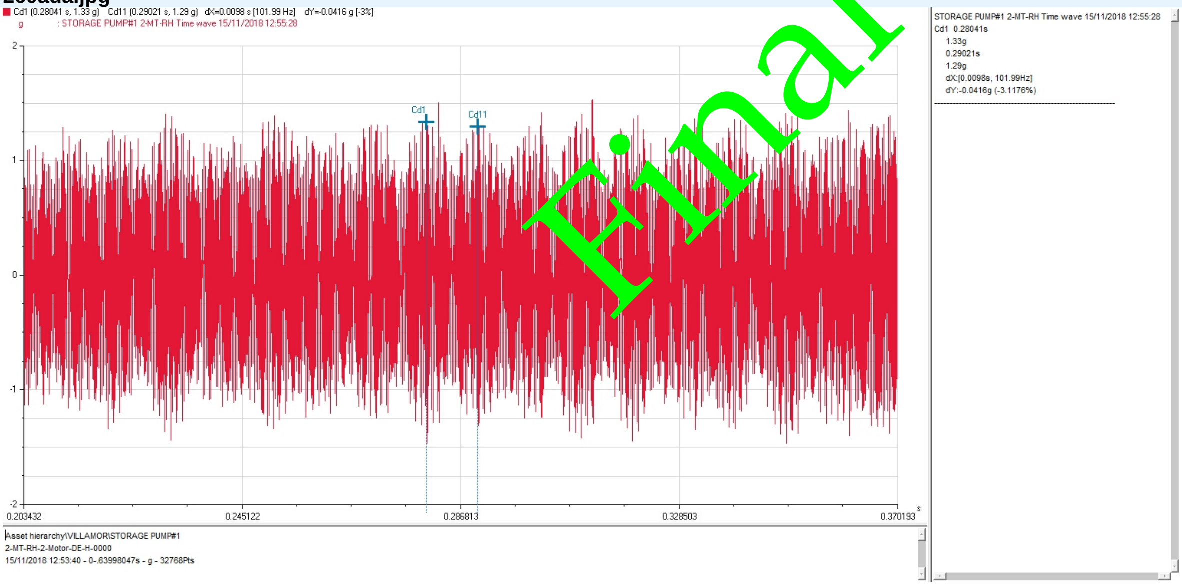
Regrease bearings periodically. Continue monitor evolution

f09a0.jpg

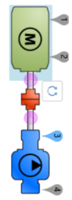


Early Stage Motor DE Bearing Defect

260ada.jpg



Location	VILLAMOR\	Fixed speed
Designation		
Equipment	STORAGE PUMP#2	
Designation		
Abbreviation	SP#2	
Serial No		
Model		
Periodicity (d)	*Normal* 60 *Alarm* 15	
Previous Advice	***Condition***	***Rotation Speed***



Date	FAIR	*Speed*	17.2 Hz / 1031 rpm
15/11/2018 12:44:29	***Health is not acceptable for a long time service.***	*Author*	u1
Condition		*System - Serial*	FALCON - 11407
DfCnd		*Sensor*	
		Connector	

Diagnosis & Recommendation

Parameters sheet

Diagnosis

Early Stage Motor Bearing DE Defect

Fair state for component 'Electric motor'.

Early Stage Motor Bearing DE Defect - Inner Race

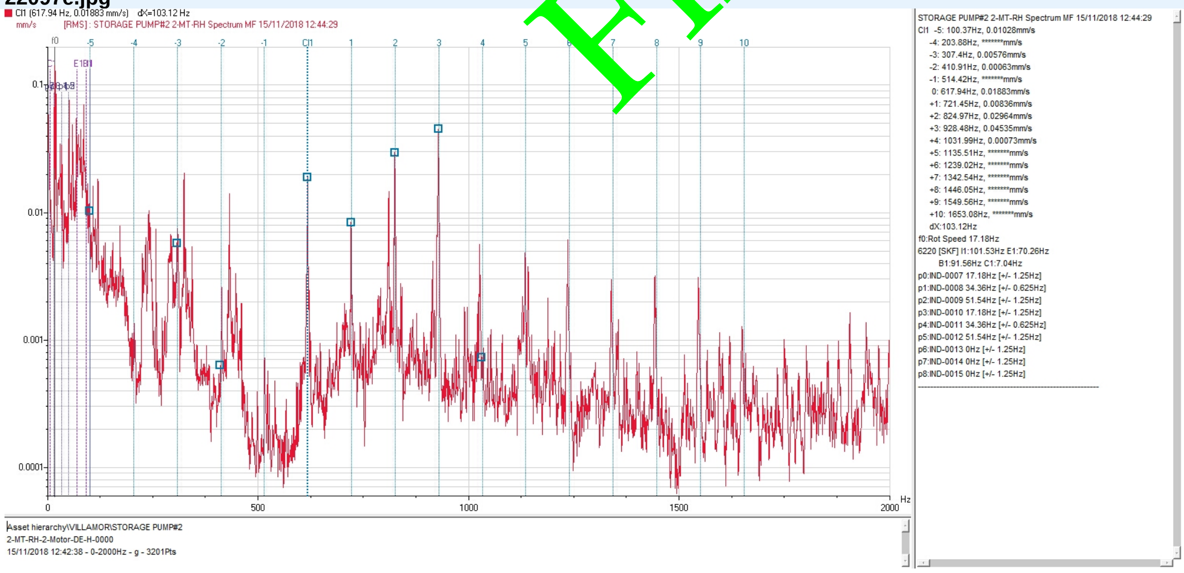
Good overall state for component 'Pump'.

Recommendations

Regrease bearings periodically

Regrease bearings periodically. Continue monitor evolution.

22097e.jpg



Early Stage Motor DE Bearing Defect

c0966.jpg


Cd2 (0.47109 s, -0.9195 g) Cd21 (0.47384 s, -0.9345 g) dX=0.00275 s [363.11 Hz] dY=-0.015 g [1%]
g : STORAGE PUMP#2 2-MT-RH Time wave 15/11/2018 12:44:29
2
STORAGE PUMP#2 2-MT-RH Time wave
Cd1 0.39445s
0.99689g
0.398s
0.96863g
dX:[0.00355s, 281.31Hz]