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Maintenance Strategy Selection for Continuously Operated Beverage Industry Utility Machines: A case Study

BY

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A Thesis submitted to the School of Graduate Studies of Addis Ababa University, Addis Ababa Institute of Technology in partial fulfillment of the requirements for the Degree of Master of Science in Industrial Engineering.

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Approved By Board of Examiners

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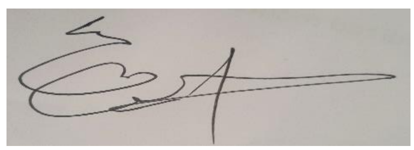
Declaration

"I hereby declare this research report entitled "Maintenance Strategy Selection for Continuously Operated Beverage Industry Utility Machines: A case Study" represents my own wok which has been done after registration for the Master of Science degree in Industrial Engineering except where a due reference is made. It has not been previously included in a thesis or dissertation submitted to this or any other institution for a degree, diploma or other qualifications."



Name: Eskinder Wondwossen

Date: June 8, 2020.

Abstract

This research paper focuses on a case company where downtimes from set of utility machines are a major setback to the main production lines due to extensive breakdowns. Nailing down the management to focus on firefighting, the downtimes had an effect on the departments KPIs and the company's profitability.

Onwards, the research sets on finding the right maintenance strategy for each set of utility sub-system. This was accomplished by first filtering the information gained from the company's ERP system by an aid of AHP and Pareto tools to select the downtime causes that can be controlled and critically affects the output delivery of the machines. Thereafter, the data gained was used as an input for a proved maintenance strategy selection tool of DMG to select a maintenance strategy for each set of machines in the utility system.

From the analysis, the most machines contributing to the downtimes were identified, and a maintenance strategy as well as maintenance policy was suggested. A Design out Maintenance was proposed from the DMG tool for the electric supply system and the HP compressor that mainly contributed for most of the downtime accounting for a total of 71%.

Though the integration of AHP and DMG tool is new in the selection of maintenance strategy for continuous operating utility set of machines, it matched the current situation with the management decisions on modifying the design of the two mentioned systems, showing it can also be useful in maintenance strategy selection of such continuous operating equipment.

The strategies selected for each sub plant and a continued use of this tool is expected to save 39 million birr and 26,106,000 bottles worth of production time. This estimate is considered to bring the new downtime rate of the department to an acceptable level of 0.92%, which is below the company standard of 2.5%. In addition, following a maintenance strategy aids management to get rid of firefighting mentality to focus on proactive maintenance.

Acknowledgment

I would like to start my appreciation with the CCBA's utility engineering team, as it would not have been possible to commence with the research as if it had not been for their participation in the process. I would like to thank; Habtamu Beijiga(Utility Unit Manager), Zerihun Kassa(Country Utility Specialist), Yifru Kura(Electrical Specialist), Melesse Abate (Maintenance Controller) and Tamirat Seyoum(Mechanical Specialist) for their involvement & sharing in the research process.

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Nomenclature

AHP	Analytical Hierarchy Process
ANP	Analytical Network Process
CAPEX	Capital Expenditure
CBM	Condition Based Monitoring
CCBA	Coca-Cola Beverages Africa
CI	Critical Index
CM	Corrective Maintenance
CO2	Carbon Dioxide
CR	Critical Ratio
CTMC	Continuous Markov Chain
DMG	Decision Making Grid
DOM	Design out Maintenance
EABSC	East Africa Bottling Share Company
ERP	Enterprise Resource Planning
FAHP	Fuzzy Analytical Hierarchy Process
FANP	Fuzzy Analytical Network Process
FGD	Focus Group Discussion
FTM	Fixed time Maintenance
HP	High Pressure
IPR	Internal Production Report
Kg	Kilogram
KPI	Key Performance Index
KVA	Kilo Volt Ampere
KW	Kilo Watt
LP	Low Pressure
MCDM	Multi-Criteria Decision Making
OEM	Original Equipment Manufacturer
OTF	Operate to failure
PET	Polyethylene Terephthalate
PM	Preventive Maintenance
RCA	Root Cause Analysis
RCM	Reliability Centered Maintenance
RGB	Returnable Glass Bottle
RI	Random consistency Index
SAW	Simple Additive Weighting
SIS	Supervisory Information System
SLU	Skill level Upgrade
TOPSIS	Technique for Order Performance by Similarity to Ideal Solution
TPM	Total Productive Maintenance

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CHAPTER ONE: INTRODUCTION

1.1 GENERAL

Maintenance is one of the most essential factors in today's competitive manufacturing world. Machine failures may cause business related problems impacting delivery, product quality, reputation, profit and opportunity (P.M. Muinde, 2014). Inadequate machine availability and high maintenance cost could arise from poor maintenance practices. Maintenance also has an effect on environment, safety, and overall plant efficiency & effectiveness concerns (Seecharan et al, 2018; Momeni et al, 2011; Sagar et al, 2013).

Maintenance strategy is a well-defined approach to sustain facilities & equipment considering the case of facility to facility. Velmurugan and Dhingra (2015) stated maintenance strategies incorporated exploring, defining, and replacement as well as inspection decisions while taking into account the best life plan of the unit in accordance of functions concerned. Every maintenance strategies have their own benefits. Fraser et al.(2011) mentioned that Total Productive Maintenance(TPM) has an impact on reduction of breakdowns, minor stoppages and defects while enhancing yield and speed. As per Prabhaker et al. (2014) benefits like prolonged equipment life, sustainability and enhanced reliability are achieved via Reliability Centered Maintenances (RCM). Researches like Mungani and Visser (2013) mentioned similar benefits of cost saving and downtime reduction of the two strategies of TPM & RCM.

M. Dachyar et al (2018) puts preventive maintenance based on timeliness and operating schedules which is used to increase asset lifetime along with the reduction of any unscheduled maintenance activities, stating benefits on equipment life on the long term. PM according to (Momeni et al, 2011) allows the maintenance engineer to define a periodic maintenance program, whereas Condition based monitoring needs set of measurement and data acquisition systems to monitor machine performance in real-time where the continuous survey will clearly point out the abnormal situation showing signs for further actions to prevent failure. Emovon (2016) defined corrective maintenance as a maintenance management systems on which equipment are allowed to fail up-to some extent before being repaired in order to save maintenance cost whereas the strategy is usually recommended for low cost – low risk machines.

Maintenance strategies are essential in minimizing breakdowns while enhancing quality and reduction/ elimination of waste (Matlas et al. 2015). Careful selection of strategies, according to Parida & Kumar (2006), critically support heavy and capital intensive industries in terms of keeping machinery and equipment in safe operating condition. To achieve high strategic goals, selection of a single maintenances strategy for plant asset is not enough. Patidar et al.(2017) concluded desired results are more effectively achieved through the integration of different maintenances strategies.

Manickkam (2016) states even though utility is not a reactant or product, an efficient management of utilities generate Profits. Utility is required to maintain adequate conditions with inclusions of different outputs from boilers, refrigerators, water treatment plants and similar support systems which are mandatory to carry out the normal production process. Utility output has features of a continuous production characteristics with a dedicated plant for each required output with no product differentiation. Goldense (2015) implicates continuous production operations usually run 24/7 with outputs of gas, liquid and slurries ensuing a predetermined operation flow and product.

This paper proposes a maintenance strategy selection model for continuous running beverage industry utility machines based on machine history of downtime and downtime frequency. It will select maintenance strategies to be followed for each machine relying on its individual history through the use of a decision making grid specifically designed for this purpose. Unlike previous researches, this study will filter the input data for the DMG through the use of multi-criteria decision making tool of AHP to identify the most relevant inputs from real time data gained from an ERP system that should be considered for the main strategy selection.

1.2 BACKGROUND

In the case study Addis Ababa's plant of Coca Cola Beverages Africa (CCBA), there are three production lines which produce packaged soft drinks in glass bottles (RGB bottles) whereas the last new line packages products in plastic bottles (PET Bottles). The RGB lines have capacities varying from the oldest line with 28,000 bottles/hr. up to 47,000 bottles/hr. of the most recently modified glass bottle packing line. The PET production line being the only plastic bottle packaging line for CCBA in Ethiopia, has the highest capacity with the ability to produce greater than 36,000 plastic bottles every hour.

The Utilities department serves as the backbone for the mentioned production lines with continuous supply of required energy inputs of power, compressed air, steam, CO_2 & water. It is also responsible for the supply of main raw materials and ingredients required to make a soft drink which are: final syrup, treated water and carbon dioxide (CO_2).

Utilities in CCBA is composed of different set of plants. The first plant is the electricity plant composed of two transformers, a UPS system and set of generators with a combined capacity exceeding 5000KVA. This system is responsible for the supply of electricity throughout the main plant. The second plant which is a composition of four low pressure compressors is the air supply plant. This plant is designed to supply a maximum of 10 bar pressure air to the production as well as other utility plants required. This pressurized air is required for various valve operations in the main packaging process and the utility department itself. The third system is a high pressure air supply plant that is required to give out up to 40 bar of compressed air to the production plants. 40 bar pressure is required in molding process that come right before PET line packaging.

As refrigeration unit, the fourth plant is a collection of three cooling towers, four chillers and a set of pumps that is used as a cooling system for the final production of soft drink. This system enables the production plants to produce with the desired 14 °C that is required for the packaging process directly.

The fifth plant of syrup production is a pre-requisition to the packaging, as it's composed of sugar processing, filtration, pasteurization and at last final syrup production which shall then be blended with water and CO_2 in the packaging plant. This syrup production plant and the main packaging lines get their steam from the steam plant. This sixth plant in CCBA utilities is composed of two boilers, steam trap systems and heat exchangers that circulate steam and condensate water throughout the production plants.

The CO_2 plant supplies the packaging lines one of the main ingredients in the soft drink making process. Comparing to the other utility systems in the company, this is considered to be the simplest with two storage thanks, a heat exchanger to turn liquid CO_2 to gas & a delivery pipe system.

The eighth plant is the water treatment system, responsible for the supply of all cleaning, drinkable and production water in the main plant. The system initially gets the water from boreholes deeper than 100 meters via three borehole pumps. To get the water to the proper standard, this system uses different stages of filtration systems. It's composed of water softeners, sand filters, carbon filter and reverse osmosis equipment to get the water to the required standard of production and operation.

Desired world class breakdown rate for Utilities according to CCBA standards is 0%. However, the A.A. plant was forced to develop its own standard of 2.5% due to its history of high breakdowns. The case study plant was supposed to reduce this internal standard by 10% every year so as to progress towards the world class standard. However, its inability to even achieve the company standard has restrained it to do so. With an average breakdown rate greater that 3.5% every year, this utility plant has never been able to achieve the standards set for the past 5 years.

Utilities department is considered very different from the rest of the production lines in the company as it runs continuously throughout the year (Manickkam, 2016). With a total of four production lines, the company cannot spare an off time for this department. Production lines have one day a week off for maintenance alone with every production stopping on a different day. This department always has its machines operating continuously from month to month 24/7 with only few hours of maintenance to stop every month end. If we try to consider it from the type of operation, production lines can be classified as the mass production type whereas the utilities can be considered as a continuous production due to the nature of the operation.

Out of the 70 million unit cases sold in 2019 by CCBA, 38 million unit cases were contributed from this case study plant. If we take and add the *lost cases* of the 3.9% breakdown rate of that year the total production contributed from this plant would toll up to 39.75 million. *1,756,300 cases* in 2018 were lost due to downtimes caused by the utilities department. With a profit of

1.5 birr of per bottle, it could be estimated the company profits of the total unit cases from the above loss will sum up to 61.4 million, without considering other loss of production and maintenance.

Table 1: Breakdown rate, Downtime per year & Lost case

Year	B.D rate	Downtime (Hr.)	Cases lost (Unit)
2015	6.10%	2139	2,780,000
2016	3.50%	1197	1,556,100
2017	3.41%	1181	1,535,000
2018	3.90%	1351	1,756,300
2019	3.30%	1138	1,503,900

Above is shown the total downtime of the utility department from 2015 till 2019 mid-November. It is possible to see the breakdowns from this specific department are causing the company to lose millions of cases of production every year. If we consider the loss in terms of profit it's very clear to see why the world class breakdown standard for this department is zero.

1.3 PROBLEM STATEMENT

As mentioned in the background, CCBA's world-class downtime standard for utility department is zero. As a means to approach the world class standard, the case study plant has developed its own internal standard of 2.5% as one of its major KPIs. Nevertheless, the department's annual breakdown rate has always been higher than the put forward 2.5% downtime rate. Based on a data gathered from *Tableau*, CCBA's higher management platform to track KPIs and performance, annual downtime rates recorded from 2015 onwards show a mean breakdown rate of utilities to be about 4 %'for Addis plant which is higher than the desired result.

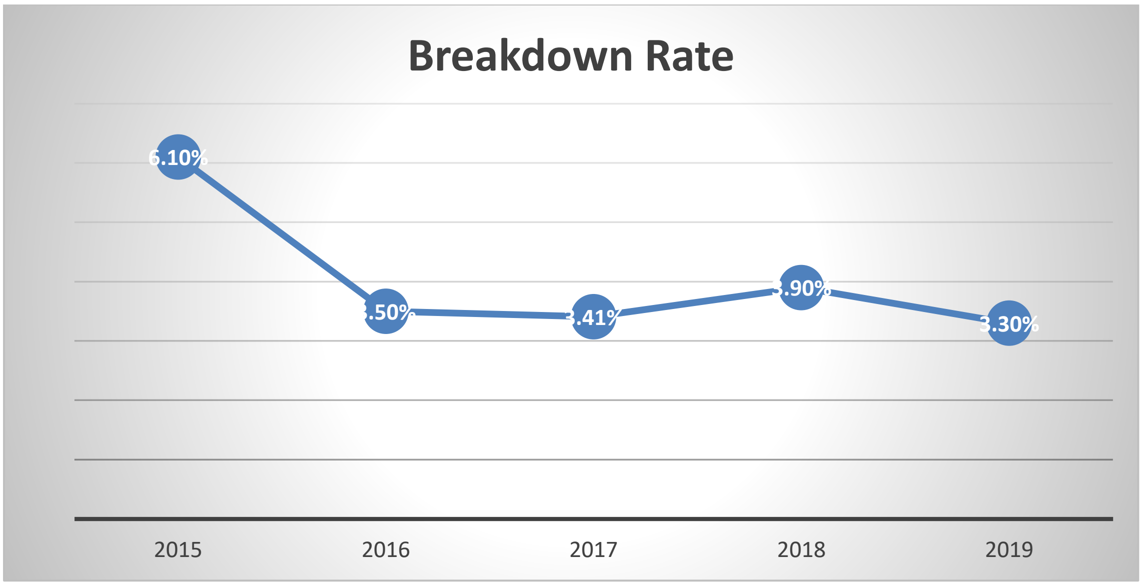

Figure 1: Breakdown rate since 2015, Tableau

Where, WCS (CCBA World Class Standard) = 0 %, CS (EABSC Company Standard) = 2.5%

As seen from the data above, the actual breakdown rate has been high in each of the years with 2015 being the highest with 1.5 times out of the standard. In most recent years its trend indicates it's somehow stable between 3 to 4% breakdown rates. However despite showing a stable trend, it is still 20% above the required standard which is a major problem for the plant.

Utilities Lost Time by Plant

Country No	Plant	ly 2019	August 2019	Septembe r 2019	October 2019	Novembe r 2019	Decembe r 2019	Grand Total
ET	Addis Ab..	323	140	50	47	31	26	1,005
	Ambo Pr..	94	176	91	43	25	25	1,005
	Bahir Dar..	4	3	11	17	3	5	75
	Dire Daw..	18	31	18	27	25	8	326
	Total	439	349	170	134	84	64	2,412
Total		439	349	170	134	84	64	2,412
Total		439	349	170	134	84	64	2,412
Total		439	349	170	134	84	64	2,412
Grand Total		439	349	170	134	84	64	2,412

Figure 2: 2019 Utilities Downtime, Tableau

Considering 2019, from the data obtained from Tableau, on average the CCBA plant has lost 1,005 hours of production due to utilities downtime. c, it indicates we have lost 38,190,000 bottles. With 1.5 birr profit per bottle, the company has lost more than 57 million birr profit in 2019 without even considering other costs of maintenance and repair. Along with the high breakdown rates the department has used about 25.4 million birr as repair and maintenance cost.

Actual v Budget   Date: 08.06.2020   Page: 2 / 2

Column: 1 / 2

Cost Center/Group   02-PRD_SER   Production Services
Person responsible: *
Reporting period: 1 to 12 2019

Cost elements	Act.costs	Budget	Abs. var.	Var.(%)
552000 R&M: Plant & Mach	22,442,124.30	10,954,729.00	11,487,395.30	104.86
* Debit	22,442,124.30	10,954,729.00	11,487,395.30	104.86
** Over/underabsorption	22,442,124.30	10,954,729.00	11,487,395.30	104.86

Figure 3: 2019 R&M Cost, SAP ERP

Furthermore, frequent breakdowns and piled up problems has pinned down the management to focus on firefighting rather than prevention leading to a reactive management strategy. Safi and

Mozar (2004) clearly state a typical reactive system spends its efforts and time on responding to breakdowns, and in the process incur a high cost from unplanned stoppages. Bigdeli and Safi (2005) also emphasize in such reactive situations, maintenance teams are constantly engaged in addressing breakdowns, with very little if any time is allocated to preventive work. It also adds, due to pressure, works done in a hurry are associated with higher cost and poor quality without enabling reliability engineers to address the major reliability issues preventing the problems from reoccurring.

1.4 RESEARCH QUESTIONS

1. What are the main downtime causes in utility department?
2. Which machine experiences the most frequent downtimes?
3. Which machine downtimes has the highest impact?
4. What maintenance strategies should be applied for each machine?

1.5 OBJECTIVE

1.5.1 General Objective

The general objective of this research is to select an optimum maintenance strategy for utility equipment.

1.5.2 Specific Objectives

- Identify main downtimes and downtime frequencies for each set of equipment
- Identify main areas resulting in high downtimes
- Select a general maintenance strategy per set of equipment
- Select a maintenance policy per utility system

1.6 SCOPE

This thesis project focuses on selecting a maintenance strategy for continuous running equipment with only few maintenance opportunities per year. It tries to analyze the downtimes and downtime frequencies of each utility set of equipment to select a specific and total strategy for each area using a tool called Decision Making Grid, taking a case company of a soft drink beverage industry found in Addis Ababa.

It works with a prerecorded data stored in an enterprise resource planning software (SAP ERP) that allows access to pull out data per machine as of (Labib et al., 2008). For each set of machine system, researcher will attempt to select a strategy with a DMG tool based on the pulled data along with the use of a second multi criteria decision making tool known as analytical network processing tool (Seecharan et al., 2018) to serve as a primary data filter. With the combination of the two tools the researcher will select a strategy that can benefit the case company by setting a focus maintenance strategy for each set of utility machine which run nonstop for a long time.

This research only considers one plant of CCBA's beverage company that is located in the center of Addis Ababa with a continuously operating utility machines. Implementation technique and results shall not be considered for this thesis research.

1.7 METHODOLOGY

This research initially starts with identification of problem by selecting a case study. The problems are extracted from the case company's higher management KPI tracking system known as TABLEAU. The research then proceeds by defining objectives and initial set point to conduct the study on a case company's utility operations, aided by set of tools that can assist in strategy selection in such industries with similar operation and ERP system. It then proceeds to literature review where different tools and maintenance strategies are analyzed qualitatively with main inputs being journals and previous articles on related subjects.

In the next chapter data is collected from different sources. Primary and quantitative data will be collected from SAP ERP system on each utility machine whereas secondary data collection is performed from article journals and books.

Preceding collected data, the problem is thoroughly analyzed by calculating the downtimes of each machine and frequency of the breakdowns. Here different set of tools are used to select the most critical causes that could be reduced via maintenance strategy selection. Similar to (Labib, 2004) where AHP was integrated to DMG to get root causes of downtimes, this paper integrates AHP and Pareto tools to select the downtime causes. In this research though, AHP will be used to identify factors that can be controlled and critically affects the output delivery of the machines in the maintenance strategy selection process.

In the next phase of the strategy selection, DMG (Decision Making Grid) is majorly used to select the appropriate maintenance strategy per equipment found in utilities on bases of previously calculated downtimes and associated downtime frequencies on each equipment. According to (Seecharan et al., 2018) The data is first sorted out into the required downtime frequency per machine and actual downtimes per equipment as per the output from the mentioned combination of AHP and Pareto, the result of which is the major input for DMG. Hereafter, the position of each equipment is laid down in the DMG positioning grid and a specific maintenance strategy is selected for each equipment.

Thereafter the author will discuss the results of each analysis per equipment and what general and specific strategies to use. If the selected strategies are found to be unsatisfactory the research shall reanalyze the data that shall affect the DMG input. Thereafter, after satisfactory selection, the thesis will be concluded relating the objective and achieved results with further suggested recommendations on future work on possible gaps and improvement areas.

CHAPTER TWO: LITRATURE REVIEW

2.1 REVIEW APPROCH

This research takes on a theoretical framework model to conduct a review. After analyzing researches with a main focus on maintenance strategy selection tools, researcher outlines the gap found proceeding to the selected tool for this research. Hereafter, this review continues on answering questions of; what proposed model is used in this research, why it was selected and finally how it is used in this research.

2.2 LITRATURE COMPARISON

Table 2: Literature Comparison

No.	Research	Case study	Tool Used	GAPs
1	M. Bashiri et. al.(2010)	Proposed interactive fuzzy linear assignment model (IFAM) with two main features of qualitative and quantitative data utilization with decision making was through interaction with three maintenance experts. The qualitatively evaluated maintenance strategies, which was linguistically turned to a fuzzy quantitative approach to select between CBM, TBM and PM on a general basis. PM was selected to be the best method.	Fuzzy Linear Method	As per the research as the number of criteria decreases its precision also declines. Furthermore it highly relies on human judgment and doesn't take into consideration history of the equipment/machine. Considering simplicity, it's found to be one weakness of it.
2	M. Momeni et. al.(2011)	Five maintenance strategies (PM, OM, CM, predictive maintenance & CBM) were considered and analyzed to select the best strategy using a fuzzy TOPSIS approach. An Iranian Electro fan company was used as a case study where the best strategy was selected based on a concept of most suiting solution having a shortest distance from the positive ideal solution and longest distance from the negative ideal solution of TOPSIS analysis. PM was selected to be the best strategy for the company.	Fuzzy TOPSIS	This research also doesn't involve the use of machine history as a criteria and highly relies on human judgment. No justification has been presented on the success of this model.

3	Jafari and Jafarian (2008)	Based on an interview with maintenance staff and managers, this concept uses a fuzzy Delphi method to choose specific goals and analyze the capacity of proposed maintenance strategies to evaluate their compatibility on satisfying the selected goals. Upon using Yager ranking the fuzzy numbers are converted back to crisp numeric which will be used as an input to the multi-criteria selection tool of SAW to arrive at a specific strategy presumably to be the best one.	Fuzzy Delphi + Yager Ranking+ SAW	This tool doesn't take into account history of equipment. According to the research, intangible goals could result in imprecision on selection of the right strategy. It highly relies on human decision making. In addition, the selected tool hasn't been justified as it was only used on a hypothetical example.
4	P.M. Muinde et. al,(2014)	The research starts by identifying maintenance strategies from various literatures. It proceeds to identifying the initiators of maintenance from previous machine history where maintenance variables are converted into maintenance objectives. Thereafter decision tree of AHP comes to effect to select maintenance strategies. Decision of AHP is finally analyzed for consistency via use of consistency index. A cement factory was used as a case study with proactive maintenance was selected to be the best suit from this tool.	Data reduction multivariate analysis + AHP	Selection of a single strategy for all causes of maintenance objectives and equipment.
5	I. Emovon(2016)	The researchers tries to select a best maintenance strategy for centrifugal pumps of a ship through the integration of three tools finally selecting corrective maintenance as the best strategy. Decision criteria against which maintenance strategies shall be analyzed were initially selected through the use of Delphi	Delphi + AHP + TOPSIS	This method lacks simplicity as it employs 2 multi-criteria selection tools with complex calculations. According to the research it requires maintenance analysts to define the decision criteria of the preference function.

		method. AHP was then used to determine the weights of the strategies where TOPSIS was employed as a selection tool.		
6	Dachyan et. al.(2018)	In this research a tool that integrated a model of AHP and TOPSIS was used to select a most suitable maintenance strategy for a steam power plant in Indonesia. Four set of criteria were set to select a maintenance strategy with AHP serving as a weight determining criteria whereas TOPSIS was used as the main strategy selection tool. RCM was selected as the best strategy, where the result was confirmed through sensitivity analysis re-confirming it.	AHP + TOPSIS	The main considered determination factors were manly economical, technical, environmental and social. Therefore emphasis was not given to probable downtime and machine history in the selection process. Use of MCDM tools do appear to be complex too.
7	Li et. al.(2009)	An integration of Cost model along with continuous Markov Chain (CTMC) degradation model was formulated to apply CBM. It was proposed for a systems of sufficient resource of multiple machine system by extending it from a single machine CBM maintenance system, whereas the data was gathered from an automotive company.	Cost Model + CTMC Degradation Model	This method was actually proposed and relies on abundant resource. As per the article, this shall not be considered for cases of resource constraints.
8	M.K. Sagar et al.(2013)	The research aimed to select an optimum maintenance strategy suiting a material handling equipment through the use of fuzzy SAW method. Five experts were selected to linguistically rate ten criteria along with set of maintenance strategies. These ratings were then changed into triangular fuzzy numbers which were	Fuzzy SAW	This method seems to be highly dependent on human judgment. Furthermore, it doesn’t consider loss of production as a criteria when choosing breakdown maintenance strategy as the best one to improve reliability and maintenance cost.

		used as an input for the MCDM tool of SAW. The final strategy selected to best suit this system was break down maintenance strategy where predictive maintenance was identified as the poorest suit.		
9	Borjalilu and Ghambari(2018)	Research focused on selection of a maintenance strategy via a fuzzy analytical network processing (FANP) model for a 5MW powerhouse. A team of experts came up with criteria of selection along with respective maintenance strategies to be considered linguistically, which were then converted into triangular fuzzy system. The method selected PM as the most suitable strategy for the powerhouse.	FANP	Among the six criteria considered, Downtime and machine history were not given emphasis. Furthermore, method fully relied on human judgment.
10	Pourjavad and Shirouyehzad (2014)	This research used the fuzzy ANP approach as well for a category of equipment in mining industry. This research only employed Reliability, availability & maintainability as a major criteria and proceeded the same method as the above mentioned study, selecting CBM as the best strategy.	FANP	This research also doesn't consider status of the equipment as an input. Furthermore, it only proceeded on selection of a single strategy.

2.3 LITRATURE GAP REVIEW

One gap identified from reviewed literature was the high dependency on human judgment on the selection of decision criteria and the rating of maintenance strategy evaluation for the final selection. Literatures like (M. Bashiri et al, 2010; Jafari and Jafarian, 2008; Emovon, 2016; M.K. Sagar, 2013) initiated their research based on expert selection of criteria, and ranking of the relation of these selected criteria with proposed maintenance strategies by the same team. Therefore any knowledge gap on either stages of selection and ranking will have a direct output on the final selected result.

Another gap identified was the integration of more than one MCDM tools as an input for selection criteria. Literatures of (Dachyan et al., 2018; Emovon, 2016; Li et al., 2009) propose the use of more than one MCDM tools as integration of TOPSIS, AHP, ANP and CTMC complex degradation models on the selection process. Based on (Labib, 2004) managers do not have confidence in mathematical models that are complex and encompasses multiple number of characteristic assumptions. As the MCDM tools are added the number of selection criteria will also increase respectively, creating more complex process.

The major gap identified from these strategy selection tools is the fact that they have not indicated the effectiveness of the methods. Mentioned literatures have not been put in practice to test their validation on the strategy they have selected nor have they discussed. Most of the tools used are a general MCDM tools that can be applied in a vast number of areas where used for the selection among different choices is possible based on the interrelationship of the assessment criteria put forward.

The selection of a single maintenance strategy for the entire system was found to be one gap of the reviewed researches. Except from (M.K Sagar et al, 2013) which selected a maintenance strategy for a similar centrifugal pumps of a ship and (I. Emovon, 2016) which selected a B.D. maintenance strategy for a material handling system, majority of the researchers evaluated ended up selecting one maintenance strategy as a general.

One missing criteria observed from the literatures was the use of actual machine history as selection criteria of maintenance strategy. Apart from (P.M Muinde, 2014; Li et al., 2009) rest of reviewed researches put their selecting criteria and objective with neither the consideration of actual downtime history, nor the downtime rate.

2.4 SELECTED TOOL

Upon the observed literature gaps, the researcher has selected Decision making Grid, DMG as a major strategy selection tool based on the gaps mentioned. The tools designed ability to be integrated with CMMS and ERP systems make it the ideal tool for the selection analysis (Labib, 2004). It mainly uses machine downtime and downtime frequency as its main input to select a strategy, with a main objective of movement of machine towards improvement towards the mentioned criteria (M.I. Desa et al, 2007).

According to (Seecharan et al., 2018) maintenance strategies are incomparable and one strategy should not be applied for all equipment. Furthermore, DMG's has the ability to determine a specific strategy for each machine as well as a general and overall strategy for set of machines based on downtime and frequency. DMG has the potential to analyze captured data to aid in the decision process of selecting performance enhancing maintenance strategies (Labib et al., 2008).

Labib (2004) also emphasized DMG was majorly designed as a maintenance strategy selection tool for companies with CMMS and ERP that had a black hole on making decisions. Author also mentioned the flexible ability of the tool to be used along MCDMs. The research gave an emphasis for AHP coming right after the strategy selection process of DMG on worst performing machines to determine focused action to be implemented with regards to failure categories, failure details, failed components and additional criteria.

Different integration of strategies is possible with DMG. Researches of (Seecharan et al., 2018, Labib et al., 2008) clearly indicate DMG is different on the fact it offers a decision map that uses TPM & RCM as a general approach due to their nature of application in various industries. Furthermore, rather than treating TPM and RCM as competitors it unifies then under single analytical model. Labib (2004) also mentions the tool's advantage on selection of strategies of CBM, TPM & RCM via a decision map adapted from a collated real time data.

DMG has been proven successful when brought to the ground. From Litratures of "(Fernandez et al., 2003; Buranuddin, 2007; Tahir et al., 2008; Shahin and Attarpour, 2011; Aslam-Zainudeen and Labib, 2011; Tahir et al., 2014; Mc Leod et al., 2015)" (Seecharan et al., 2018) DMG as a maintenance strategy selection tool has been implemented and proven to be successful in different industries.

The big picture of achieving world class standards through the use of ERP and CMMS by creating a platform for decision analysis is possible with the DMG tool (Labib, 2004).

Though the tool has been proven to successfully integrate with AHP, the mentioned MCDM tool has not been used as a pre-filter to the input data of DMG, and neither has been any other tool. All the research investigated used DMG input data as it is without any selection criteria or filter. According to a data from the companies ERP system, one source of downtime is power interruption that arise from the country's situation. Therefore the researcher believes the need for an input data filter mechanism to select the most critical information that can influence

Based on (Labib, 2004) The DMG acts as a map where the performance of the machines are located on a grid based on the frequency of downtimes and the total number of downtimes in a specific period of time. A scale of low, medium and high are put forward with the aim of monitoring worst performing machines with respect to both downtime and downtime frequency.

The Objective is to come forward with the appropriate measure which will lead to the movement of the worst performing equipment towards the top-left corner section of low downtime and frequency.

		DOWNTIME	
FREQUENCY	LOW	MEDIUM	HIGH
LOW	O.T.F	F.T.M	C.B.M
MEDIUM	F.T.M	F.T.M	F.T.M
HIGH	S.L.U	F.T.M	D.O.M

Figure 4: Decision making Grid Layout (Labib, 2011)

The Rule found at the top left corner is Operate to failure (OTF), signifying corrective maintenance as a strategy, for machinery that does not breakdown often and with downtime impact being very low. For equipment with a high downtime frequency and low total downtime, it’s suggested Skill level upgrade (S.L.U) found at the bottom left corner of the grid. This indicates the machine has been dealt with many times and the maintenance is relatively easy as it doesn’t impact the total downtime significantly. Hence, the maintenance of this machine can be passed to the operators by upgrading their skill level. (Seecharan et al., 2018; Aslam-Zainudeen and Labib, 2011)

Machine/Equipment falling on the top-right corner are a serious concern as they appear to have a very high downtime. These machines do not breakdown frequently, but on those few cases they cast an impact on total downtime taking impacting time to fix. Condition Based Monitoring (C.B.M) is the one appealing for such cases (Tahir et al., 2014; Labib, 2004).

For the machines having the highest downtimes and frequencies usually end up in the right bottom corner, indicating the need to consider a major design change and structural modification. The grid is labeled as Design out Maintenance (D.O.M), designating the necessity of design alteration (Labib, 2004, Fernandez et al., 2003).

The ones labeled F.T.M in the grid indicates Fixed Time maintenance as in for preventive maintenance. However different F.T.Ms could mean different meanings. The F.T.Ms close to the top left corner indicate the easy fixed time maintenance. The F.T.M found between O.T.F and S.L.U for instance concerns with who will do the work. When considering the F.T.M between O.T.F and C.B.M it indicates more on the timing of the work that should be addressed. Hence, this F.T.M requires emphasis on when to carry through the work (Labib, 2004).

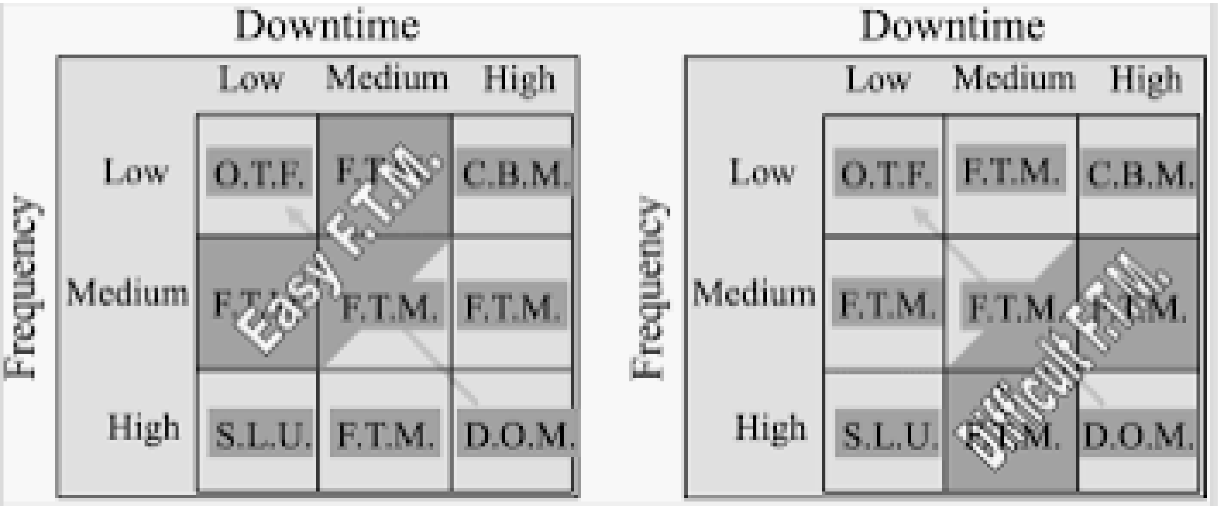

Figure 5: FTM Layout in DMG, (Labib, 2004)

The other preventive maintenance decisions should be addressed in a peculiar way. For the F.T.M found between S.L.U and D.O.M the main thing to address is the how the job is handled itself. It indicates the right type of preventive maintenance is not being executed adequately. The other F.T.M located between C.B.M and D.O.M shows the wrong problem is covered in the job, giving a rise to the question of what must be done to avoid the problems (Labib, 2004).

DMG as a policy suggests TPM and RCM, based on the equipment placement location on the DMG grid. For a highly repetitive, small problems that are usually bedraggled; incapability of the user is mostly the cause where S.L.U is the best fit strategy for such issues. In relation to this TPM is the best suited policy for the areas covering around S.L.U as it is rudimentary to TPM’s elements.

RCM shall be applied for equipment susceptible to a high degree of failure with high downtimes and low frequency. Hence, for areas on the grid surrounding C.B.M, RCM is the one to be considered as a policy (Labib,2004; Aslam-Zainudeen and Labib, 2011).

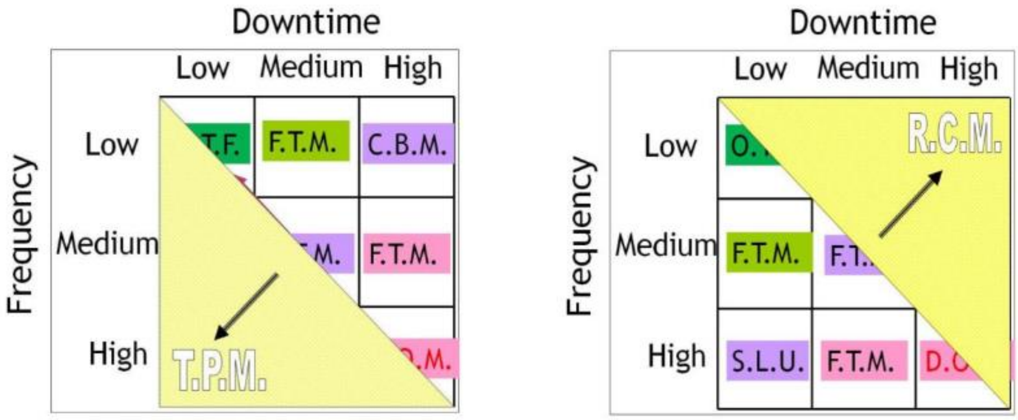

Figure 6: T.P.M & R.C.M placement in DMG

CHAPTER THREE: METHODOLOGY

3.1 GENERAL

This section covers the direction used to conduct this research study. It will present the data collection methods in each step of the analysis along with how they are interpreted with regards to the focus area. It describes the research approach used on how to reach the selection of final strategy intended for each machine system considered in the case company. It also describes how the tools are effectively used to select the strategies and policies per each set of machine.

3.2 RESEARCH APPROCH

In the case of this particular research, the main purpose is to come up with a tool that selects a different set of maintenance strategy for continuously operated utility equipment with a minimal maintenance period due to its operational circumstances. This is achieved through the use machine history as a main data input.

The collected data is analyzed with an integration of a multi criteria tool of AHP, Pareto and a strategy selection tool of DMG. The aim here is to select a maintenance strategy and policy per each set of utility equipment that could continuously improve the performance of each equipment based on the current machine running state.

3.3 RESEARCH METHOD

The method used to achieve the strategy selection process is mainly composed of a quantitative research method. The outlook of the study mainly relying on machine history as well as the tools used to analyze the data requiring quantitative information as a main processing approach, directs the research analysis method to be composed of mainly the quantitative research method.

That being the case, qualitative comparison is also used to relate the current situation in the case company to the result achieved on selecting a maintenance strategy based on the quantitative analysis.

3.4 DATA SOURCE

Data considered in this study are from different sources. Primary and quantitative data are collected from the following sources. SAP ERP system is used to collect each downtime and downtime frequency for each utility sub plant. TABLEAU will also be used to determine the total downtime of each sub-plant. FGD is used to collect possible AHP alternatives and their ratings from the departments' experts to filter the downtime and downtime frequency.

Secondary data is used to select the strategy selection tools of AHP, Pareto and DMG from different literatures. AHP criteria is selected from company IPR document, whereas the DMG analysis techniques are gained from A. Labib research literature.

3.5 METHOD OF ANALYSIS

Preceding data collection, a combination of AHP and Pareto is used as a data filtration in this research. The AHP selection criteria are taken from the case company document (CCBA IPR Input Document, 2017). The AHP Alternative from which the data were to be considered as a data filter of downtime and downtime frequency for the input of DMG tool were selected by the case company's utility team experts. This focused group considered personnel with more than five years of experience in the department that are familiar with the machine history.

Based on the FGD team's individual's experience and opinion the group identifies and ranks major alternatives as the main reasons for the loss of production time in utility machines from which it's possible to sort the downtime data for the DMG tool consideration.

After developing a hierarchical structure, team proceeds with data analysis and Pair-Wise comparison for every alternative based on the goal of selecting most appropriate data filter. Every element in the upper level is used to compare the elements found immediately in the next lower level, with respect to each other. The desired gain is to obtain a prioritized comparative judgments of the every element of the same level while taking the higher elements as the base comparing criteria using the below formula.

$$a'_{ij} = a_{ij} / \sum_{i=1}^{n} a_{ij}\,, i, j \ = 1,2, \dots , n$$

$$\mathcal{W}_i = (1/n) \sum_{i=1}^{n} a'_{ij}{}', i, j = 1,2, \dots, n$$

After Prioritization judgment is analyzed, the consistency of the judgment is analyzed by using a consistency ratio. To proceed with the determined priorities the C.R. gained must be less than 0.1. If the consistency ratio is found to be greater than or equal to 0.1, there is inconsistency and the judgments must be reevaluated in the pairwise comparison stage.

$$C.R. = \frac{C.I.}{R.I.} \quad , C.R. < 0.1$$

After AHP analysis, the prioritization proceeds to 80/20 rule and identifies the most impactful alternatives that shall be considered in the succeeding step. Here the major alternatives ranked by the FGD resulting in the main downtime loss will be pinpointed that will aid in the advance on DMG calculation.

After identifying the main factors, the pre-collected data is filtered according to the prioritized alternatives. The filtered data now are directly applied to the DMG according to rules of (Seecharan et al., 2018). The recommended technique for this research paper with different machine set and heterogeneous data is based on the method of clustering. Here, boundary partitions are set on the basis of the maximum difference on the list. The data is first set in a descending order and the maximum difference values are identified by subtracting the immediate following value from the preceding one while following the descending order. The largest two Values will mark the boundary lines for the categories.

$$Medium/High\ Boundary = \boldsymbol{Max}(\boldsymbol{Hn} - \boldsymbol{Hn}{-}\mathbf{1})$$

Accordingly, each sub-pant will be laid out in the grid according to the ranking made on both the downtime and downtime frequency. Thereafter the strategy selected for each set of equipment is discussed briefly taking in comparison with the current running state of each sub plant and failure causes leading to the conclusion.

3.6. SCHEMATIC DIAGRAM

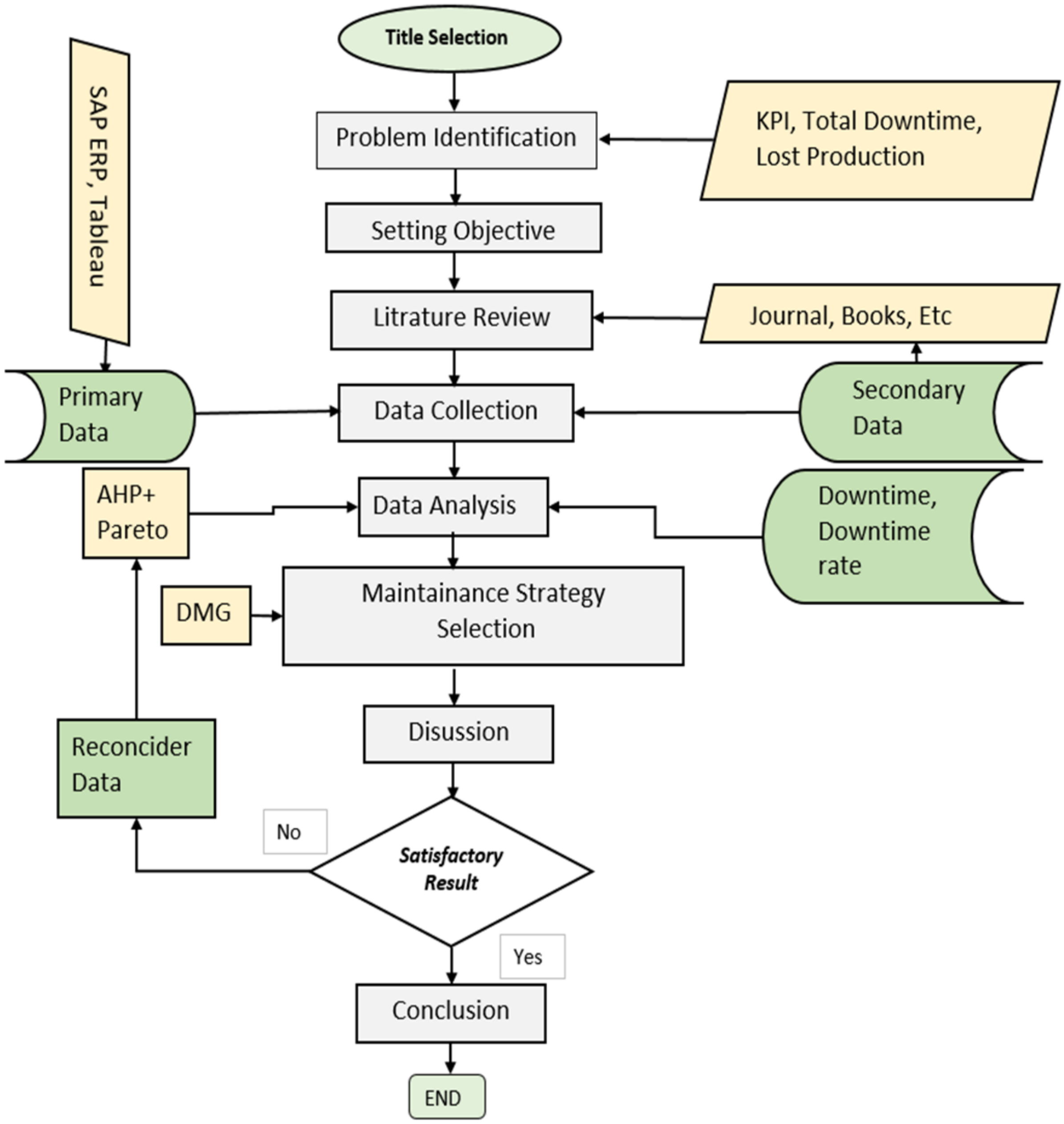

Figure 7: Methodology Schematic Diagram

CHAPTER FOUR: DATA ANALYSIS

4.1 AHP ANALYSIS

As discussed in previous session, for the researcher to proceed with the data collection, it must be known what data should be considered for the maintenance strategy selection analysis with AHP tool.

In the AHP tool used as a data filtration in this research, the selection criteria are taken from the case company document (CCBA IPR Input Document, 2017) where the criteria are; Performance Losses, Downtime Losses, Equipment Loss and Quality Losses. These are chosen because the company identifies these losses as the major types of losses of the equipment that affect output in direct relation to breakdowns and machine wastes tying up with efficiency affecting production time and output with respect to the operational equipment within the department.

Downtime losses are the same as a major machine breakdowns of a vital equipment where the production operation has totally stopped, until the issue is rectified. According to the *IPR document of the company* about 12% of total production time is considered to be lost due to downtime losses.

Equipment Stoppages are considered from a rapid and frequent equipment short stops that can't be justified as a breakdown, however affecting the total output and efficiency. About 7.5% of total production time is expected to be lost from equipment short stops.

Performance losses are the ones that arise from the efficiency loss from the actual dispatch output of a running machine. There are no straight breakdowns or shortstops, however the machine/ equipment is unable to deliver the required output that is expected of it. 7.5% of total production time are also expected to be lost from performance losses.

Quality Losses are considered when there are significant production time that are lost from producing defective products that don't meet the standard. Instead of producing value adding work, equipment has been producing waste, consuming precious value adding time. 1.2% of the total production time has been considered to be lost due to quality losses.

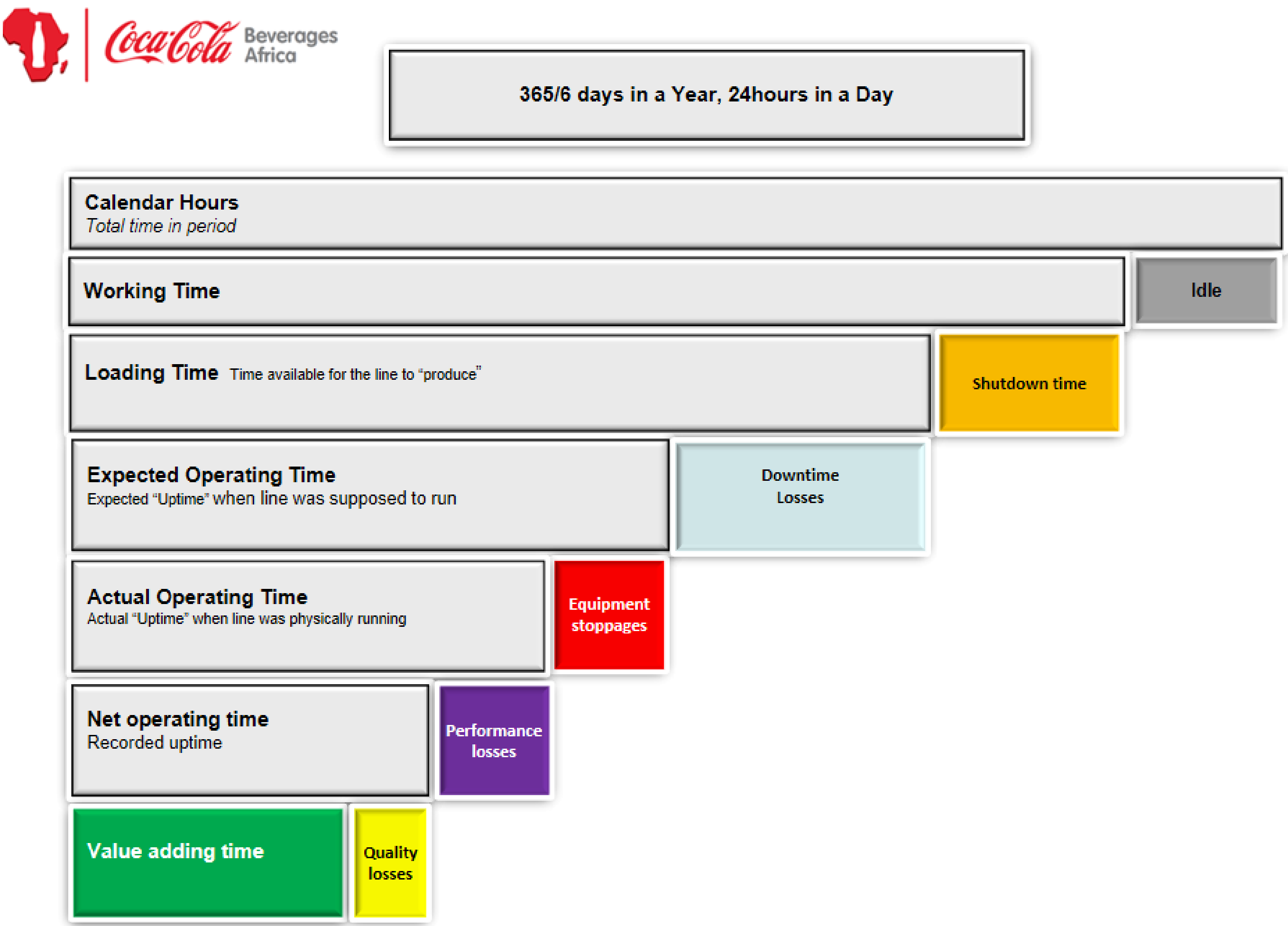

Figure 8: Losses in CCBA

The AHP Alternative from which the data were to be considered as an input to the DMG tool were selected by the case company's utility team experts. This focused group considered personnel with more than five years of experience in the department and are familiar with the machine history. The team was compromised of the Utility Unit Manager, Mechanical Specialist, Electrical Specialist, Maintenance controller, Country Utility Specialist and finally the Maintenance Planner (With an exception of 3 years of experience). The team is a composition of two Electrical and Four Mechanical Engineers.

Table 3: FGD Discussion answers

Q1- Do You Believe there is a problem regarding the maintenance effectiveness in utility department? Please state reasons Yes, there is a problem. • Re-appearing breakdowns • lack of organization as a team • Team focuses on firefighting, awaiting a breakdown or failure to occur before engaging

- Ineffective/lack of preventive measures taken - Insufficient spare part availability - worn out and aged machinery - Incorrect initial design and commissioning of equipment interconnection systems and environments - Insufficient consideration of factors in system design - lack of skill to tackle problems on highly specialized equipment
Q2 - Thinking back to all your years of experience in the department, what were the major challenges resulting in the experienced high downtimes? - Reappearing issues from not tackling the right RCA - Reappearing issues from operational negligence - Breakdowns from not sustaining basic operational conditions - Inter-related failures, where one failure leading to another - Frequently down aged machinery with unavailable spare - Uncontrolled failures associated with other stakeholders - Equipment failure from out of specification operational conditions - limitation on spare availability, forcing equipment to stop for days
Q3 - 3. What do you think about maintenance strategies? Would you believe implementing a strategy would actually assist you? Yes, it will definitely assist since it aids the team to be more organized focusing on specific actions to be carried out with a detailed activity to follow.
Q4 - 4. AHP as a tool is composed of Goal, Criteria and Alternatives. In this case the goal is to select a data filter for the DMG tool where the criteria are taken directly from the IPR document. As an experts, what shall be put as alternatives to select the data to be considered in the DMG? - Human Errors - Spare Availability & Ageing - Uncontrollable & External Factors - Operational & Basic Sustenance Problem - Initial Design/Installation problems - Unresolved RCAs & Secondary Failures

Based on the FGD team's individual's experience and opinion the group has identified and ranked six major alternatives as the main reasons for the loss of production time in utility machines from which it's possible to sort the downtime data for the DMG tool consideration.

The considered alternatives from the focus group discussion for the lost time causes are; Human errors, Spare availability & ageing, Uncontrollable and external factors, Unresolved

RCAs & secondary failures, Operational and Basic Sustenance problems, and finally Initial design and Installation problems.

Human Errors: considers any breakdowns or lost time incidents that could arise from intentional or unintentional errors, mis-operation, misuse and abuse of machine knowingly or unknowingly by operating, cleaning, maintaining or any other personnel in direct contact of the machinery.

Spare Availability & Ageing: Considers breakdowns or lost time incidents due to any type of losses arising from ageing of machinery as well as lack of spare due to reasons like unavailability at the needed moment and forex problems.

Uncontrollable & External Factors: This are the problems that are affecting production time and breakdown rates, however the case study group cannot effectively void/rectify them as they appear to be out of the group's control.

Operational & Basic Sustenance Problem: These are issues arising from not executing preventive tasks as per the OEM requirements and problems arising from not full filing operational condition on the machines.

Initial Design/Installation problems: This consists of the breakdowns and other efficiency losses due to an initial design consideration and has been corrected if parameters and situations has been adjusted to the correct form.

Unresolved RCAs & Secondary Failures: these are due to the failures either arising from a preexisting failure/failed component or from a repeatedly arising failure from which the real root cause has not been identified.

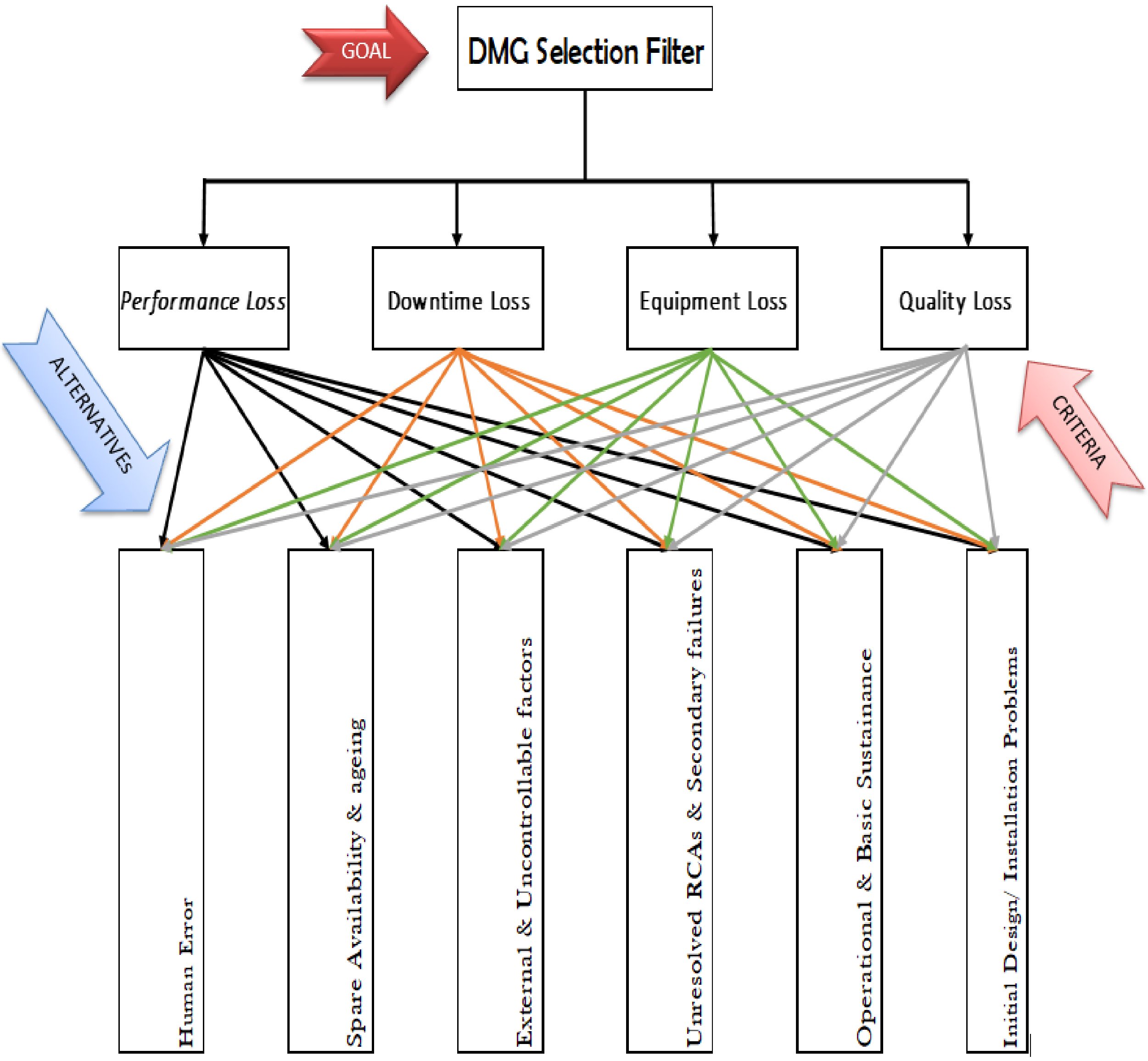

Figure 9: AHP filter for DMG tool

Step 1

The first Step in AHP is developing a hierarchical structure as shown above. It is put in a descending order from the total objective to the various criteria, sub criteria and finally the alternatives. In this paper the goal is put at the top level, whereas the criteria are found at the second level and finally the alternatives are put at the third and lowest level.

Step 2

The second step is the Pair-Wise comparison for criteria based on the goal. Every element in the upper level is used to compare the elements found immediately in the next lower level, with respect to each other. The desired gain is to obtain a prioritized comparative judgments of the every element of the same level while taking the higher elements as the base comparing criteria. This is achieved via a nine scale point of relative importance which is shown below.

Table 4: Relative importance nine scale point

Scale of Relative Importance	
1	*Equal Importance*
3	*Moderate Importance*
5	*Strong Importance*
9	*Extreme Importance*
2, 4 , 6, 8	Intermediate Values
1/3, 1/5, 1/7, 1/9	Values for Inverse Comparison

Step 3

The step comprises Prioritization. To obtain this, Additive normalization method is used where the elements of each column of matrix A are divided by the sum of the column (I.e. Normalizing the column), thereafter elements of the resulting row are added, and finally the sum is divided by the number of elements in the row to get the results.

$$a'_{ij} = a_{ij} / \sum_{i=1}^{n} a_{ij}\ , i, j\ = 1,2, \dots , n$$

$$\mathcal{W}_i = (1/n) \sum_{i=1}^{n} a'_{ij}\ ', i, j = 1,2, \dots , n$$

Step 4

The last step is the Measurement of the consistency of the judgments. This step is essential as it examines the accuracy of the judgments with respect to each other. The consistency is measured by the use of Consistency Ratio (C.R.). To achieve this, it's mandatory to first calculate consistency index (C.I.) and Lambda max (λ_{max}).

The C.I. of a n x n matrix is defined by -

$$C.I. = \frac{\lambda max - n}{n-1}$$

Where, λ_{max} is the maximum Eigen value of the matrix.

Thereafter C.R. is calculated as –

$$C.R. = \frac{C.I.}{R.I.} \quad , C.R. < 0.1$$

Where, R.I. is a standard random consistency index.

Table 5: Consistency Index for d/f matrix orders

Order of Matrix	1	2	3	4	5	6	7	8
R.I.	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41

To proceed with the determined priorities the C.R. gained must be less than 0.1. If the consistency ratio is found to be greater than or equal to 0.1, there is inconsistency and the judgments must be re-evaluated in the pairwise comparison stage.

4.1.1 Criteria Weighting

The calculation for the pairwise comparison made for the criteria is put with respect to each other based on the general goal as per the hierarchy.

Step 2: Ranking

	Downtime L.	Performance L.	Equipment L.	Quality L.
Downtime L.	1	4	4	9
Performance L.	1/4	1	1.00	5
Equipmennt L.	1/4	1	1	5
Quality L.	1/9	1/5	1/5	1
SUM	***1.611111111***	***6.2***	***6.2***	***20***

Step 3: The ranking is the Normalized

	Downtime L.	Performance L.	Equipment L.	Quality L.
Downtime L.	0.620689655	0.64516129	0.64516129	0.45
Performance L.	0.155172414	0.161290323	0.161290323	0.25
Equipmennt L.	0.155172414	0.161290323	0.161290323	0.25
Quality L.	0.068965517	0.032258065	0.032258065	0.05

Step 3: The main section criteria weight is now calculated

	Downtime L.	Performance L.	Equipment L.	Quality L.	Criteria Weight
Downtime L.	0.620689655	0.64516129	0.64516129	0.45	0.590253059
Performance L.	0.155172414	0.161290323	0.161290323	0.25	0.181938265
Equipment L.	0.155172414	0.161290323	0.161290323	0.25	0.181938265
Quality L.	0.068965517	0.032258065	0.032258065	0.05	0.045870412

To proceed with the obtained weight for the criteria, we now proceed with calculating the Consistency of the Judgment.

Step 4: Checking for Consistency

	Downtime L.	Performance L.	Equipment L.	Quality L.	Weighted Sum Values	Eigen Values
Downtime L.	0.590253059	0.727753059	0.727753059	0.412833704	2.458592	4.16532
Performance L.	0.147563265	0.181938265	0.181938265	0.229352058	0.740791	4.07166
Equipment L.	0.147563265	0.181938265	0.181938265	0.229352058	0.740791	4.07166
Quality L.	0.065583673	0.036387653	0.036387653	0.045870412	0.184229	4.01630

Since we now have the Eigen Values, we will proceed λ_{Max}

$$\lambda_{Max} = \frac{4.16532 + 4.071666 + 4.071666 + 4.016301}{4} = 4.0812$$

Next for the C.I & C.R.

$$C.I. = \frac{4.0812 - 4}{3} = 0.0270$$

$$C.R. = \frac{0.0270}{0.9} = 0.03$$

Where, R.I = 0.9 for a 4 x 4 Matrix

Since, The Consistency result is below 0.1, we can proceed with the acquired priority weights.

Table 6: Achieved Criteria weight

CRITERIA	**WEIGHT**
Downtime L.	0.590253
Performance L.	0.181938
Equipment L.	0.181938
Quality L.	0.04587

4.1.2 Alternative weighting

To start the calculation for the alternatives, we start with the first criteria of Downtime losses. As we have already done the AHP structure, we will just proceed with the second step of Pair-wise comparison gained from the focus group. Based on the nine scale point the initial matrix comparison is shown below.

For the sake of simplicity in putting the matrix the sub criteria are labeled as follows

Table 7: Sub criteria labeling for matrix calculation

Sub Criteria	Label
Human Error	X_1
Spare Availability & Ageing	X_2
External & uncontrollable factors	X_3
Operational and Basic sustenance	X_4
Unresolved RCAs and secondary failures	X_5
Initial Design & Installation Problem	X_6

	X_1	X_2	X_3	X_4	X_5	X_6
X_1	1	3	9	3	1	5
X_2	1/3	1	7	0.2	1/3	3
X_3	1/9	1/7	1	1/9	1/7	1/7
X_4	3	5	9	1	4	5
X_5	1	3	7	1/4	1	3
X_6	1/5	1/3	3	1/5	1/3	1
Sum	**5.644**	**12.476**	**36.042**	**2.094**	**6.808**	**17.33**

Step 3: Now to normalize the rankings

	X_1	X_2	X_3	X_4	X_5	X_6
X_1	0.1771644	0.2404574	0.2497066	0.1591498	0.1468717	0.28846159
X_2	0.0590548	0.0801524	0.1942162	0.0954908	0.0489567	0.17307695

X_3	0.0196849	0.0114503	0.0277451	0.0530504	0.0208557	0.01923058
X_4	0.5314985	0.4007623	0.2497068	0.4774543	0.5874868	0.28846159
X_5	0.1771644	0.2404598	0.1953886	0.1193635	0.1468717	0.17307695
X_6	0.0354328	0.0267174	0.0832363	0.0954908	0.0489572	0.05769231

Step 3: Criteria weight calculation for the alternatives W.R.T Downtime Losses

	X_1	X_2	X_3	X_4	X_5	X_6	Criteria Weight
X_1	0.1771644	0.2404574	0.2497066	0.1591498	0.146871	0.288461	0.210
X_2	0.0590548	0.0801524	0.1942162	0.0954908	0.048956	0.173076	0.108
X_3	0.0196849	0.0114503	0.0277451	0.0530504	0.020855	0.019230	0.025
X_4	0.5314985	0.4007623	0.2497068	0.4774543	0.587486	0.288461	0.422
X_5	0.1771644	0.2404598	0.1953886	0.1193635	0.146871	0.173076	0.175
X_6	0.0354328	0.0267174	0.0832363	0.0954908	0.048957	0.057692	0.057

Step 4: Consistency check for the judgments on alternatives W.R.T. Downtime Losses

	X_1	X_2	X_3	X_4	X_5	X_6
X_1	0.210302	0.3254740	0.2280259	0.1408525	0.175387	0.2896059
X_2	0.070101	0.1084913	0.1773538	0.0845123	0.058461	0.1737635
X_3	0.023367	0.0154987	0.0253362	0.0469512	0.024905	0.0193068
X_4	0.630912	0.5424567	0.2280261	0.4225617	0.701550	0.2896059
X_5	0.210302	0.3254773	0.1784240	0.1056404	0.175387	0.1737635
X_6	0.04206	0.0361637	0.0760093	0.0845123	0.058462	0.0579211

Table 8: Downtime loss Edgen value for sub-criteria

Weighted Sum Value	Edgen Value
1.369648	6.512769
0.672683	6.20034
0.155365	6.132133
2.815113	6.662015
1.168995	6.665211
0.35513	6.131255

$$\lambda_{Max} = \frac{6.5127+6.2+6.1321+6.6620+6.665211+6.1312}{6} = 6.384$$

$$C.I. = \frac{6.384 - 6}{5} = 0.0768$$

$$C.R. = \frac{0.0768}{1.24} = 0.062$$

Where R.I. is 1.24 for a 6x6 Matrix

Since, The Consistency result is below 0.1, we can proceed with the acquired priority weights for the alternatives W.R.T. Downtime losses.

Table 9: Sub criteria weight for Downtime loss

Alternatives	Criteria Weight
Human Error	0.210
SPARE Availability & Ageing	0.108
External & Uncontrollable factors	0.025
Operational & Basic Sustenance	0.422
Unresolved RCA & Secondary Failures	0.175
Initial Des& I/n Prob.	0.057

Now, to perform the same calculation for the alternatives with respect to the second criteria of Performance Loss, it starts with the Pair-Wise comparison gained from the focus group.

	X_1	X_2	X_3	X_4	X_5	X_6
X_1	1	1/5	5	1/5	3	1/3
X_2	5	1	9	3	7	5
X_3	1/5	1/9	1	1/7	1/3	1/5
X_4	5	1/3	7	1	5	3
X_5	1/3	1/7	1/3	0.2	1	1/4
X_6	3	0.2	5	1/3	4	1
Sum	14.5334	1.9873	30.04255	4.8753	20.3333	9.78333

Step 3: Now to normalize the rankings

	X_1	X_2	X_3	X_4	X_5	X_6
X_1	0.068807	0.100639	0.166431	0.041023	0.147541	0.034071
X_2	0.344036	0.503195	0.299575	0.615343	0.344263	0.511073
X_3	0.013761	0.055911	0.033286	0.029126	0.016392	0.020443
X_4	0.344036	0.167732	0.234409	0.205114	0.245902	0.306644
X_5	0.022936	0.071885	0.099868	0.041023	0.04918	0.025554
X_6	0.206424	0.100639	0.166431	0.068371	0.196722	0.102215

Step 3: Criteria weight calculation for the alternatives W.R.T Downtime Losses

	X_1	X_2	X_3	X_4	X_5	X_6	Criteria Weight
X_1	0.068807	0.100639	0.166431	0.041023	0.147541	0.034071	0.0931

X_2	0.344036	0.503195	0.299575	0.615343	0.344263	0.511073	0.4362
X_3	0.013761	0.055911	0.033286	0.029126	0.016392	0.020443	0.0282
X_4	0.344036	0.167732	0.234409	0.205114	0.245902	0.306644	0.2506
X_5	0.022936	0.071885	0.099868	0.041023	0.04918	0.025554	0.0517
X_6	0.206424	0.100639	0.166431	0.068371	0.196722	0.102215	0.1401

Step 4: Consistency check for the judgments on alternatives W.R.T. Performance Losses

	X_1	X_2	X_3	X_4	X_5	X_6
X_1	0.093085	0.087249	0.140766	0.050128	0.155223	0.046711
X_2	0.465427	0.436247	0.253379	0.751919	0.362187	0.700667
X_3	0.018617	0.048472	0.028153	0.035591	0.017245	0.028027
X_4	0.465427	0.145416	0.198262	0.25064	0.258705	0.4204
X_5	0.031028	0.062321	0.084468	0.050128	0.051741	0.035033
X_6	0.279259	0.087249	0.140766	0.083547	0.206964	0.140133

Table 10: Performance loss Edgen value for subcriteria

Weighted Sum Value	**Edgen Value**
0.573162	6.157385
2.969826	6.807663
0.176105	6.255243
1.738849	6.93765
0.31472	6.0826
0.937918	6.693034

$$\lambda_{Max} = \frac{6.157+6.8076+6.2552+6.9376+6.0826+6.930}{6} = 6.4889$$

$$C.I. = \frac{6.4889 - 6}{5} = 0.09778$$

$$C.R. = \frac{0.0978}{1.24} = 0.078$$

Where R.I. is 1.24 for a 6x6 Matrix

Since, The Consistency result is below 0.1, we can proceed with the acquired priority weights for the alternatives W.R.T. Performance losses.

Table 11: Sub criteria weight for performance loss

Alternatives	Criteria Weight
Human Error	0.093085
SPARE Availability & Ageing	0.436247
External & Uncontrollable factors	0.028153
Operational & Basic Sustenance	0.25064
Unresolved RCA & Secondary Failures	0.051741
Initial Des& I/n Prob.	0.140133

Next, perform a similar calculation for the alternatives with respect to the third criteria of Equipment Loss, again it starts with the Pair-Wise comparison gained from the focus group.

	X_1	X_2	X_3	X_4	X_5	X_6
X_1	1	1/3	1/7	1/3	0.2	3
X_2	3	1	1/5	1	1/3	5
X_3	7	5	1	5	3	9
X_4	3	1	1/5	1	1/3	4
X_5	5	3	1/3	3	1	7
X_6	1/3	0.2	1/9	1/4	1/7	1
Sum	19.3336	10.53333	1.98730	10.5836	5.00948	29

Step 3: Now to normalize the rankings

	X_1	X_2	X_3	X_4	X_5	X_6

X_1	0.051723	0.031642	0.071885	0.031495	0.039924	0.103448
X_2	0.155185	0.094937	0.100639	0.094486	0.06654	0.172414
X_3	0.362063	0.474684	0.503195	0.472428	0.598864	0.310345
X_4	0.155171	0.094937	0.100639	0.094486	0.066534	0.137931
X_5	0.258616	0.284813	0.167732	0.283485	0.199621	0.241379
X_6	0.017241	0.018987	0.055911	0.023621	0.028517	0.034483

Step 3: Criteria weight calculation for the alternatives W.R.T Performance Losses

	X_1	X_2	X_3	X_4	X_5	X_6	Criteria Weight
X_1	0.051723	0.031642	0.071885	0.031495	0.039924	0.103448	0.0550
X_2	0.155185	0.094937	0.100639	0.094486	0.06654	0.172414	0.1140
X_3	0.362063	0.474684	0.503195	0.472428	0.598864	0.310345	0.4535
X_4	0.155171	0.094937	0.100639	0.094486	0.066534	0.137931	0.1082
X_5	0.258616	0.284813	0.167732	0.283485	0.199621	0.241379	0.2392
X_6	0.017241	0.018987	0.055911	0.023621	0.028517	0.034483	0.0297

Step 4: Consistency check for the judgments on alternatives W.R.T. Equipment Losses

	X_1	X_2	X_3	X_4	X_5	X_6
X_1	0.05502	0.038007	0.064799	0.036094	0.047855	0.08938
X_2	0.165075	0.114033	0.090719	0.108283	0.079757	0.148967
X_3	0.385138	0.570167	0.453596	0.541414	0.717823	0.268141
X_4	0.165061	0.114033	0.090719	0.108283	0.07975	0.119174
X_5	0.275098	0.342103	0.151199	0.324881	0.239274	0.208554
X_6	0.01834	0.022807	0.0504	0.027071	0.034182	0.029793

Table 12: Equipment loss Edgen value for sub criteria

Weighted Sum Value	**Edgen Value**
0.331155	6.018856
0.706835	6.198497
2.936279	6.473332
0.67702	6.252326
1.54111	6.440764
0.182592	6.128615

$$\lambda_{Max} = \frac{6.0189+6.1985+6.4733+6.2523+6.4407+6.1286}{6} = 6.2520$$

$$C.I. = \frac{6.2520-6}{5} = 0.05004$$

$$C.R. = \frac{0.05004}{1.24} = 0.0406$$

Where R.I. is 1.24 for a 6x6 Matrix

Since, The Consistency result is below 0.1, we can proceed with the acquired priority weights for the alternatives W.R.T. Equipment short stop losses.

Table 13: Sub criteria weight for Equipment loss

Alternatives	**Criteria Weight**
Human Error	0.05502
SPARE Availability & Ageing	0.114033
External & Uncontrollable factors	0.453596
Operational & Basic Sustenance	0.108283
Unresolved RCA & Secondary Failures	0.239274
Initial Des& I/n Prob.	0.029793

For the last alternative priority calculation, the comparison is made for the alternatives with respect to the fourth criteria of Quality Loss, like the previous alternative comparisons it starts with the Pair-Wise comparison gained from the focus group.

	X_1	X_2	X_3	X_4	X_5	X_6
X_1	1	1/3	7	5	5	6
X_2	1/3	1	9	5	7	7
X_3	1/7	1/9	1	1/3	1/3	1/3
X_4	1/5	1/5	3	1	1	2
X_5	0.2	1/7	3	1	1	3
X_6	1/6	1/7	3	1/2	1/3	1
Sum	4.70982	1.930125	26.00009	12.83333	14.6666	19.33333

Step 3: Now to normalize the rankings

	X_1	X_2	X_3	X_4	X_5	X_6
X_1	0.2123221	0.1726830	0.2692298	0.3896104	0.3409091	0.310344
X_2	0.6370302	0.5181010	0.3461526	0.3896104	0.4772728	0.362069
X_3	0.0303317	0.0575667	0.0384614	0.0259737	0.0227270	0.017241
X_4	0.0424644	0.1036202	0.1153853	0.0779220	0.0681818	0.103448
X_5	0.0424644	0.0740144	0.1153853	0.0779220	0.0681818	0.155172
X_6	0.0353870	0.0740144	0.1153853	0.0389610	0.0227272	0.051724

Step 3: Criteria weight calculation for the alternatives W.R.T Quality Losses

	X_1	X_2	X_3	X_4	X_5	X_6	Criteria Weight
X_1	0.2123221	0.1726830	0.2692298	0.3896104	0.340909	0.310344	0.2825
X_2	0.6370302	0.5181010	0.3461526	0.3896104	0.477272	0.362069	0.4550
X_3	0.0303317	0.0575667	0.0384614	0.0259737	0.022727	0.017241	0.0320
X_4	0.0424644	0.1036202	0.1153853	0.0779220	0.068181	0.103448	0.0851
X_5	0.0424644	0.0740144	0.1153853	0.0779220	0.068181	0.155172	0.0888
X_6	0.0353870	0.0740144	0.1153853	0.0389610	0.022727	0.051724	0.0563

Step 4: Consistency check for the judgments on alternatives W.R.T. Quality Losses

	X_1	X_2	X_3	X_4	X_5	X_6
X_1	0.282517	0.151665	0.224352	0.425852	0.444284	0.338199
X_2	0.847635	0.455039	0.288453	0.425852	0.621997	0.394566
X_3	0.04036	0.05056	0.03205	0.02839	0.029619	0.018789
X_4	0.056503	0.091008	0.096152	0.08517	0.088857	0.112733
X_5	0.056503	0.065006	0.096152	0.08517	0.088857	0.1691
X_6	0.047086	0.065006	0.096152	0.042585	0.029619	0.056367

Table 14: Quality loss Edgen Value for subciteria

Weighted Sum Value	**Edgen Value**
1.866869	6.607996
3.033542	6.666548
0.199767	6.232913

0.530423	6.227792
0.560788	6.311142
0.336814	5.975429

$$\lambda_{Max} = \frac{6.6079+6.665+6.2329+6.2277+6.3111+5.9754}{6} = 6.3369$$

$$C.I. = \frac{6.3369 - 6}{5} = 0.0674$$

$$C.R. = \frac{0.0674}{1.24} = 0.054$$

Where R.I. is 1.24 for a 6x6 Matrix

Since, The Consistency result is below 0.1, we can proceed with the acquired priority weights for the alternatives W.R.T. Quality losses.

Table 15: Sub criteria weight for Quality loss

Alternatives	**Criteria Weight**
Human Error	0.282517
SPARE Availability & Ageing	0.455039
External & Uncontrollable factors	0.03205
Operational & Basic Sustenance	0.08517
Unresolved RCA & Secondary Failures	0.088857
Initial Des& I/n Prob.	0.056367

To get the alternative priorities, the previous alternative calculations with respect to the criteria shall be considered along with the main criteria weights calculated in the beginning of the AHP analysis. Therefore, it's proceeded accordingly with the criteria, criteria weights, alternatives and alternative priorities for each criteria as follows.

4.1.3 AHP Result

Table 16: Alternative Priority against each Criteria

	Downtime Loss	***Performance Loss***	***Equipment Loss***	***Quality Loss***
Weight	0.59	0.182	0.182	0.046
Human Error	0.210301943	0.093085342	0.055019659	0.282516604
Spare Availability & Ageing	0.108491357	0.436247462	0.114033338	0.455039376
External & Uncontrollable factors	0.025336211	0.02815318	0.45359631	0.032050327
Operational & Basic Sustenance	0.422561771	0.25063953	0.108282886	0.085170373
Unresolved RCA & Secondary Failures	0.17538752	0.051740996	0.2392744	0.088856769
Initial Des& I/n Prob.	0.057921197	0.14013349	0.029793406	0.056366551

Now considering the weight of each criteria on the respective compared alternative priorities will give the following normalized value.

Table 17: Normalized alternative against each criteria

	Downtime Loss	***Performance Loss***	***Equipment Loss***	***Quality Loss***
Weight	0.59	0.182	0.182	0.046
Human Error	0.124078147	0.016941532	0.010013578	0.012995764
Spare Availability & Ageing	0.0640099	0.079397038	0.020754068	0.020931811
External & Uncontrollable factors	0.014948365	0.005123879	0.082554528	0.001474315
Operational & Basic Sustenance	0.249311445	0.045616395	0.019707485	0.003917837
Unresolved RCA & Secondary Failures	0.103478637	0.009416861	0.043547941	0.004087411
Initial Des& I/n Prob.	0.034173506	0.025504295	0.0054224	0.002592861

Now considering the above-normalized priority for the final combined alternative priority, it gives the following result.

Table 18: Alternative Priority

Alternative	***Priority***
Human Error	0.164029
Spare Availability & Ageing	0.185093
External & Uncontrollable factors	0.104101
Operational & Basic Sustenance	0.318553
Unresolved RCA & Secondary Failures	0.160531
Initial Des& I/n Prob.	0.067693

Hereafter, based on the above achieved priority, we will proceed with the Pareto analysis to consider the data that can serve as the input for the DMG tool.

4.2 PARETO ANALYSIS

The researcher now proceeds to 80/20 rule and identifies the most impactful alternatives that shall be considered in the succeeding step. Here the major alternatives resulting in the main four loss will be pinpointed that will aid in the advance on DMG calculation.

Table 19: Critical Alternative Pareto Table

Alternative	**Priority**	**Percent of Total**	**Cumulative Percent**
Operational & Basic Sustenance	0.318553	31.86%	31.86%
Spare Availability & Ageing	0.185093	18.51%	50.36%
Human Error	0.164029	16.40%	66.77%
Unresolved RCA & Secondary Failures	0.160531	16.05%	82.82%
External & Uncontrollable factors	0.104101	10.41%	93.23%
Initial Des& I/n Prob.	0.067693	6.77%	100.00%
Total	**1**	**100.00%**	

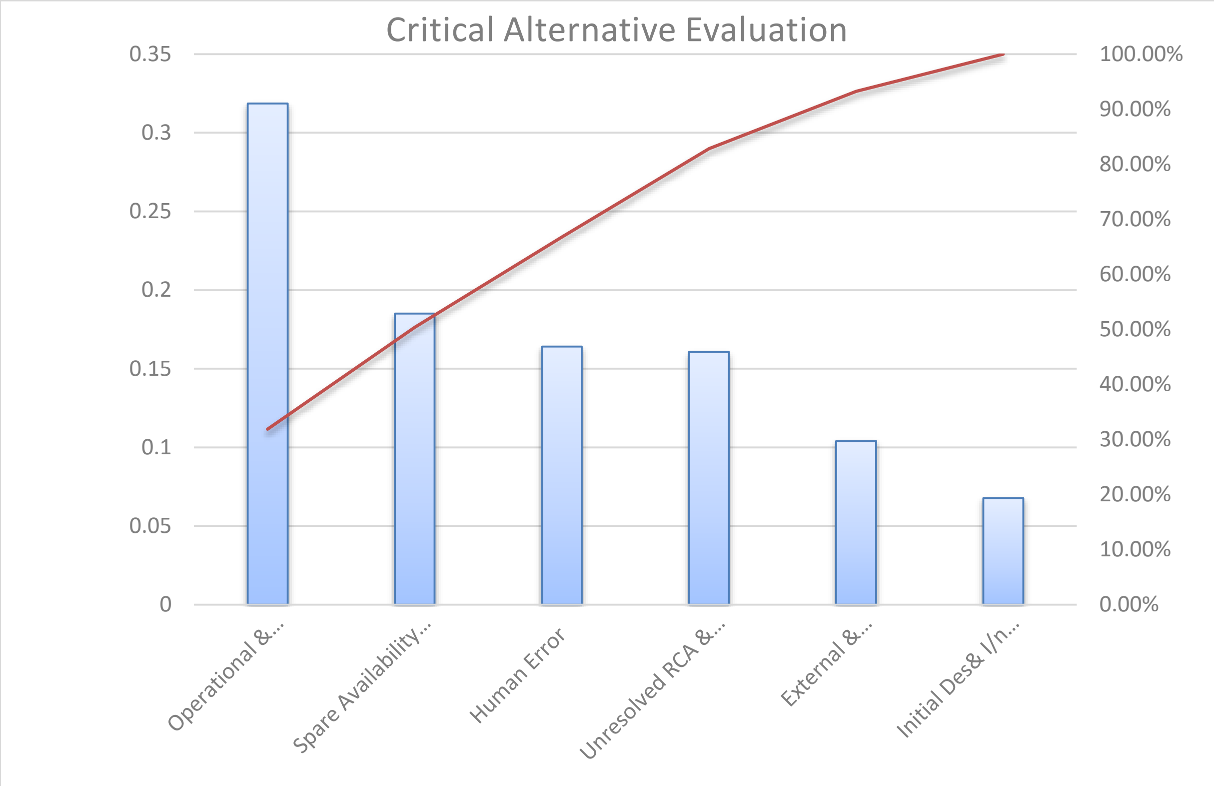

Figure 10: Critical Alternative Pareto Evaluation

Based on the Pareto Analysis, the data to be considered for the final DMG maintenance selection tool shall be proceeded with the top alternatives which account for the most weights of the total value rating with 82%. Underpinning this, from the total of six alternatives data relating to the following four alternatives will be considered in the final maintenance strategy selection analysis.

Thus, rooting on the above Pareto analysis; downtime data in relation to *Operational and basic sustenance problems*, *Spare availability & Ageing*, *Human errors*, and finally *Unresolved RCAs and secondary failures* are going to be considered in the DMG analysis.

4.3 DMG ANALYSIS

Data was collected from the most recent two years of 2018 & 2019 according to the data selection criteria above. It was then sorted out based on the below group of machines that are found in the utility department. With regards to total downtime the electric supply system and the HP compressor were found to have the highest downtime covering 70.9% of the total downtime, the same two machines have been identified as the most frequently happening in the considered recent two years. The Steam production boilers and the CO2 supply system has been listed as the least in regards to both downtime and downtime frequency.

Table 20: Downtime per set of machine

Set of Machine	***Down Time (Hr.)***
Electric Supply Plant	773.5
HP Compressor	772.8
Syrup Production Equipment	199.3
Water Treatment System	166.2
Air Supply Plant	129.2
Refrigeration System	79.5
CO2 Plant	32.7
Steam Production machinery	32.7

Contemplating downtime frequencies, the High Pressure compressor (HP Compressor) has been noted to bring in the highest number of reoccurrence with 258 incidents in the two years considered. The steam production plant has again came up as the least frequently stopping system.

Table 21: Downtime Frequency per set of Machinery

Set of Machine	***Frequency***
Electric Supply Plant	*258*
HP Compressor	*222.25*
Syrup Production Equipment	*133.75*
Water Treatment System	*79.75*
Air Supply Plant	*55.5*
Refrigeration System	*49.75*
CO2 Plant	*10.5*
Steam Production machinery	*6*

According to (Seecharan et al., 2018) there are three methods to select the threshold partitions boundaries between the low, medium and high values for both frequency and downtimes. The first one is to use the difference of the highest and the smallest value observed, and subtracting a third of the value from one boundary to the next.

Thus,

$$Medium/High\ Boundary = H - 1/3(h)$$

$$Low/Medium\ Boundary = H - 2/3(h)$$

$$Low\ Boundary = l$$

Where,

$$l\ is\ the\ Lowest\ Value$$

However this can only be used when data are homogeneous and where almost equal no. of machines are found in every category and is inapplicable in this case.

The second method relies on the judgment of the decision maker in which membership functions are set for each category representing the three category boundaries of low, medium and high.

The other method and based on the mentioned author (Seecharan et al., 2018), the recommended technique for this research paper with different machine set and heterogeneous data is based on the method of clustering. Here, boundary partitions are set on the basis of the maximum difference on the list. The data is first set in a descending order and the maximum difference values are identified by subtracting the immediate following value from the preceding one while following the descending order. The largest two Values will mark the boundary lines for the categories.

Thus,

$$Medium/High\ Boundary = \boldsymbol{Max}(\boldsymbol{H_n} - \boldsymbol{H_{n-1}})$$

Table 22: Boundary and Grid location for Downtime

Set of Machine	Downtime	Max(H_n-H_{n-1})
Electric Supply plant	*773.5*	_
HP Comp.	*772.8*	*1*
Syrup Production	*199.3*	***573.5***
Water Treatment System	*166.2*	*33.1*
Air Supply Plant	*129.2*	*37*
Refrigeration System	*79.5*	***49.7***
CO2	*32.7*	*46.8*
Steam Production System	*32.7*	*0*

Based on the selected clustering method the Boundaries between the High/Medium values are set between the HP Compressor and the Syrup production equipment, whereas the Low/Medium boundary is set between the Refrigeration equipment and Low Pressure compressors (Air supply plant). The Generators and the HP Compressor has been identified as the most critical machines with the highest downtime with a huge gap from the rest of the system. Syrup production equipment, Water Treatment equipment and air supply plant have been identified as the medium downtime machines. The remaining Refrigeration equipment, CO2 plant and steam production has been labeled as the equipment with the lowest downtime.

Table 23: Boundary and Grid location for Downtime Frequency

Set of Machine	Frequency	$Max(H_n-H_{n-1})$
HP Comp.	258	_
Electric Supply plant	222.25	*35.75*
Syrup Manufacture	133.75	***88.5***
Air Supply plant	79.75	54
Refrigeration System	55.5	24.25
Water Treatment	49.75	5.75
CO2	10.5	***39.25***
Steam production plant	6	4.5

For the analysis considering frequency breakdown per line, Boundaries between the High/Medium values are set between the Generators and the Syrup production equipment. However, unlike the downtime, the Low/Medium boundary is set between the Water Treatment equipment and the CO2 plant. The Generators and the HP Compressor has again been identified as the most critical machines with the highest downtime frequencies with a considerable gap with the rest of the system. Syrup production equipment, Water Treatment equipment and LP Compressors have been identified as the medium downtime machines with the inclusion of the Refrigeration equipment as opposing to the downtime. CO2 plant and steam production, just like the downtime, has shown the lowest downtime frequencies.

Now, having the Downtime and Downtime Frequency label, the researcher can proceed with the Maintenance strategy selection by lying the above data on the grid.

For the sake of simplicity in the placement process, the following labels found in the next table have been given for the set of machines to put on the grid.

Table 24: Machinery/System Labeling

Set of Machine	Label
Generators(Electric Supply Plant)	G
HP comp.	H
Syrup Production	SP
Water Treatment	WT
LP Compressor (Air Supply Plant)	LP
CO2	C
Refrigeration System	RF
Boiler(Steam Production)	Bo

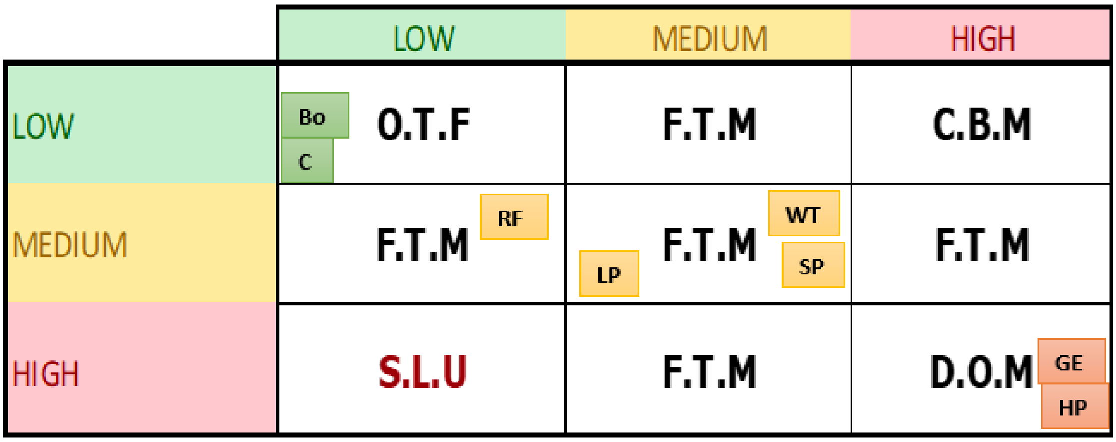

Figure 11: Machinery placement on the DMG layout

From the DMG grid, it is now possible to see where the equipment are lying and what strategies shall be considered for each set of machine.

4.4 SELECTED STRATEGIES

Based on the analysis, the result has turned up as the previous figure shown. Because of a very high and frequent downtimes, the electric supply plant (Generators) and the blow molding high pressure 40 bar compressor have appeared to be in the D.O.M grid. This strategy suggests the machine systems need a major design modification to rectify the reappearance of high downtimes.

According to the DMG calculation equipment's of operation to water treatment system, syrup production, air supply plant & finally the refrigeration system turn up at the F.T.M. as the best strategy. However depending on the position the F.T.M strategy applied has a different set of meaning.

Water treatment equipment and syrup production as strategy appear to need a strategy with a rather difficult strategy of F.T.M. that majorly indicating there are several wrongly tackled problems and how the job is handled by itself. For water treatment system it's mainly the issue that there are wrongly addressed problems in the system. In relation to syrup production system, it’s a combination of both wrongly addressed problem and how the maintenance job is executed by itself that needs to be mainly considered.

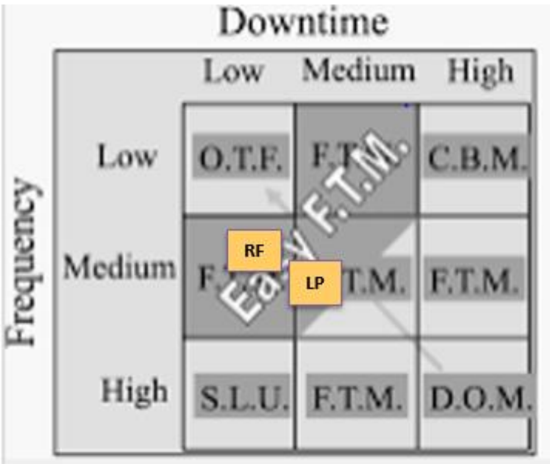

Figure 12: Easy F.T.M Equipment

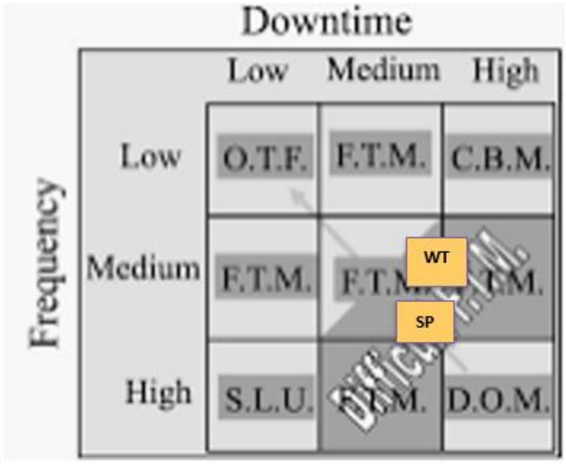

Figure 13: Difficult F.T.M Equipment

As of the refrigeration system and the air supply plants, they require the easier F.T.M strategy, both dealing with on who/when to perform the job.

The steam production plant and the CO2 supply system appear to be the least failing both in regards to downtime and frequency. An O.T.F. strategy is suggested by the grid, as to replace parts on the first indication of failure (***Not running the equipment to failure***).

As a maintainance policy, R.C.M was majorly suggested for the equipment of water treatment operation, syrup production, electric supply plant and high pressure compressor. These machines have the tendency to impact the downtime significantly with every occurance.

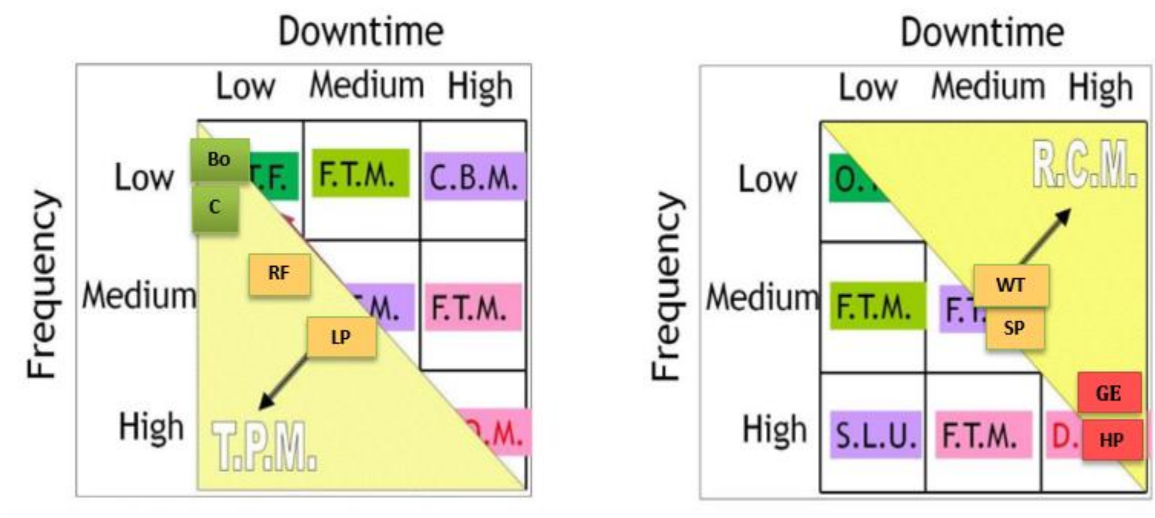

Figure 14: Maintenance Policy for each equipment

For equipment of air supply plant, refrigeration system, stem production plant and finally the CO2 system, a policy of TPM has been suggested based on the lower downtime in comparison to the downtime frequency rate. These equipment tend to exhibit a low downtime but appear to happen frequently.

Table 25: Selected Strategy & Policy Summary

Set of Machine	Label	Strategy Selected	Policy Selected
Generators(Electric Supply Plant)	G	D.O.M	R.C.M
HP comp.	H	D.O.M	R.C.M
Syrup Production	SP	F.T.M	R.C.M
Water Treatment	WT	F.T.M	R.C.M
LP Compressor (Air Supply Plant)	LP	F.T.M	T.P.M
CO2	C	O.T.F	T.P.M
Refrigeration System	RF	F.T.M	T.P.M
Boiler(Steam Production)	Bo	O.T.F	T.P.M

4.5 COMPARISON AND DISCUSSION

The analysis suggested through the overall process suggest a variety of strategies for each set of machine was different for the individual utility systems. The researcher has found it rather important to discuss the strategies along with what is going on with each system machine to verify the relation with the suggested strategy and the current status.

In the case of the electric supply plant the previous results suggest a design improvement strategy in the system and a reliability centered maintenance policy. The system currently accommodates a set of generators with a total power giving about 5000 KVA, however a team from the OEM and the company's maintenance experts has identified a major design problem regarding installation and operation. Considering de-aeration with altitude and other efficiency factors the total capacity drops to 3500 KW. However, in full capacity, the plant requires an estimate of 3200 KW exceeding the recommended OEM operation load of 70%. Furthermore it was found the airflow supply system was insufficient along with a wrong synchronization program leading to frequent fluctuation, overheating and frequent mechanical and electrical failures.

Thereafter, the higher management has put on a design change to the whole system of redesigning the whole supply plant, greatly enhancing the airflow, reinstallation of the synchronization. Furthermore, the management has a CAPEX plan to install an additional

2000KVA generator to balance the load back to recommended rate. This proofs the AHP-DMG analysis has in-fact came up with the right strategy for this system. As policy, RCM would be fit from the literature ((Labib,2004; Aslam-Zainudeen and Labib, 2011), as a failure in the current system would result in an impactful downtime as shown from the data. Fraser et al.(2011) also added RCM functions much better than TPM for complicated physical asset, with a better understanding on how the assets can fail together with the root causes.

Regarding the HP system, the analysis result has suggested a design improvement strategy in the system and RCM policy. All the facts with this equipment suggest the compressor needs a huge 365KW energy to load a required amount of 40 bar pressure. However the main problem relies on the frequent loading and unloading operation leading to a sudden load increase in the electrical supply system leading to harmonic system failures and damaging electrical cards. According to the OEM this could be rectified with the installation of a SIS system (Supervisory information system) to balance and maintain a certain load. The management has once again approved a CAPEX budget for this load control system design improvement and expected to install it by the beginning of 2021. This again has proved the AHP-DMG tool to be correct in selecting a strategy.

Considering the syrup production and water treatment plants, the analysis result suggested the use of F.T.M as a strategy with the main focus on ways on properly handling maintenance activities & addressing the correct problems. Most of the downtime with the syrup production plant was due to the failures on critical syrup filtration equipment and various transfer pumps. According to the breakdown data 60 % of these failures are related to reassembly error, the use of improper spare or tackling a wrong problem. Another downtime cause that accounted about 30% of the downtime recorded was a syrup thank change problem which was not resolved until recently, pointing down on unaddressed problems, and the methods applied in addressing the issues.

For the water treatment plant, as the AHP-DMG tool suggested the main cause for the downtime was a wrongly addressed problem. Issues of frequent borehole failures and blocked cartridge filters threw in a good share in the downtime numbers of the water system. For instance when either of the Boreholes failed production plant had to stop until the pumps were taken out and replaced. The team initially assumed it was from the quality of the pumps, but through an extensive study has found the error to be an origin of operational condition. OEMs of the pumps suggest the pumps not to stop and start operation for more than 10 to 20 times a day to prevent overheating leading to the burning of the pump motors. Despite this, it was found this pumps were actually starting more than 120 times in a day. This shows rather than addressing the problem, maintenance personnel were just changing the pumps. This problem alone accounted for about 45% of the total breakdown in the water treatment system, once again proving the analysis result to be right.

Taking the air supply and refrigeration plant the AHP-DMG analysis suggests to carry out the proper preventive maintenance along with TPM as a policy focusing on personnel. Prabhaker et al. (2014) notes TPM focuses on preventive maintenance mostly done by operator level focusing on autonomous maintenance. From the machine histories and like the grid's suggestion it's found the main problems were usually due to not executing simple preventive maintenance that should be carried out by the operators themselves. An RCA on LP compressors show the main cause for the air supply compressors shutting down was mostly from overheating due to the missed cleaning and inspection schedules by operators.

The same case was observed with the refrigeration plants as the circulation pumps are usually blocked resulting in lower pressures in evaporator and condenser circulating water, resulting in a higher output temperature causing a forced shutdown. Another issue observed with the refrigeration plant is, it completely needs to be maintained by OEM maintenance specialists due to the requirement of special tools and trainings. However due to forex constraints, most minor maintenance are done by the company's personnel resulting in frequent reworks until getting the system properly functioning.

TPM policy with O.T.F was suggested for the remaining systems of steam and CO_2 supply. If we consider these systems, they appear to be the least complicated from the other Utility plants. The boiler system incorporates two boilers, interconnected pipes and valves. O.T.F can be a good strategy as one boiler is redundant with almost little to do preventive maintenance other than following the standard operating procedures. The CO_2 supply system is composed of two storage tanks with a total capacity of 37000Kg and a set of interconnected pipes and valves. O.T.F as suggested by the grid appears to be the right strategy as any failure that occurs in this system is either from a leakage on the pipe endings & worn out valves or the failure of the valves themselves, which can only be addressed after first indication of failure. Allay

Based on (Hernandez and Labib, 2017) the DMG tool design intended output goal is to reduce the occurring downtime and downtime frequency to the possible minimum range below O.T.F.

on the DMG grid. This will be achieved through continuous improvement by rapid analysis and implementation of selected strategies for each set of equipment until the result falls below the OTF minimum range.

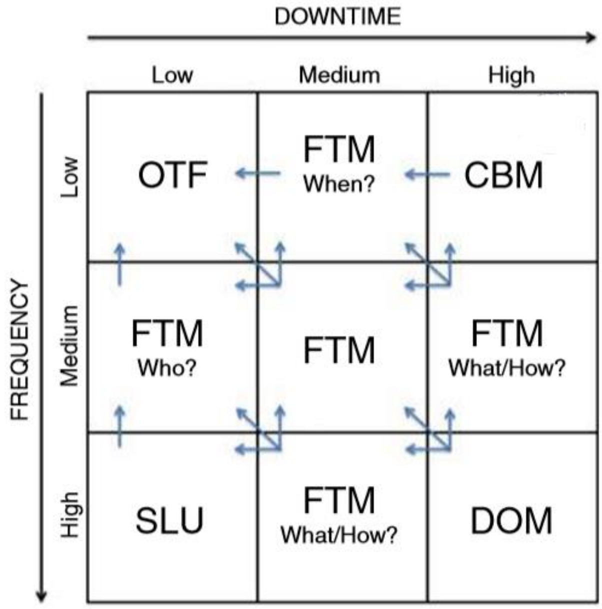

Figure 15: DMG Continuous Process, (Hernandez and Labib, 2017)

Therefore, this initial analysis could be taken as the first computation of the continuous improvement process, where the result should be below the current OTF range with each set of equipment. The downtime theoretically estimated is not to succeed greater 79.5 hour with a frequency of maximum 10.5 times for a period of two years.

The theoretical total downtime after applying the strategies will be 318 hours with a total of 42 frequencies in a year. After considering the data of 2019 maximum downtime from SAP ERP with 1138 hours with 3.3% breakdown rate, are estimated to be reduced to 318 hours with 0.92 % of total breakdown rate. According to this estimate this tool shall be able to eliminate 2.4% of the breakdown happening in the utilities department.

This indicates a significant improvement in breakdown reduction in the department. With the production plant's ability to produce 38,000 bottles per hour. The new estimated production loss is to be 12,084,000 bottles with a profit of birr 18,126,000. This shows a 39 million birr and 26,106,000 bottles expected save from the use of the implied strategies.

CHAPTER FIVE: CONCLUSION & RECOMMENDATION

5.1 CONCLUSION

As in the case company, Inability of a company to prevent high downtime and downtime frequencies could mean a loss in a considerable amount of profit. A reactive system from frequent breakdowns and piled up problems pins down management to focus on firefighting rather than prevention.

Downtimes and downtime frequencies for each set of machine was first identified through analyzing the data from the ERP system on each utility system. Data was sorted out in the analysis chapter with the aid of AHP tool to prioritize the main losses. Each machine system's downtime and downtime frequency were listed to find out the system with the highest downtime impact. The electric supply system and the HP compressor were found to have the most impact with the highest downtime coverage of 70.9% of the total time analyzed, making them the main areas with the most focus.

From the mentioned listed findings on the downtimes and downtime frequencies, the research proceeds to selecting a maintenance strategy and maintenance policy for each system via the use of the DMG tool from the input gained from the downtime and downtime frequency. The results from the tool's layout clearly put forward a strategy and policy to be followed for each set of machine.

Finally, the introduction of the AHP and Pareto data filter system for the DMG tool has been successful, as was the DMG introduction for continuously operated utility systems implying the possibility of using the maintenance strategy selection tool of DMG on a new operation system. The analysis results matching the reality on the ground where a case in point being the D.O.M strategy laid out by the analysis result for the worse performing utility plants is a main indication.

Furthermore the strategies selected for each sub plant and a continued use of this tool is expected to save 39 million birr and 26,106,000 bottles worth of production time. This estimate is considered to bring the new downtime rate of the department to an acceptable level of 0.92%, which is below the company standard of 2.5%. In addition, the ability of the department to follow a strategy on each sub plant empowers the management to switch to a proactive system unlike the old ways of reactive maintenance that focused on breakdowns.

5.2 RECOMMENDATION

Based on the analysis, the researcher recommends the implementation of the maintenance strategies in each set of plants. The results can be used as a direction pointing to a more structured and organized approach to the maintenance execution process in the utility department.

The implementations allows improvement in machine performance and operational conditions based on the current state of the equipment behavior. It lays forward actions and individual strategies to follow for each sub plant in the department to improve the overall status of the utility plants and their maintenance operation.

The DMG layout clearly indicates where the problem relies. The use of the strategies and policies in actions for each subsequent plant according to the position in the DMG grid allows the focus areas to work on in relation to a strategy policy according to breakdown effect. As in the layout put in analysis, for a highly repetitive, small problems that are usually bedraggled; incapability of the user is mostly the cause where skill levels should be improved in relation to TPM whereas, RCM shall be applied for equipment susceptible to a high degree of failure with high downtimes focusing on equipment.

With the consideration DMG is a continuously improvement tool, the researcher suggests the use of this tool periodically to identify the status of the equipment with regards to their respective downtime and downtime frequencies to further achieve CCBA’s world class standard of 0% Breakdown on utilities.

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34. WWW. TABLEAU.CCBAGROUP.COM

Appendix A: Focus Group Discussion Guideline

Thank you for agreeing to participate in this Focus Group Discussion. I am very interested to hear your valuable opinion regarding the main factors contributing to utilities downtime and your expert input in the maintenance downtime data selection process.

- *The purpose of this study is to collect primary data for a thesis work which is being done as a partial fulfillment of MSc degree in Industrial Engineering.*
- *The Title of the thesis is* Maintenance Strategy Selection for Continuously Operated Beverage Industry Utility Machines: A case Study
- *The main objective of this FGD is to select a set of alternatives which shall be used as a data filter in a maintenance strategy selection process.*
- *The information you give me is completely confidential, and I will not associate your name with anything you say in the focus group.*
- *You may refuse to answer any question or withdraw from the study at any time.*
- *I understand how important it is that this information is kept private and confidential. I will ask participants to respect each other's confidentiality.*
- *If you have any questions or more information now or after you have completed the questionnaire, you can always contact me through my contact details.*

Contact Details: Eskinder Wondwossen

Mobile +251910885636

Email: ewondwossen@ccbagroup.com

Introduction:

1. Welcome
   Researcher Introduction, and sending the Sign-In Sheet with a few quick demographic questions around to the group while

   Review the following:

   - What the researcher is trying to accomplish
   - What will be done with this information
   - Why researcher asked you to participate
   - If you are a supervisor, we would like to excuse you at this time

2. Explanation of the process
   Before starting the discussion, Researcher gives short brief about the AHP tool, and the DMG data selection process and the possible output strategies.

   About focus groups

   - You are the experts in this Department
   - Aim is to identify the major maintenance challenges in all your service years in the department
   - No virtue in long lists: looking for priorities
   - In this research, we are doing both questionnaires and focus group discussions. The reason for using both of these tools is that we can get more in-depth information from a smaller group of people in focus groups. This allows us to understand the context behind the answers given.

   Logistics

   - Focus group will last about one hour
   - Feel free to move around
   - Where is the bathroom? Exit?
   - Help yourself to refreshments

3. Ground Rules
   Ask the group to suggest some ground rules. After they brainstorm some, make sure the following are on the list.

   - Everyone should participate.
   - Information provided in the focus group must be kept confidential
   - Stay with the group and please don’t have side conversations
   - Stick to the subject matter
   - Turn off cell phones if possible
   - Have fun

4. Ask the group if there are any questions before we get started, and address those questions.

5. Introductions
    - Go around table: job here, where you were born

Discussion begins, make sure to give people time to think before answering the questions without moving too quickly. Use the probes to make sure that all issues are addressed, but move on when starting to hear repetitive information.

Discussion.

That concludes our focus group. Thank you so much for coming and sharing your thoughts and opinions with us. We have a short evaluation form that we would like you to fill out if you time. If you have additional information that you did not get to say in the focus group, please feel free to write it on this evaluation form.

Materials and supplies for focus group discussion

- Sign-in sheet
- Consent forms (one copy for participants, one copy for the team)
- Relative Importance Nine Scale Point Sheet for each participant
- Pads & Pencils for each participant
- Focus Group Discussion Guide for Facilitator
- Notebook for note-taking
- Refreshments
- 55’’ Screen to assist in alternative selection and ranking
- Laptop
- Digital table to put down the alternatives
- Digital table to perform the alternative ranking

Appendix B: Focus group Participatory Demographic Questionnaire

Please answer the following questions in the spaces provided, circle or tick the most appropriate options.

1. Do you agree to participate in this FGD? ☐ Yes ☐ No

2. What is your professional background?

   □ Mechanical Engineering

   □ Electrical Engineering

   □ Other (please describe)

   ____

3. What is your position and job in the company?

   ____

4. How many years of experience have you had in CCBA?

   □ <1 Year □ 1-2 Years

   □ 2-5 Years □ 5-10 Years

   □ >10 Years

5. How many years of experience do you have in CCBA's Utilities department?

   □ <1 Year □ 1-2 Years

   □ 2-5 Years □ 5-10 Years

   □ >10 Years

Thank you for taking the time to complete this questionnaire

Appendix C: Guiding Questions for Discussion

1. Do you believe there is a problem regarding the maintenance effectiveness in the utility department? Please state reasons.
2. Thinking back to all your years of experience in the department, what were the major challenges resulting in the experienced high downtimes?
3. What do you think about maintenance strategies? Would you believe implementing a strategy would actually assist you?
4. AHP as a tool is composed of Goal, Criteria and Alternatives. In this case the goal is to select a data filter for the DMG tool where the criteria are taken directly from the IPR document. As an experts, what shall be put as alternatives to select the data to be considered in the DMG?
5. As an expert group, please rank the alternatives based on Downtime losses.
6. As an expert group, please rank the alternatives based on Equipment losses.
7. As an expert group, please rank the alternatives based on Performance losses.
8. As an expert group, please rank the alternatives based on Quality losses.