Development of an Excel Based Spreadsheet of Analytical Hierarchy Process And Decision Making Grid For Maintenance Policy Decision

by

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Dissertation Submitted In Partial Fulfilment Of The Requirements For The Bachelor Of Engineering (Hons)
(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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Approved by,

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(Dr. Masdi bin Muhammad)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

SEPTEMBER 2013

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or person

AHMAD NADZRIN SHAH BIN SALLAHUDDIN

ABSTRACT

Maintenance policies are created to fulfill the company needs to ensure smooth and continuous operation. In Lean Manufacturing, the importance of an effective maintenance program cannot be overlooked. Since most of the industries used machinery in their plant, of course there must be proper maintenance to ensure continuous production and smooth operation. Maintenance policies such as Preventive Maintenance (PM), Corrective Maintenance (CM) and Condition Based Maintenance (CBM) are widely used as a way to solve maintenance problems. Maintenance selection can be very hard and complex when there are a lot of criteria that need to be considered since their importance are nearly significant to each other. Selecting the proper maintenance strategy can ensure high system's reliability and availability. Decision Making Grid (DMG) and Analytical Hierarchy Process (AHP) are often used to identify strategies for maintenance decision. Automation using these methods through specialized software is very costly. Therefore, a cheaper alternative is needed. Two Excel spread sheets are developed by applying the formula for calculating AHP and DMG. One of the main objective of this project is to produce an integrated decision making tool depending on available data and depth of analysis. Validation is done by inserting data from selected research papers then compared to their actual value which is obtained from the datum. For DMG model, after inserting the inputs, the results are displayed on the DMG grid view. Based from the validation of data using case studies, it can be found that some of the actual data from the paper has inaccurate and incorrect results due to mistakes in calculations. Others are validated and both the tools and case studies produced the same result. Therefore, the tools are ready to use. If all of the steps for the development of the spread sheet are followed, the best maintenance policy can be selected by using both of these models. The user can select either to choose AHP or DMG as their decision making tool.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Project Background

A lot of companies think of maintenance as an inevitable source of cost. Therefore, they created maintenance policies in order to fulfil the company needs such as profits and productivity.

In Lean Manufacturing, the importance of an effective maintenance program cannot be overlooked. As in personal health care insurance, maintenance may be considered the health care of our manufacturing machines and equipment. In order to effectively reduce waste and run an efficient, continuous manufacturing operation, maintenance is required. Regular maintenance can be in small cost when it is compared to the cost of a major breakdown at which time there is no production.

The main purpose of maintenance is to ensure that all equipment required for production is operating at 100% efficiency at all times. Through short daily inspections, cleaning, lubricating, and making minor adjustments, minor problems can be detected and corrected before they become a major problem that can shut down a production line. A machine's breakdown true cost is sometimes difficult to measure. A recent survey showed that the cost for a machine breakdown is more than just the maintenance labor and materials to make the repair. A recent survey showed the actual cost for a breakdown between four to fifteen times the maintenance costs. When the breakdown causes production to stop, the costs are very high because no parts are being produced. Maintenance policies such as Preventive Maintenance (PM), Corrective Maintenance (CM) and Condition Based Maintenance (CBM) are created as a way to solve problems regarding these uncertainties. The right maintenance policy is needed to ensure that it provides the best maintenance in terms of quality, cost and time.

Since there are a lot of criteria that needs to be considered in order for us to decide the best maintenance policy, optimizations of important criteria such as cost, failure rates, and time to repair are very crucial in determining the best maintenance policy. Methods such as making a Decision Making Grid (DMG) and Analytical Hierarchy Process (AHP) are often being used as tools to select the best maintenance policy. AHP is a decision-making procedure originally developed by Saaty in the 1970s [3]. This is a structured technique for organizing and analyzing complex decisions. This project will be focusing on developing Excel spread sheets of the AHP and DMG models.

1.2 Problem Statement

Maintenance selection can be very hard and complex when there are a lot of criteria such as cost, time, and manpower need to be considered since their importance are nearly significant to each other. Selecting the proper maintenance strategy can ensure high system's reliability and availability. Since there are various maintenance strategies created and they are often used without being properly selected, the maintenance decision is left being not optimized due to multiple criteria that need to be evaluated. A Decision Making Grid (DMG) and Analytical Hierarchy Process (AHP) are often used to identify strategies for maintenance decision. Though these methods are popularly used already, automation using these methods through specialised software is very costly. Therefore, a cheaper alternative is needed.

1.3 Objectives

This project will produce two independent decision making tools. The user can decide to either use AHP or DMG for their maintenance analysis.

The objectives of this project are:

1) To produce an integrated decision making tool depending on available data and depth of analysis
2) To produce Analytical Hierarchy Process tool specifically for maintenance policy decision.
3) To develop a DMG model based on maintenance policy. The user can insert maintenance data and view their output on a DMG model.
4) To select the best maintenance policy for equipment or system from a set of possible alternatives.

1.4 Scope of Study

This project is using two decision making tools which are AHP and DMG. For AHP tool, the examples of the types of maintenance policy covered are Preventive Maintenance, Corrective Maintenance and Condition Based Maintenance. As for the DMG tool, the maintenance policies that is available are Operate To Failure (OTF), Fixed Time Maintenance (FTM), Condition Based Maintenance (CBM), Skill Level Upgrade (SLU) and Design Out Maintenance (DOM).

1.5 Relevancy and Feasibility of Project

AHP and DMG have been widely used around the world as decision making tools. A lot of criteria need to be considered. So, to perform AHP or DMG manually can be very tedious. The purpose of making this project is to give the user to have access on performing AHP and DMG in an excel spread sheet while saving cost of not buying expensive decision making tool softwares.

CHAPTER 2

LITERATURE REVIEW

2.1 Background of Study

Decision Making Grid and Analytical Hierarchy Process

The use of decision making tools is widely used in today's rapidly expanding industries. Since all plant use machines and equipment for their production, they need to have a system that actually can help in decision making. The deterioration and failure of systems might lead to excessive maintenance cost and production losses [1]. Furthermore, there can also be unplanned intervention on the system and safety hazards. In relative to these problems, an appropriate maintenance policy strategy is necessary in order to replace the deteriorated system before failure [2]. While DMG only covers two factors which are downtime and frequency of failure, AHP can be used to widen the selection range of criteria. AHP is a decision-making procedure originally developed by Saaty in the 1970s [3]. By incorporating AHP into industrial maintenance policy selection, we can make a decision by inputting quality and quantity data into formulas by constructing pairwise comparisons. The process requires the user to give weightage to those qualitative data. A matrix is then created after determining the measure of importance of the criteria and the weightage of the scores are obtained after normalizing the matrix and tested for consistency using the Eigenvector Method. Since there is not always a solution to the linear equations, there has been criticism by decision analyst on the use of AHP mainly based on the lack of normative foundation and on possible ambiguity of the questions the decision makers must answer [4,5]. The computational requirement is tremendous even for a small problem. But, we know that it considers either objective or subjective considerations or either quantitative or qualitative information and any level of details about the main focus can be listed or structured in this method. By this way the overview of the main focus or the problem can be represented very easily.

2.2 Types of Maintenance

What is maintenance and why is there a lot of type of maintenance? Past and current maintenance practices in both the private and government sectors would imply that maintenance is the actions associated with equipment repair after it is broken [6]. Maintenance can be define as “the work of keeping something in proper condition; upkeep.” This would imply that maintenance should be actions taken to prevent a device or component from failing or to repair normal equipment degradation experienced with the operation of the device to keep it in proper working order. There are three types of maintenance that has been generally applied over the last 30 years. They are corrective maintenance, condition based maintenance, and preventive maintenance.

2.2.1 Corrective Maintenance

Corrective maintenance has been known as the “run it till it breaks” maintenance mode. There will be no actions taken to maintain the equipment since it is only design to meet its expected life. The referenced study breaks down the average maintenance program as follows:

- >55% Corrective
- 31% Preventive
- 12% Predictive
- 2% Other.

Note that more than 55% of maintenance resources and activities of an average facility are still corrective. Corrective maintenance is known to have minimal cost of operation. If the maintenance program is purely corrective, we will not spend manpower dollars or incur capital cost until something breaks. Since we do not see any associated maintenance cost, we could view this period as saving money [7, 8].

Corrective maintenance is applied to items whose conditions cannot be monitored and for which the cost of applying corrective maintenance is less than the cost of applying time based maintenance. However, failure of an item can occur at a time, which is inconvenient to both the user and the operator. Significant costs can be incurred obtaining emergency manpower and very often it is difficult to obtain spare parts at short notice possibly could lead to unplanned shutdown of operations.

2.2.2 Time Based Maintenance (Preventive Maintenance)

Time Based maintenance is a part of preventive maintenance where it performed on a time- or machine-run-based schedule that detect, preclude, or mitigate degradation of a component or system with the aim of sustaining or extending its useful life through controlling degradation to an acceptable level [7].

Although this cannot provide optimum maintenance result, it does have several advantages over that of a purely corrective program. By performing the preventive maintenance as the equipment designer envisioned, we will extend the life of the equipment closer to design. This translates into dollar savings. Preventive maintenance (lubrication, filter change, etc.) will generally run the equipment more efficiently resulting in dollar savings.

2.2.3 Condition Based Maintenance

Condition Based maintenance can be defined as measurements that detect the onset of system degradation (lower functional state), thereby allowing causal stressors to be eliminated or controlled prior to any significant deterioration in the component physical state. Results indicate current and future functional capability [9].

The difference between condition based and preventive maintenance is condition based maintenance is done by inspecting the actual condition of the machine then proceed to maintenance rather than give time allocation or schedule for maintenance (preventive). For example, if preventive maintenance, no concern is given to the actual condition and performance capability of the oil. It is changed because it is time. Whereas on the other hand, the operator of the car discounted the vehicle run time and had the oil analyzed at some periodicity to determine its actual condition and lubrication properties, he/she may be able to extend the oil change until the vehicle had traveled 10,000 miles. This is the fundamental difference between condition based maintenance and preventive maintenance, whereby condition based maintenance is used to define needed maintenance task based on quantified material/equipment condition [10].

Table 2.2.1: Advantages and disadvantages of the types of maintenance

	Advantages	Disadvantages
Corrective Maintenance		Increased cost due to unplanned downtime of equipment.
	Low cost.	Increased labor cost, especially if overtime is needed
	Less staff.	Cost involved with repair or replacement of equipment.
		Possible secondary equipment or process damage from equipment failure.
		Inefficient use of staff resources.
Time Based Maintenance	Cost effective in many capital-intensive processes.	Catastrophic failures still likely to occur.
	Flexibility allows for the adjustment of maintenance periodicity.	Labor intensive.
	Increased component life cycle.	Includes performance of unneeded maintenance.
	Energy savings.	Potential for incidental damage to components in conducting unneeded

		maintenance.
	Estimated 12% to 18% cost savings over reactive maintenance program.	
	Reduced equipment or process failure.	
Condition Based Maintenance	Increased component operational life/availability.	Savings potential not readily seen by management.
	Allows for preemptive corrective actions.	Increased investment in staff training.
	Decrease in equipment or process downtime.	Increased investment in diagnostic equipment.
	Decrease in costs for parts and labor.	
	Better product quality.	
	Improved worker and environmental safety.	
	Improved worker morale.	
	Energy savings.	
	Estimated 8% to 12% cost savings over preventive maintenance program.	

2.3 Theory (Analytical Hierarchy Process)

The first stage in applying AHP method in this project is to develop an AHP hierarchical framework which shows a systematic overview of the relationship between the project goal or objective and the set of criteria and alternatives related to it [3].

AHP is a method for formulating and analysing decisions. It uses four steps in solving a problem [25]. The first step involves structuring of the decision into a hierarchical model. This includes the categorizing the problem into elements according to their common characteristics and forming a hierarchical model at different levels. Every level corresponds to the common characteristic of the elements in that level. The top level represents the main goal or focus of the problem. The middle levels correspond to the criteria and sub-criteria, while the lowest level contains the decision alternatives. The elements of a particular level are compared pair-wise with respect to a specific element in the immediate upper level in the second step. A comparison matrix is formed and used for computing the priorities of the corresponding elements. First, criteria are compared pair-wise with respect to the goal. A comparison matrix, denoted as A, will be formed using the comparisons. Each entry (a_{ij}) of the comparison matrix is formed comparing the row element (A_i) with the column element (A_j):

$A = (a_{ij})$ (i,j = 1,2, ..., the number of criteria)

The comparison of any two criteria, C_i and C_j, with respect to the goal is made using questions such as, "Of the two criteria C_i and C_j which is more important with respect to the best alternative, and how much more?" Saaty [3] suggested the use of a nine-point scale to transform verbal judgments into numerical quantities, representing the values of a_{ij}. The scale is explained in Table 2.3.1.

Table 2.3.1: Relative Importance Measurement Scale

Importance Intensity	Definition
1	Equal importance
3	Weak importance
5	Moderate importance
7	Strong importance
9	Extreme importance
2,4,6,8	Intermediate values

The entries in a_{ij} are governed by the following rules:

$$a_{ij}. > 0; a_{ii} = 1 \text{ for all } i$$

If a_{ij} is the element of row i column j of the matrix, then the lower diagonal is filled using this formula:

$$a_{ji} = 1/ a_{ij}$$

The comparison matrix A will be a positive reciprocal pair-wise comparison matrix because of the rules. Below are the examples of the matrix based from rules:

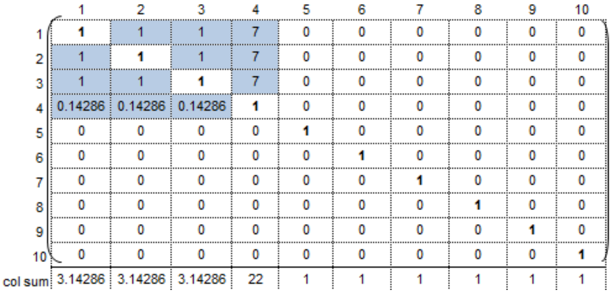
$$\begin{array}{cc} & \text{Criteria} \\ A = \quad \text{Criteria} & \begin{array}{c|ccccc|} & 1 & 2 & 3 & 4 & 5 \\ 1 & 1 & a_{12} & a_{13} & a_{14} & a_{15} \\ 2 & 1/a_{12} & 1 & a_{23} & a_{24} & a_{25} \\ 3 & 1/a_{13} & 1/a_{23} & 1 & a_{34} & a_{35} \\ 4 & 1/a_{14} & 1/a_{24} & 1/a_{34} & 1 & a_{45} \\ 5 & 1/a_{15} & 1/a_{25} & 1/a_{35} & 1/a_{45} & 1 \end{array} \end{array}$$

Figure 2.3.1: Pairwise Comparison Matrix

After constructing the comparison matrix of comparisons of criteria with respect to the goal, the next step is to obtain the local priorities of criteria by normalizing the matrix. Given pairwise comparison from example in Figure 2.3.2, we sum each column of the reciprocal matrix.

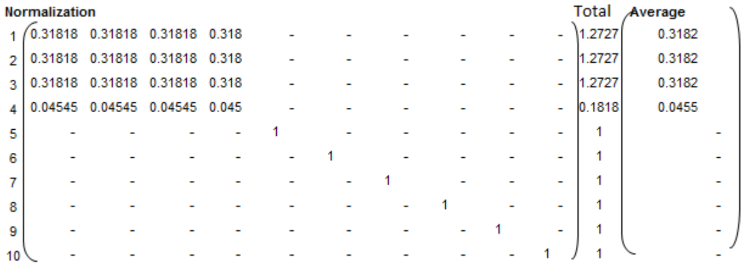
Then we divide each element of the matrix with the sum of its column, we have normalized relative weight. The sum of each column is 1. The normalized matrix is shown in Figure 2.3.3.

The normalized principal Eigen vector can be obtained by averaging across the rows.



	1	2	3	4	5	6	7	8	9	10
1	1	1	1	7	0	0	0	0	0	0
2	1	1	1	7	0	0	0	0	0	0
3	1	1	1	7	0	0	0	0	0	0
4	0.14286	0.14286	0.14286	1	0	0	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0
6	0	0	0	0	0	1	0	0	0	0
7	0	0	0	0	0	0	1	0	0	0
8	0	0	0	0	0	0	0	1	0	0
9	0	0	0	0	0	0	0	0	1	0
10	0	0	0	0	0	0	0	0	0	1
col sum	3.14286	3.14286	3.14286	22	1	1	1	1	1	1

Figure 1.3.2: Summation of matrix columns



Normalization											Total	Average
1	0.31818	0.31818	0.31818	0.318	-	-	-	-	-	-	1.2727	0.3182
2	0.31818	0.31818	0.31818	0.318	-	-	-	-	-	-	1.2727	0.3182
3	0.31818	0.31818	0.31818	0.318	-	-	-	-	-	-	1.2727	0.3182
4	0.04545	0.04545	0.04545	0.045	-	-	-	-	-	-	0.1818	0.0455
5	-	-	-	-	1	-	-	-	-	-	1	-
6	-	-	-	-	-	1	-	-	-	-	1	-
7	-	-	-	-	-	-	1	-	-	-	1	-
8	-	-	-	-	-	-	-	1	-	-	1	-
9	-	-	-	-	-	-	-	-	1	-	1	-
10	-	-	-	-	-	-	-	-	-	1	1	-

Figure 2.3.3: Normalized Matrix

The normalized principal Eigen vector is also called priority vector. Since it is normalized, the sum of all elements in priority vector is 1. The priority vector shows relative weights among the things that we compare. Aside from the relative weight, we can also check the consistency of the answer. To do that, we need what is called Principal Eigen value. Principal Eigen value is obtained from the summation of products between each element of Eigen vector and the sum of columns of the reciprocal matrix. Generally, it has been agreed that priorities of criteria can be estimated by finding the principal Eigen vector *w* of the matrix A:

$$Aw = \lambda_{max} w$$

When the vector *w* is normalized, it becomes the vector of priorities of the criteria with respect to the goal: λ_{max} is the largest eigenvalue of matrix A, and the corresponding eigenvector *w* contains only positive entries.

The consistency of the comparison matrix can be determined by the measure called consistency ratio (CR), defined as:

$$CR = CI/RI$$

Where CI is the consistency index and RI the random index. Cl is defined as:

$$CI = \frac{\lambda \max - n}{n - 1}$$

CI is the consistency index of a randomly generated reciprocal matrix from the nine-point scale. If the CR of the matrix is high, this means that the input judgments are not consistent, and hence not reliable. In general, a consistency ratio of 0.10 or less is considered acceptable. Using a very similar procedure, the local priorities of alternatives with respect to each criterion can be estimated. Once the local priorities of elements of the different levels are available as outlined in the previous step, they are then aggregated to obtain the final priorities of the alternatives.

For calculating the overall weight, the following is used:

Final priority of alternative 1 =

$$\sum \begin{pmatrix} (Local\ priority\ of\ alternative\ 1\ with\ respect\ to\ Ci) \\ (Local\ priority\ of\ Ci\ with\ respect\ to\ the\ goal) \end{pmatrix}$$

The final priorities obtained thus represent the rating of the alternatives in achieving the focus of the problem. According to AHP design, the process is presented in three levels. Level one represents the goal which is to select the best maintenance policy. The second level represents the different selection criteria, followed by the alternatives in the lower level. From the second and third levels, the best maintenance policy is selected.

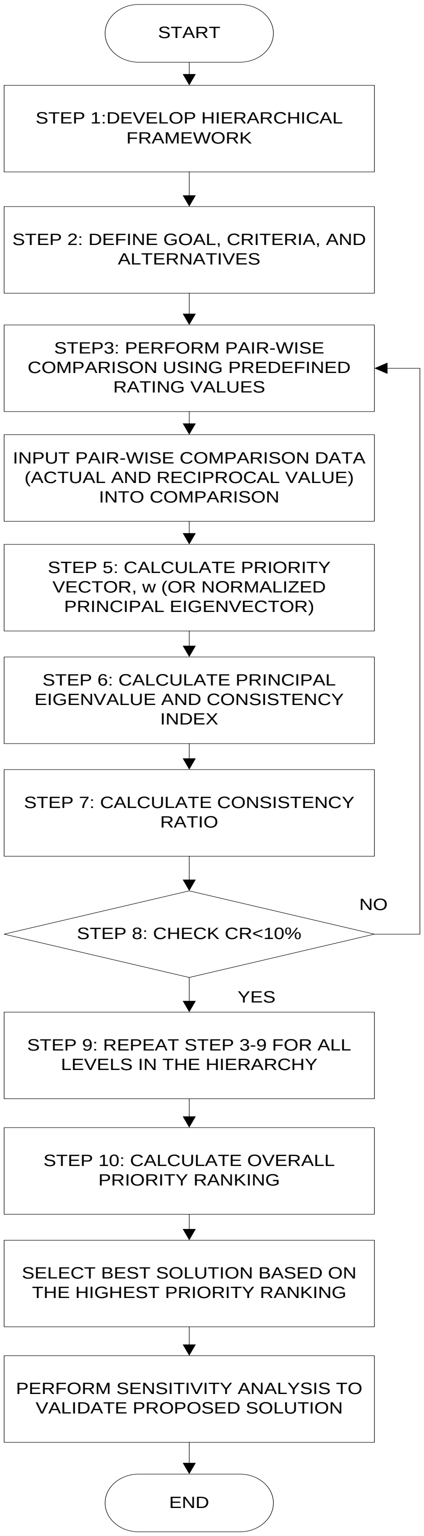


Figure 2.3.4: AHP Model Procedure [3]

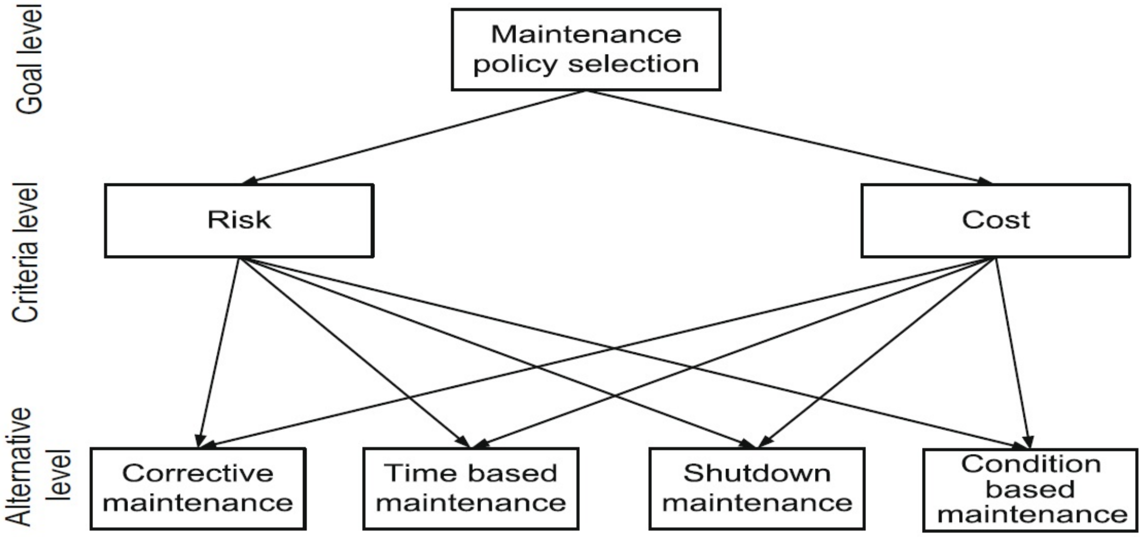


Figure 2.3.5: Hierarchical framework of decision problem in selecting the best maintenance policy.

The basic AHP structure can be demonstrated like a tree, where there are several sections or levels. The top level (level 1) is the project goal or objectives which in this case is the best decision for maintenance policy. Level 2 will be our main criteria or simply the factors that influenced our goal. Level 3 is alternative level where four types of maintenance policy are the decisions that need to be evaluated as the end results. The lines are connected to link all the information within the framework indicating their relationship with each other. The basic three level hierarchical structures can be furthermore expanded by adding a dedicated level for sub-criteria as demonstrated by Hambali et al. [13]. However, as stated by Al-Harbi [14], further expansion of the AHP structure for large evaluations required a longer analysing time and can somewhat be a burden. In this case, the purpose of proposing the AHP and DMG model to be developed in an excel spread sheet is to ease the burden of calculating all the criterion matrix using the appropriate formula. The user can somehow insert the inputs and obtain their decision form the excel spread sheet.

2.4 Decision Making Grid (DMG)

Reference [21] defined DMG as a control chart in itself in two-dimensional matrix forms. The columns of the matrix show the three criteria of the downtime, while the rows of the matrix show another three criteria of the frequencies of the failures. A better maintenance model for quality management can be formed, by handling both the rows and columns of the matrix, respectively. The matrix offers an opportunity to decide what maintenance strategies are needed for decision making, such as to practice OTF, FTM, SLU, CBM, or DOM. The matrix can also be used to decide what maintenance concepts are useful for each defined cell of the matrix, such as the TPM or RCM approaches.

Computerized Maintenance Management System (CMMS) have been used in many applications. This system is a software program that is applied to control activities and resources and also administrate and report actions. Effectiveness and efficiency of activities related to maintenance can be increased using the proper analysis and proper data collection system which can be acquired through CMMS. The term “Black Hole” exist because CMMS can only provide raw data and they are not being analysed automatically. In order to remove this shortage the concept of DMG is proposed in Reference [21]. It acts as a plan that determines the worst condition of equipment based on two criteria of the time and frequency of failures and proposes proper maintenance and repair policies as a basic solution. The objective of DMG is to determine proper policies that cause equipment’s movement towards improved condition [21]. DMG can also be used as a practical way to obtain continuous improvement. Information obtained by CMMS database is needed to produce the DMG. Below is one of the ways to determine the range for the grid. Let h be the highest value as stated in the list in Reference [23]:

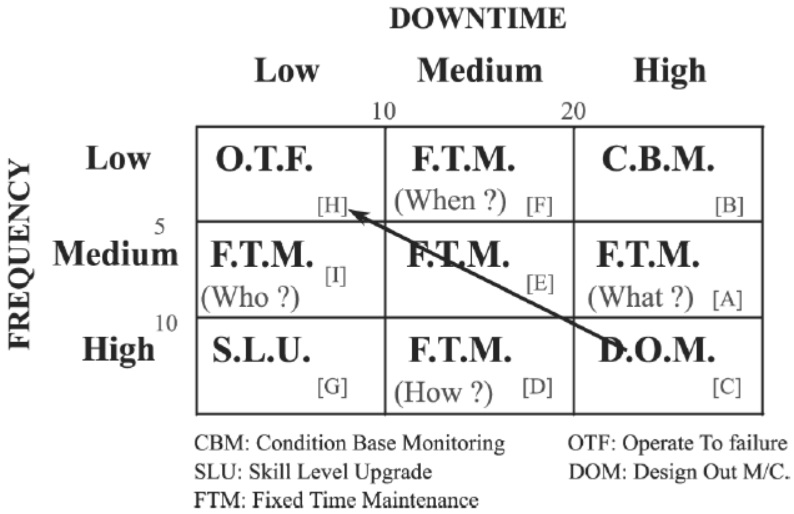
High value = Highest value = h

Highest value = Medium to high value = $h - 1/3$

Highest value = Medium to low value = $h - 2/3$

Low value = Lowest value = 1

Reference [21] suggested that in DMG, downtime can be replaced by Mean Time to Repair (MTTR), and failure frequency can be replaced by Mean time between Failures (MTBF). Considering the point that MTBF and failure frequency have reverse interrelationship, in the DMG of the study (Figure 2.3.6), the reverse of MTBF means failure frequency. It is important to note that in the DMG, all the three groups of addressed grids are included. For example, OTF refers to corrective grid and CBM and TPM are directly located in the grid. In addition, since MTTR and MTBF are the two major indicators of RCM, it seems that this maintenance policy is also included in the grid [17].



	Low	Medium	High
Low	O.T.F. [H]	F.T.M. (When ?) [F]	C.B.M. [B]
Medium	F.T.M. (Who ?) [I]	F.T.M. [E]	F.T.M. (What ?) [A]
High	S.L.U. [G]	F.T.M. (How ?) [D]	D.O.M. [C]

CBM: Condition Base Monitoring
SLU: Skill Level Upgrade
FTM: Fixed Time Maintenance
OTF: Operate To failure
DOM: Design Out M/C.

Figure 2.3.6: DMG layout from Reference [21]

From Reference [21] it is stated that for machine that is located at the top right region, it does not breakdown often (low frequency), but when it does it will lasts for a long time (high downtime). In this case the appropriate action to take is to analyze the breakdown events and closely monitor its condition, i.e. condition base monitoring (CBM). Machine in the bottom-right region is the worst performing machine on both criteria; a machine that maintenance engineers are used to seeing not working rather than performing normal duty such as Machine C. It needs to be structurally modified and major design out projects need to be considered, and hence the appropriate rule to implement will be design out maintenance (DOM). Preventive maintenance schedules are being ruled out for the medium downtime or a medium frequency. However, not all of the “medium” locations are the same. There are some that are near to the top left corner where the work is “easy” fixed time maintenance (FTM) – because the location is near to the OTF region – issues that need to be addressed include who will perform the work or when it will be carried out. For example, the performances of machine I is situated in the region between OTF and SLU and the question is about who will do the job – the operator, maintenance engineer, or subcontractor. Also, the position on the grid of a machine such as F has been shifted from the OTF region due to its relatively higher downtime and hence the timing of tasks needs to be addressed. Other preventive maintenance schedules need to be addressed in a different manner. The “difficult” FTM issues are the ones related to the contents of the job itself. It might be the case that the wrong problem is being solved or the right one is not being solved adequately. In this case machines such as A and D need to be investigated in terms of the contents of their preventive instructions and an expert advice is needed.

CHAPTER 3

METHODOLOGY

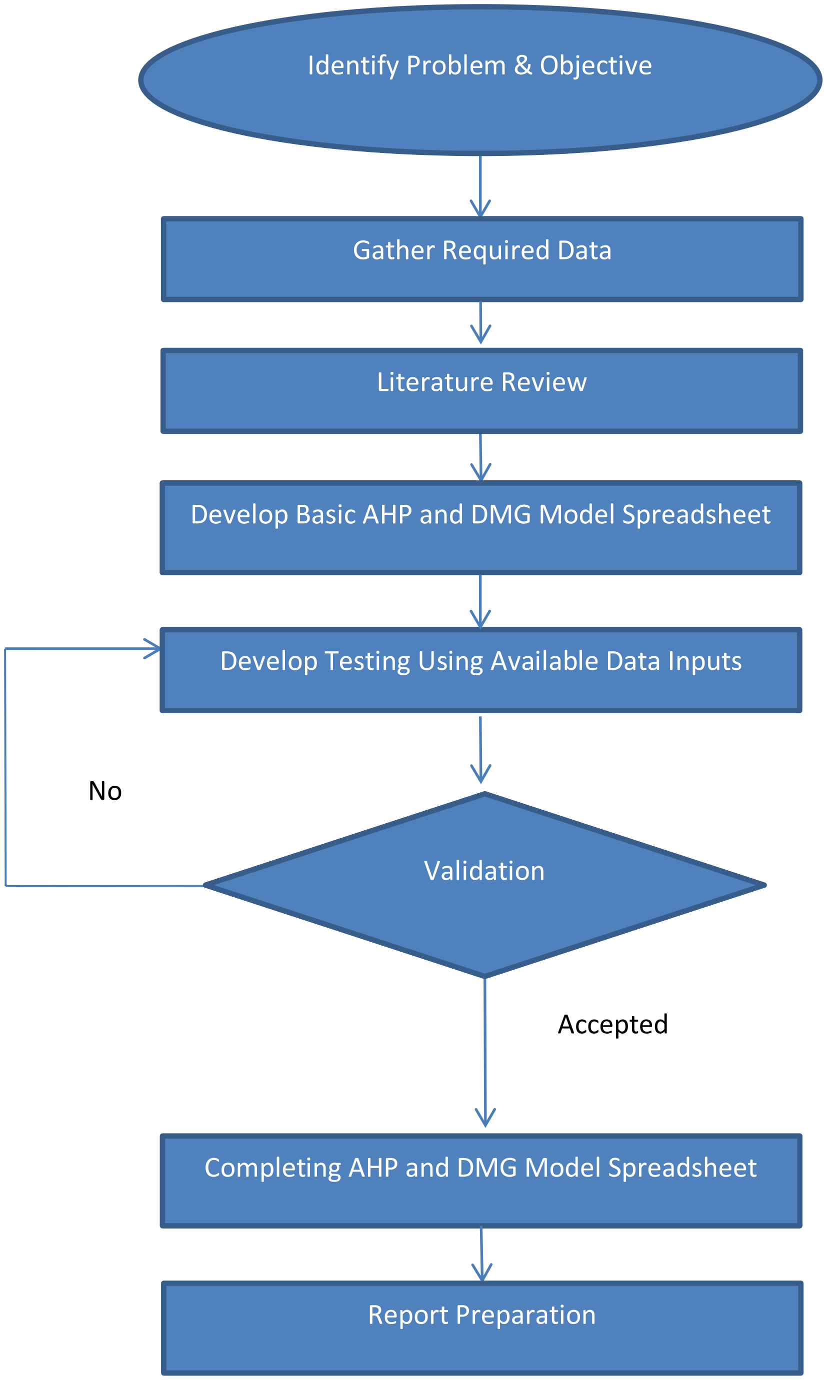


Figure 3.1: Flow Chart

3.1 Project Activities

The project begins by identifying the problem and stating the objectives. After that, the author carried out an extensive study on the project by gathering required data from available journals, articles, books and references. By collecting all these information, the author can understand more about this project especially by referring to past researchers results. A literature review is made based on the findings of all the data from the available sources.

An Excel spread sheet is developed by applying the formula for calculating AHP. The model is modified to accept sub criteria inputs to satisfy the maintenance policy criteria. The validation is done by inputting the data from the selected research papers and the results are then being compared to their actual value which is obtained from the datum. For DMG model, after inserting the inputs, the results are displayed on the DMG grid view where the user can decide the best maintenance policy for the equipment.

After validation, the results will be analyzed. They will then be discussed whether the best decision is made or not. The spread sheet will be completed and more features will be added in the future.

CHAPTER 4

PROJECT RESULTS AND DISCUSSION

Case Studies for AHP model spread sheet

4.1: Case study 1: Using data from Reference [18] to test for global weight scores.

Title: Risk-based maintenance policy selection using AHP and Goal Programming

Objective: Selecting the best maintenance policy for 5C-01 Rerun Column Equipment

Introduction:

Maintenance policy selection is a multiple criteria decision making. The criteria often considered are cost and reliability of maintenance. There has been a growing interest in using risk of accidents as a criterion for maintenance selection. This paper presents an approach of maintenance selection based on risk of equipment failure and cost of maintenance. Analytic hierarchy process (AHP) and goal programming (GP) are used for maintenance policy selection. A case study in a benzene extraction unit of a chemical plant was done. The AHP results show that considering risk as a criterion, condition based maintenance (CBM) is a preferred policy over time-based maintenance (TBM) as CBM has better risk reduction capability than TBM. Similarly, considering cost as a criterion, corrective maintenance (CM) is preferred. However, considering both risk and cost as multiple criteria, the AHP–GP results show that CBM is a preferred approach for high-risk equipment and CM for low risk equipment.

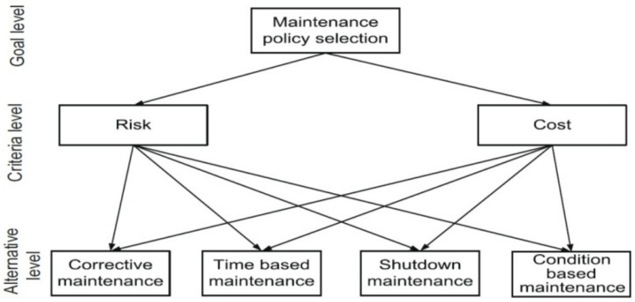
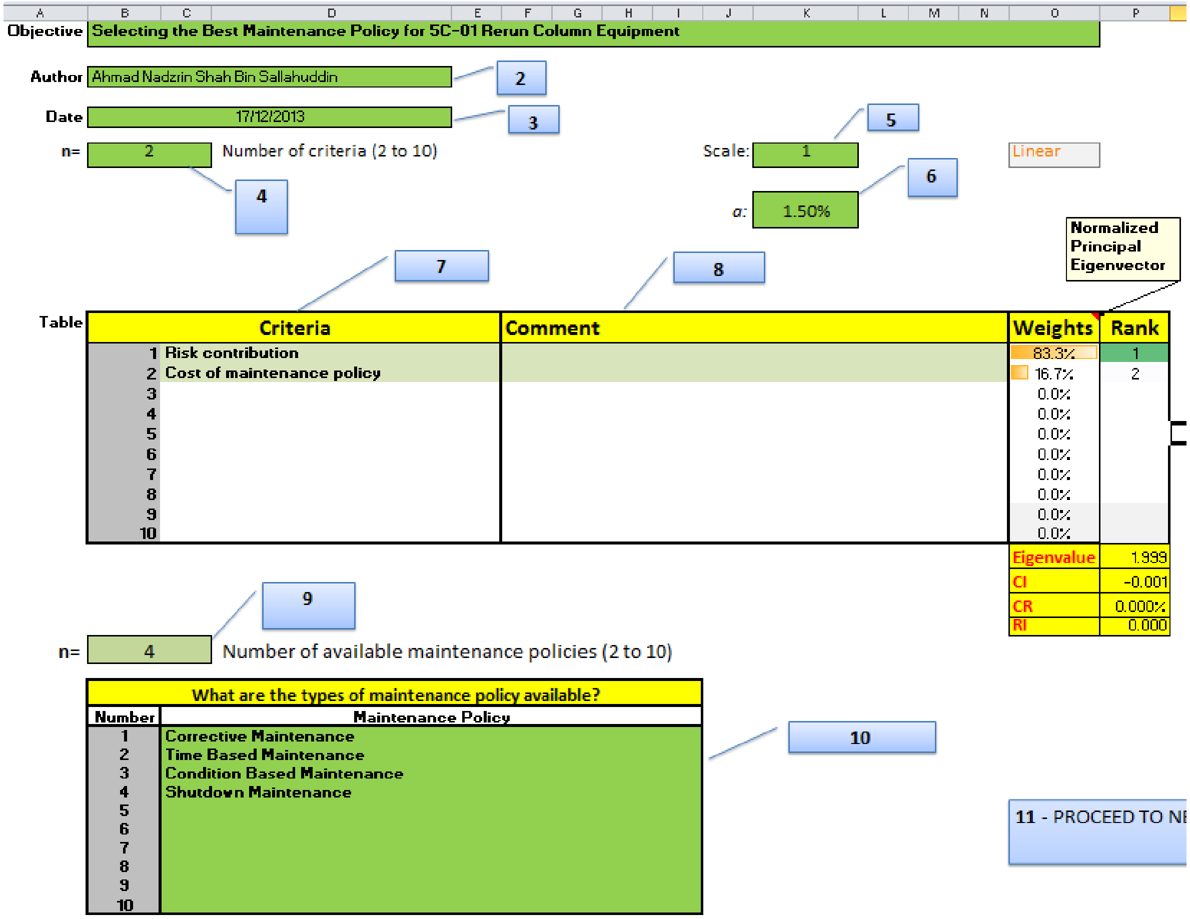


Figure 4.1.1: Hierarchical Framework of Decision Problem in Selecting the Best Maintenance Policy for Reference [18]



Objective Selecting the Best Maintenance Policy for 5C-01 Rerun Column Equipment

Author Ahmad Nadzrin Shah Bin Sallahuddin

Date 17/12/2013

n= 2 Number of criteria (2 to 10)

Scale: 1 Linear

α: 1.50%

Normalized Principal Eigenvector

Table

	Criteria	Comment	Weights	Rank
1	Risk contribution		83.3%	1
2	Cost of maintenance policy		16.7%	2
3			0.0%	
4			0.0%	
5			0.0%	
6			0.0%	
7			0.0%	
8			0.0%	
9			0.0%	
10			0.0%	

Eigenvalue	1.999
CI	-0.001
CR	0.000%
RI	0.000

n= 4 Number of available maintenance policies (2 to 10)

What are the types of maintenance policy available?

Number	Maintenance Policy
1	Corrective Maintenance
2	Time Based Maintenance
3	Condition Based Maintenance
4	Shutdown Maintenance
5	
6	
7	
8	
9	
10	

Figure 4.1.2: Summary page of AHP worksheet

Data is being inserted according to its numbering sequence of the blue callouts instructions:

1 Insert your objective here.

2 Insert your name here.

3 Insert date.

4 Input number of criteria. (From example above, the no. of criteria = 2)

5 Insert the scale of your evaluation.

6 Enter your minimum consistency of acceptance (%)

7 Insert the criteria available for evaluation.

8 Insert any comments regarding the criteria chosen.

9 Insert the number of available maintenance policies. (From example above, the no. of available maintenance policy is 4.

10 Insert the types of maintenance policy available for this evaluation.

For the AHP model, the following data is used:

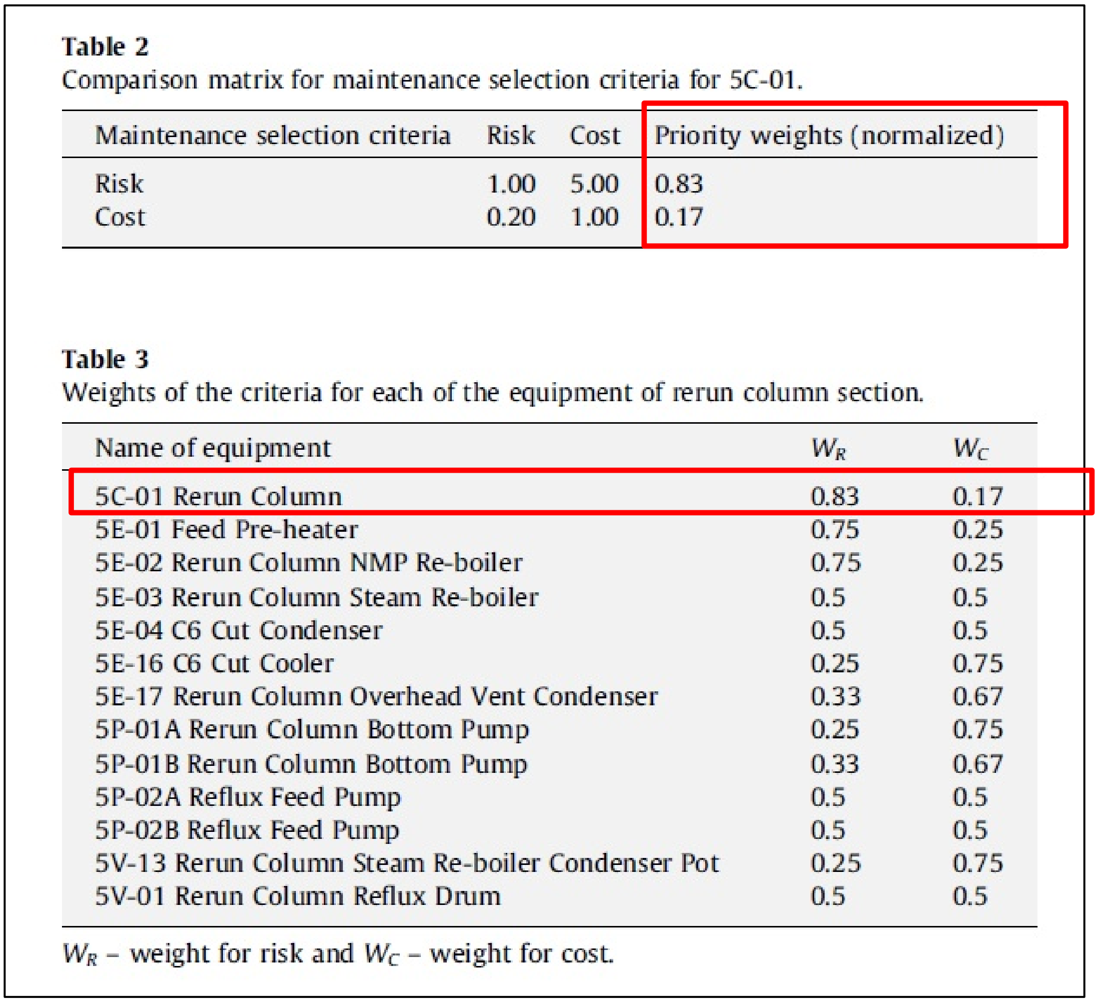


Table 2
Comparison matrix for maintenance selection criteria for 5C-01.

Maintenance selection criteria	Risk	Cost	Priority weights (normalized)
Risk	1.00	5.00	0.83
Cost	0.20	1.00	0.17

Table 3
Weights of the criteria for each of the equipment of rerun column section.

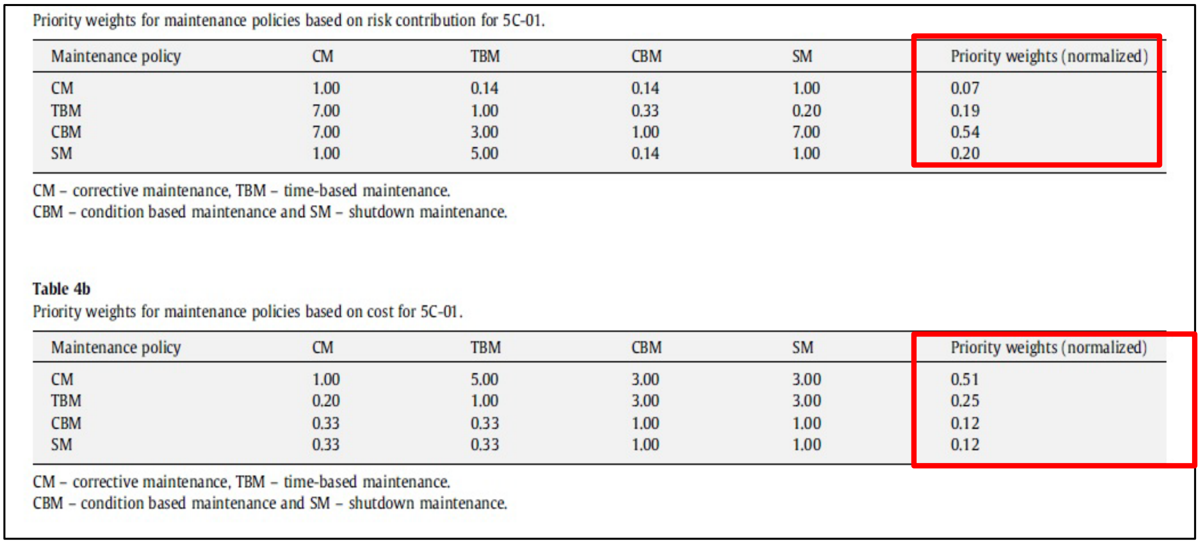
Name of equipment	W_R	W_C
5C-01 Rerun Column	0.83	0.17
5E-01 Feed Pre-heater	0.75	0.25
5E-02 Rerun Column NMP Re-boiler	0.75	0.25
5E-03 Rerun Column Steam Re-boiler	0.5	0.5
5E-04 C6 Cut Condenser	0.5	0.5
5E-16 C6 Cut Cooler	0.25	0.75
5E-17 Rerun Column Overhead Vent Condenser	0.33	0.67
5P-01A Rerun Column Bottom Pump	0.25	0.75
5P-01B Rerun Column Bottom Pump	0.33	0.67
5P-02A Reflux Feed Pump	0.5	0.5
5P-02B Reflux Feed Pump	0.5	0.5
5V-13 Rerun Column Steam Re-boiler Condenser Pot	0.25	0.75
5V-01 Rerun Column Reflux Drum	0.5	0.5

W_R – weight for risk and W_C – weight for cost.

Figure 4.1.3: Comparison Matrix and Weights for Criteria

The selected equipment is the **5C-01 Rerun Column**. Based from **Figure 4.1.3**, the level of importance/scale between two criteria which are risk and cost can be determined. Risk is 5 times more important than cost.

Table 4.1.1 Priority Weights for Risk and Cost



Priority weights for maintenance policies based on risk contribution for 5C-01.

Maintenance policy	CM	TBM	CBM	SM	Priority weights (normalized)
CM	1.00	0.14	0.14	1.00	0.07
TBM	7.00	1.00	0.33	0.20	0.19
CBM	7.00	3.00	1.00	7.00	0.54
SM	1.00	5.00	0.14	1.00	0.20

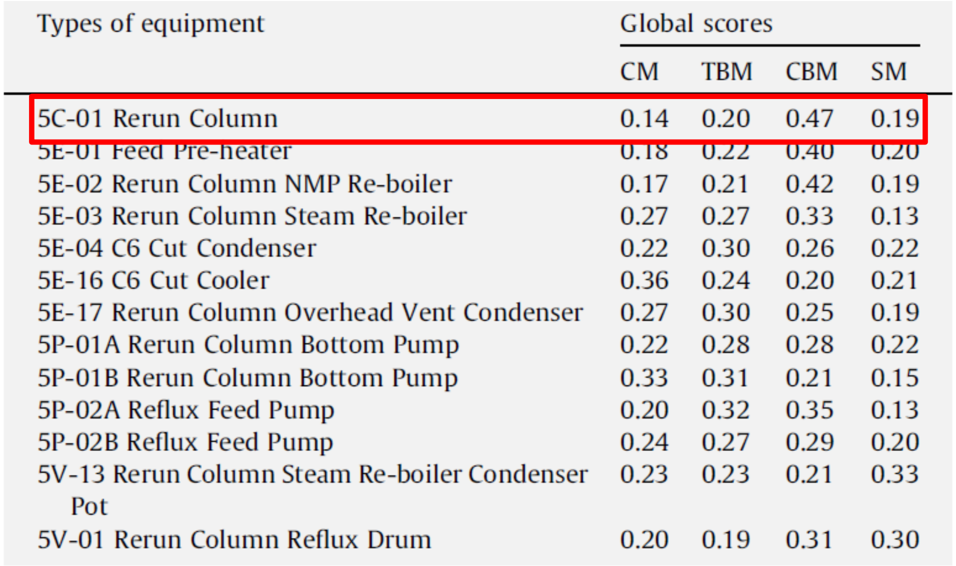
CM – corrective maintenance, TBM – time-based maintenance.
CBM – condition based maintenance and SM – shutdown maintenance.

Table 4b
Priority weights for maintenance policies based on cost for 5C-01.

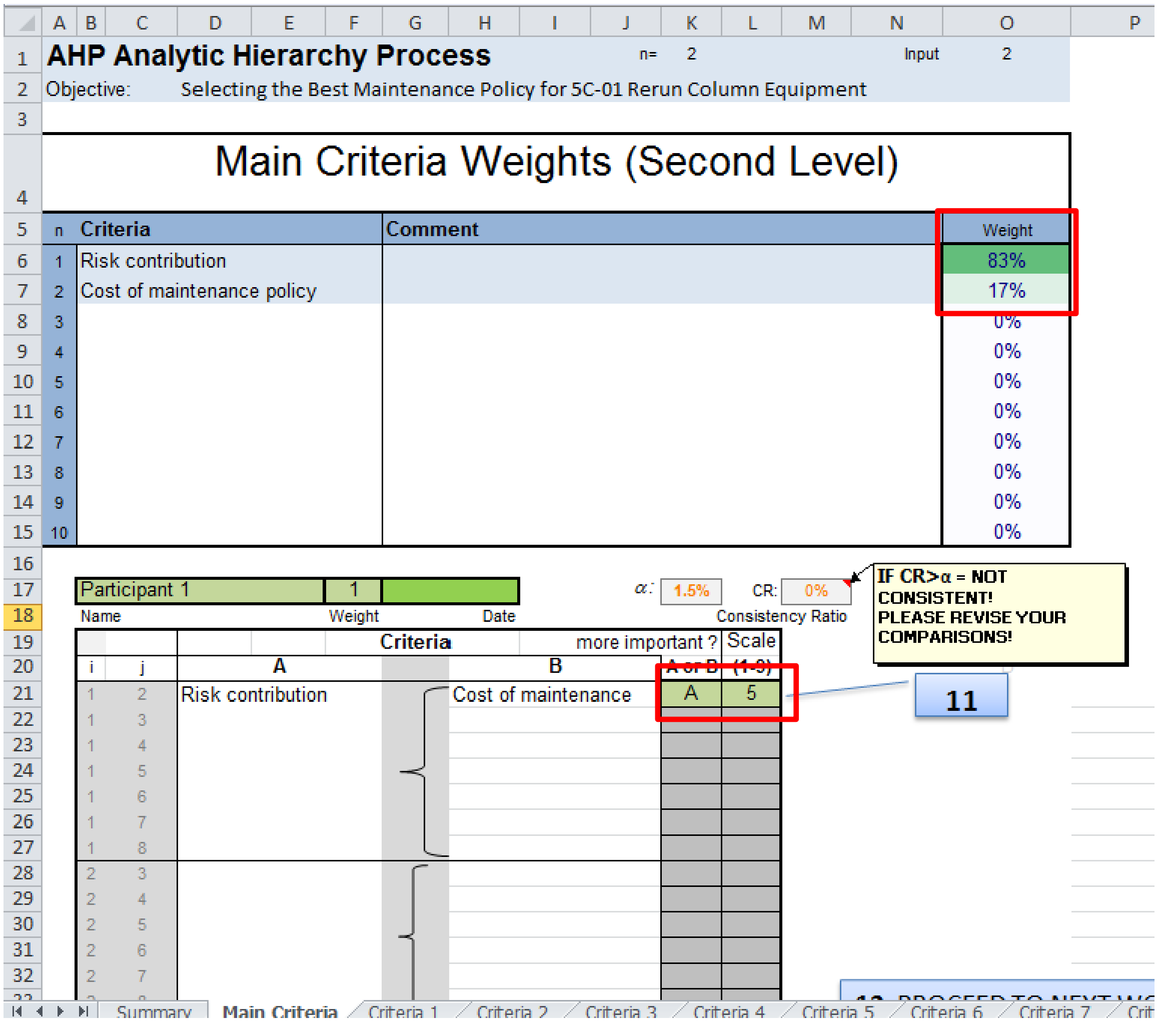
Maintenance policy	CM	TBM	CBM	SM	Priority weights (normalized)
CM	1.00	5.00	3.00	3.00	0.51
TBM	0.20	1.00	3.00	3.00	0.25
CBM	0.33	0.33	1.00	1.00	0.12
SM	0.33	0.33	1.00	1.00	0.12

CM – corrective maintenance, TBM – time-based maintenance.
CBM – condition based maintenance and SM – shutdown maintenance.

Table 1.1.2: Global score for the equipment in the rerun column section



Types of equipment	Global scores			
	CM	TBM	CBM	SM
5C-01 Rerun Column	0.14	0.20	0.47	0.19
5E-01 Feed Pre-heater	0.18	0.22	0.40	0.20
5E-02 Rerun Column NMP Re-boiler	0.17	0.21	0.42	0.19
5E-03 Rerun Column Steam Re-boiler	0.27	0.27	0.33	0.13
5E-04 C6 Cut Condenser	0.22	0.30	0.26	0.22
5E-16 C6 Cut Cooler	0.36	0.24	0.20	0.21
5E-17 Rerun Column Overhead Vent Condenser	0.27	0.30	0.25	0.19
5P-01A Rerun Column Bottom Pump	0.22	0.28	0.28	0.22
5P-01B Rerun Column Bottom Pump	0.33	0.31	0.21	0.15
5P-02A Reflux Feed Pump	0.20	0.32	0.35	0.13
5P-02B Reflux Feed Pump	0.24	0.27	0.29	0.20
5V-13 Rerun Column Steam Re-boiler Condenser Pot	0.23	0.23	0.21	0.33
5V-01 Rerun Column Reflux Drum	0.20	0.19	0.31	0.30



AHP Analytic Hierarchy Process n= 2 Input 2

Objective: Selecting the Best Maintenance Policy for 5C-01 Rerun Column Equipment

Main Criteria Weights (Second Level)

n	Criteria	Comment	Weight
1	Risk contribution		83%
2	Cost of maintenance policy		17%
3			0%
4			0%
5			0%
6			0%
7			0%
8			0%
9			0%
10			0%

Name	Weight	Date
Participant 1	1	

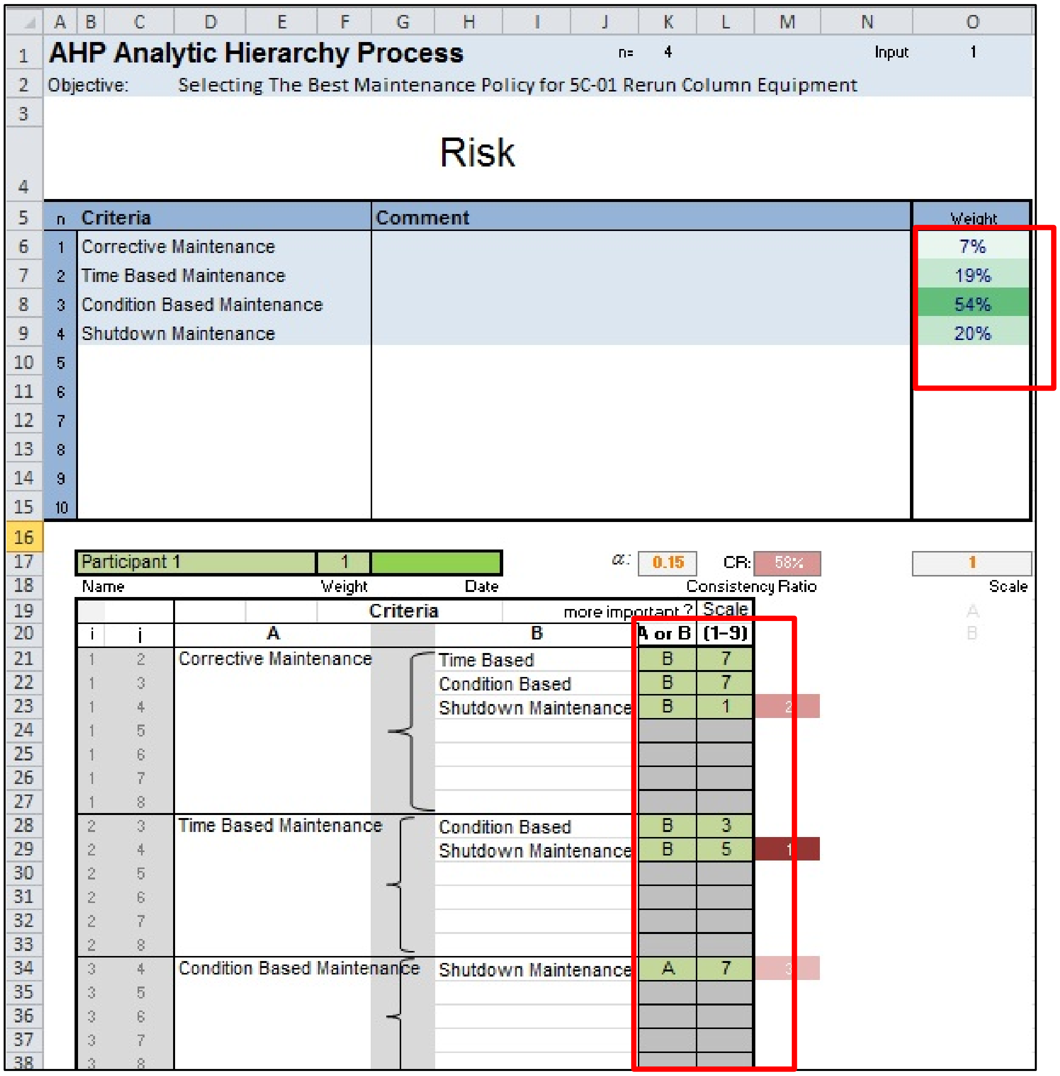
α: 1.5% CR: 0% Consistency Ratio

IF CR>α = NOT CONSISTENT! PLEASE REVISE YOUR COMPARISONS!

		Criteria		more important ?	Scale
i	j	A	B	A or B	(1-9)
1	2	Risk contribution	Cost of maintenance	A	5
1	3				
1	4				
1	5				
1	6				
1	7				
1	8				
2	3				
2	4				
2	5				
2	6				
2	7				

Figure 4.1.4: Second level criteria data input sheet

The level of importance/scale between two criteria which are risk and cost can be determined. Risk is 5 times more important than cost. It is inserted into the spreadsheet in **Figure 4.1.4.**



AHP Analytic Hierarchy Process n= 4 Input 1

Objective: Selecting The Best Maintenance Policy for 5C-01 Rerun Column Equipment

Risk

n	Criteria	Comment	Weight
1	Corrective Maintenance		7%
2	Time Based Maintenance		19%
3	Condition Based Maintenance		54%
4	Shutdown Maintenance		20%
5			
6			
7			
8			
9			
10			

Name: Participant 1 Weight: 1 Date:

α: 0.15 CR: 58% Consistency Ratio

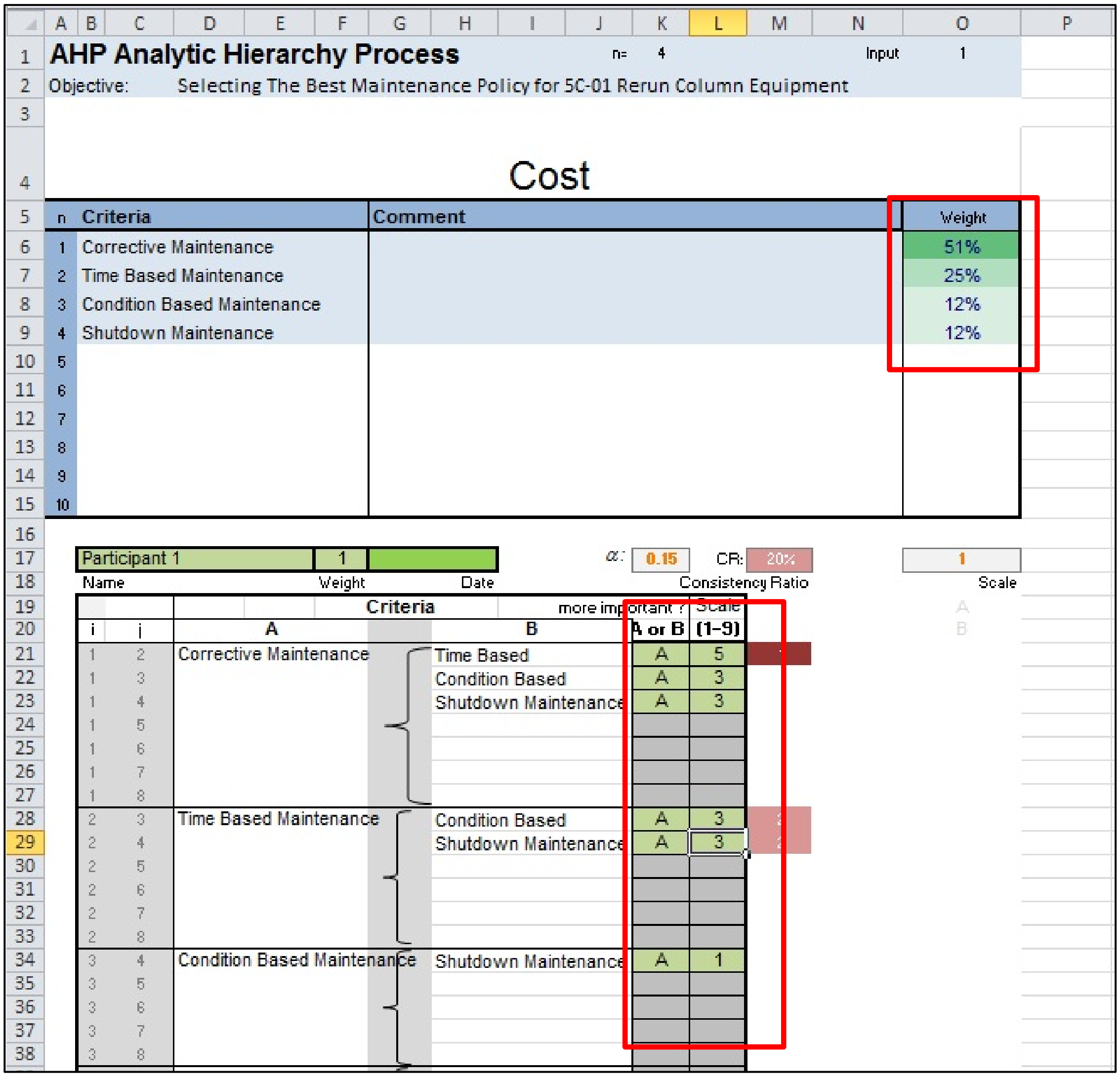
Scale: 1

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	Corrective Maintenance	Time Based	B	7
1	3		Condition Based	B	7
1	4		Shutdown Maintenance	B	1
1	5				
1	6				
1	7				
1	8				
2	3	Time Based Maintenance	Condition Based	B	3
2	4		Shutdown Maintenance	B	5
2	5				
2	6				
2	7				
2	8				
3	4	Condition Based Maintenance	Shutdown Maintenance	A	7
3	5				
3	6				
3	7				
3	8				

Figure 4.1.5: Third level for (alternatives) data input sheet for risk

Risk

From **Table 4.1.1**, the level of importance/scale can be determined. Therefore, the value can be extracted and inserted into the excel spreadsheet. For criteria of risk, time based and condition based maintenance is 7 times more important (less risky) than corrective maintenance. Shutdown maintenance is equally important (same risk) with corrective maintenance. Condition based maintenance is 3 times more important than time based maintenance whereas shutdown maintenance is 5 times more important than time based maintenance. Lastly, condition based maintenance is 7 times more important (less risky) than shutdown maintenance. All the data is then being inserted into the data input sheet as in **Figure 4.1.5**.



AHP Analytic Hierarchy Process n= 4 Input 1

Objective: Selecting The Best Maintenance Policy for 5C-01 Rerun Column Equipment

Cost

n	Criteria	Comment	Weight
1	Corrective Maintenance		51%
2	Time Based Maintenance		25%
3	Condition Based Maintenance		12%
4	Shutdown Maintenance		12%
5			
6			
7			
8			
9			
10			

Participant 1 | Weight: 1 | Date: | α: 0.15 | CR: 20% (Consistency Ratio) | Scale: 1

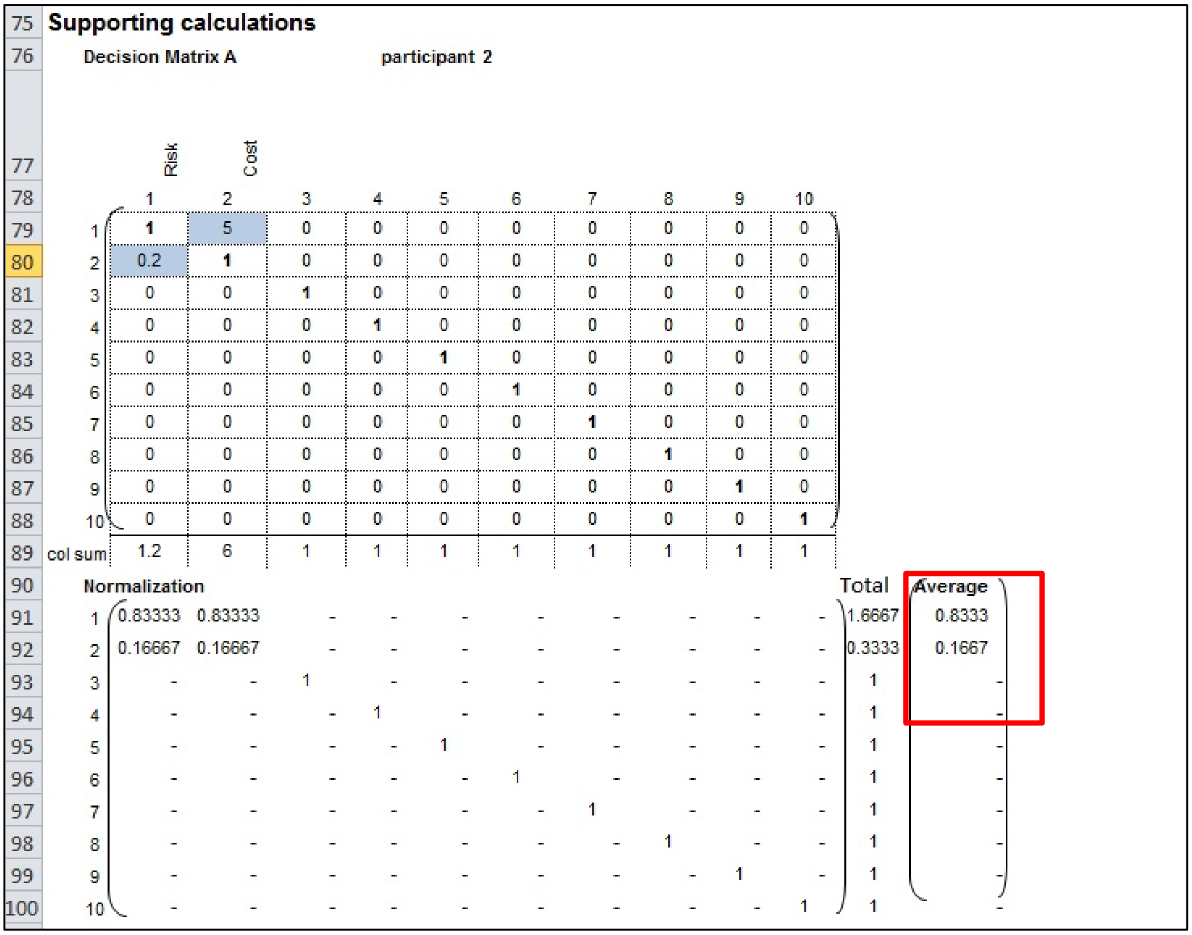
i	j	Criteria A	Criteria B	more important? A or B	Scale (1-9)
1	2	Corrective Maintenance	Time Based	A	5
1	3		Condition Based	A	3
1	4		Shutdown Maintenance	A	3
1	5				
1	6				
1	7				
1	8				
2	3	Time Based Maintenance	Condition Based	A	3
2	4		Shutdown Maintenance	A	3
2	5				
2	6				
2	7				
2	8				
3	4	Condition Based Maintenance	Shutdown Maintenance	A	1
3	5				
3	6				
3	7				
3	8				

Figure 4.1.6: Third level for (alternatives) data input sheet for cost

Cost

From **Table 4.1.1**, the level of importance/scale can be determined. Therefore, the value can be extracted and inserted into the excel spreadsheet. For criteria of cost, corrective maintenance is 5 times more economical than time based maintenance and 3 times more economical than condition based and shutdown maintenance. Time based maintenance is 3 times more economical than condition based and shutdown maintenance. Condition based and shutdown maintenance is equally economical. All the data is then being inserted into the data input sheet as in **Figure 4.1.6**.

Below are the calculation sheets of the AHP analysis:



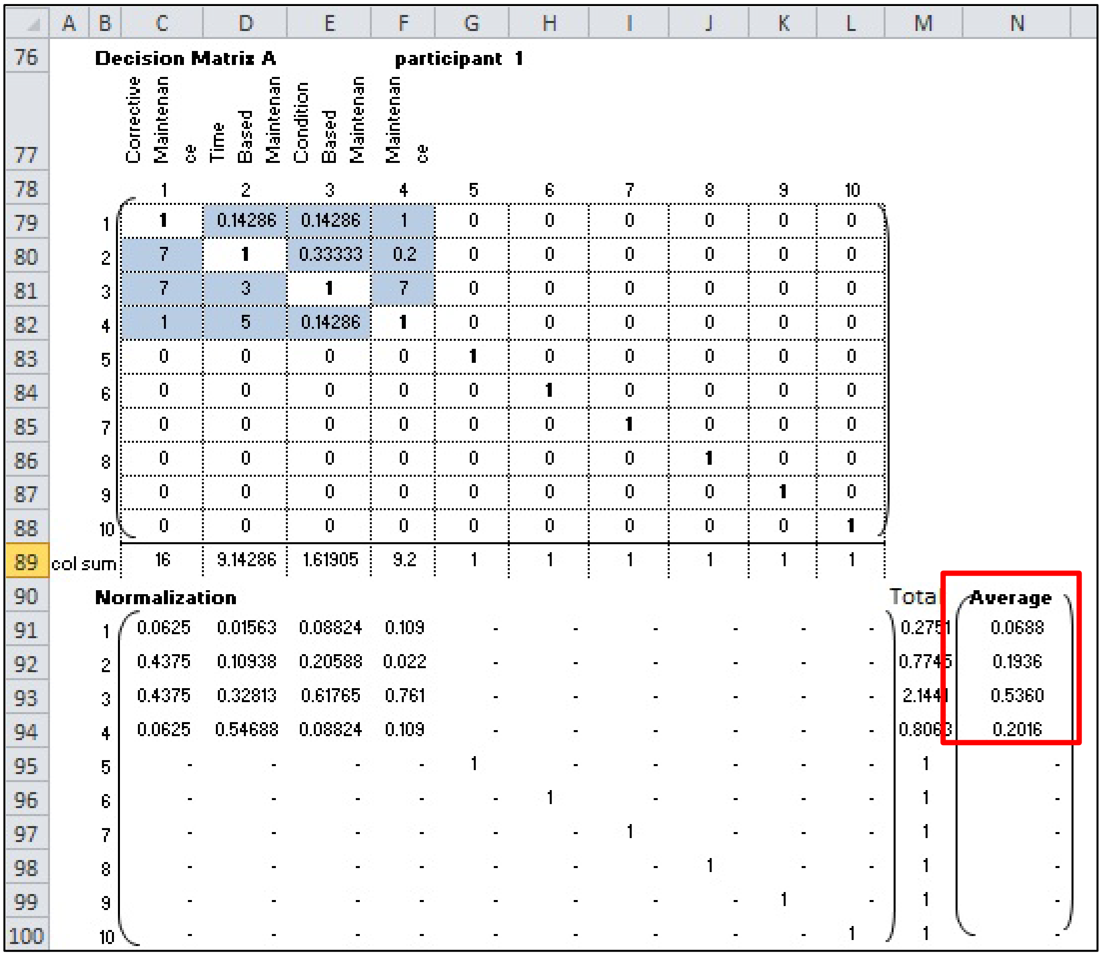
75 **Supporting calculations**

76 Decision Matrix A participant 2

			Risk	Cost								
77												
78			1	2	3	4	5	6	7	8	9	10
79	1		1	5	0	0	0	0	0	0	0	0
80	2		0.2	1	0	0	0	0	0	0	0	0
81	3		0	0	1	0	0	0	0	0	0	0
82	4		0	0	0	1	0	0	0	0	0	0
83	5		0	0	0	0	1	0	0	0	0	0
84	6		0	0	0	0	0	1	0	0	0	0
85	7		0	0	0	0	0	0	1	0	0	0
86	8		0	0	0	0	0	0	0	1	0	0
87	9		0	0	0	0	0	0	0	0	1	0
88	10		0	0	0	0	0	0	0	0	0	1
89	col sum		1.2	6	1	1	1	1	1	1	1	1

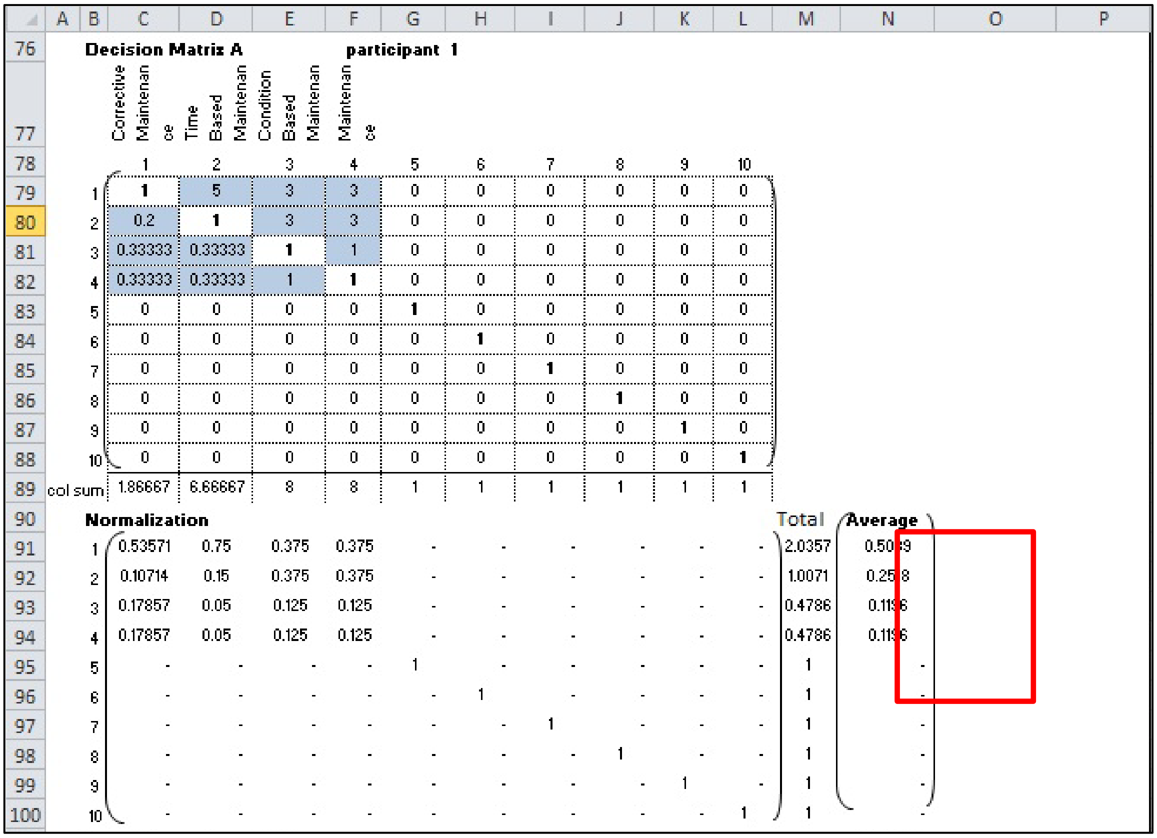
90	Normalization										Total	Average
91	1	0.83333	0.83333	-	-	-	-	-	-	-	-	1.6667	0.8333
92	2	0.16667	0.16667	-	-	-	-	-	-	-	-	0.3333	0.1667
93	3	-	-	1	-	-	-	-	-	-	-	1	-
94	4	-	-	-	1	-	-	-	-	-	-	1	-
95	5	-	-	-	-	1	-	-	-	-	-	1	-
96	6	-	-	-	-	-	1	-	-	-	-	1	-
97	7	-	-	-	-	-	-	1	-	-	-	1	-
98	8	-	-	-	-	-	-	-	1	-	-	1	-
99	9	-	-	-	-	-	-	-	-	1	-	1	-
100	10	-	-	-	-	-	-	-	-	-	1	1	-

Figure 4.1.7: Second level weight calculations



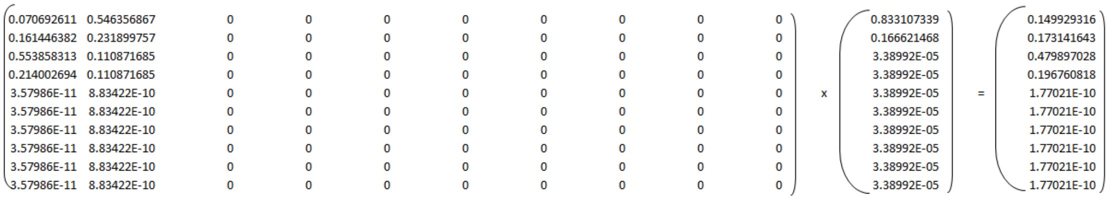
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
76		**Decision Matriz A**				**participant 1**								
77			Corrective Maintenan ce	Time Based Maintenan	Condition Based Maintenan	Maintenan ce								
78			1	2	3	4	5	6	7	8	9	10		
79		1	**1**	0.14286	0.14286	1	0	0	0	0	0	0		
80		2	7	**1**	0.33333	0.2	0	0	0	0	0	0		
81		3	7	3	**1**	7	0	0	0	0	0	0		
82		4	1	5	0.14286	**1**	0	0	0	0	0	0		
83		5	0	0	0	0	**1**	0	0	0	0	0		
84		6	0	0	0	0	0	**1**	0	0	0	0		
85		7	0	0	0	0	0	0	**1**	0	0	0		
86		8	0	0	0	0	0	0	0	**1**	0	0		
87		9	0	0	0	0	0	0	0	0	**1**	0		
88		10	0	0	0	0	0	0	0	0	0	**1**		
89	col sum		16	9.14286	1.61905	9.2	1	1	1	1	1	1		
90		**Normalization**											Tota	**Average**
91		1	0.0625	0.01563	0.08824	0.109	-	-	-	-	-	-	0.2751	0.0688
92		2	0.4375	0.10938	0.20588	0.022	-	-	-	-	-	-	0.7745	0.1936
93		3	0.4375	0.32813	0.61765	0.761	-	-	-	-	-	-	2.1441	0.5360
94		4	0.0625	0.54688	0.08824	0.109	-	-	-	-	-	-	0.8063	0.2016
95		5	-	-	-	-	1	-	-	-	-	-	1	-
96		6	-	-	-	-	-	1	-	-	-	-	1	-
97		7	-	-	-	-	-	-	1	-	-	-	1	-
98		8	-	-	-	-	-	-	-	1	-	-	1	-
99		9	-	-	-	-	-	-	-	-	1	-	1	-
100		10	-	-	-	-	-	-	-	-	-	1	1	-

Figure 4.1.8: Third level criteria risk weight calculations



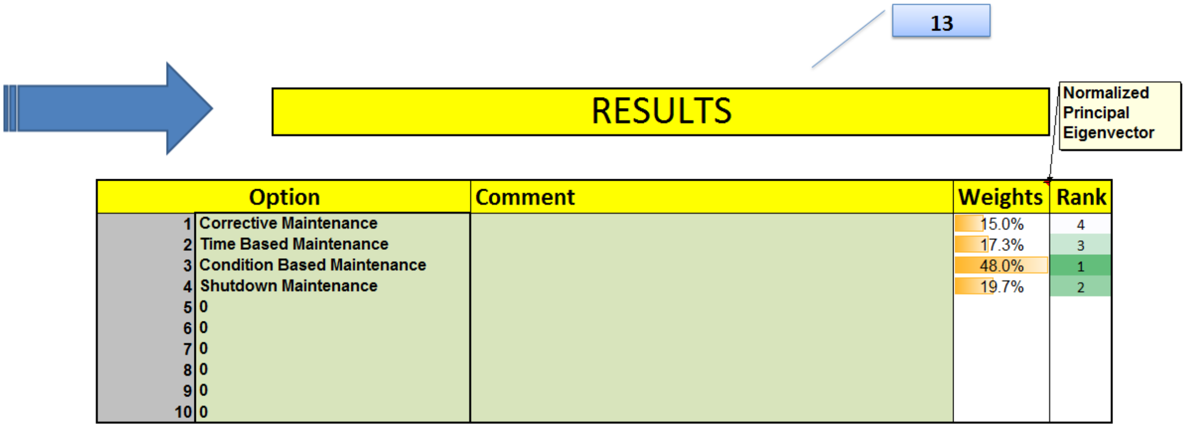
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
76		**Decision Matrix A**				**participant 1**										
77			Corrective Maintenance	Time Based Maintenan	Condition Based Maintenan	Maintenance										
78			1	2	3	4	5	6	7	8	9	10				
79		1	**1**	5	3	3	0	0	0	0	0	0				
80		2	0.2	**1**	3	3	0	0	0	0	0	0				
81		3	0.33333	0.33333	**1**	1	0	0	0	0	0	0				
82		4	0.33333	0.33333	1	**1**	0	0	0	0	0	0				
83		5	0	0	0	0	**1**	0	0	0	0	0				
84		6	0	0	0	0	0	**1**	0	0	0	0				
85		7	0	0	0	0	0	0	**1**	0	0	0				
86		8	0	0	0	0	0	0	0	**1**	0	0				
87		9	0	0	0	0	0	0	0	0	**1**	0				
88		10	0	0	0	0	0	0	0	0	0	**1**				
89	col sum		1.86667	6.66667	8	8	1	1	1	1	1	1				
90		**Normalization**											Total	**Average**		
91		1	0.53571	0.75	0.375	0.375	-	-	-	-	-	-	2.0357	0.50[illegible]9		
92		2	0.10714	0.15	0.375	0.375	-	-	-	-	-	-	1.0071	0.25[illegible]8		
93		3	0.17857	0.05	0.125	0.125	-	-	-	-	-	-	0.4786	0.11[illegible]6		
94		4	0.17857	0.05	0.125	0.125	-	-	-	-	-	-	0.4786	0.11[illegible]6		
95		5	-	-	-	-	1	-	-	-	-	-	1	-		
96		6	-	-	-	-	-	1	-	-	-	-	1	-		
97		7	-	-	-	-	-	-	1	-	-	-	1	-		
98		8	-	-	-	-	-	-	-	1	-	-	1	-		
99		9	-	-	-	-	-	-	-	-	1	-	1	-		
100		10	-	-	-	-	-	-	-	-	-	1	1	-		

Figure 4.1.9: Third level cost weight calculations



$$\begin{pmatrix} 0.070692611 & 0.546356867 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.161446382 & 0.231899757 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.553858313 & 0.110871685 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.214002694 & 0.110871685 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3.57986E-11 & 8.83422E-10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3.57986E-11 & 8.83422E-10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3.57986E-11 & 8.83422E-10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3.57986E-11 & 8.83422E-10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3.57986E-11 & 8.83422E-10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3.57986E-11 & 8.83422E-10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} x \begin{pmatrix} 0.833107339 \\ 0.166621468 \\ 3.38992E-05 \\ 3.38992E-05 \\ 3.38992E-05 \\ 3.38992E-05 \\ 3.38992E-05 \\ 3.38992E-05 \\ 3.38992E-05 \\ 3.38992E-05 \end{pmatrix} = \begin{pmatrix} 0.149929316 \\ 0.173141643 \\ 0.479897028 \\ 0.196760818 \\ 1.77021E-10 \\ 1.77021E-10 \\ 1.77021E-10 \\ 1.77021E-10 \\ 1.77021E-10 \\ 1.77021E-10 \end{pmatrix}$$

Figure 4.1.10: Matrix multiplication to obtain overall scores for the maintenance policies



RESULTS

Normalized Principal Eigenvector

Option		Comment	Weights	Rank
1	Corrective Maintenance		15.0%	4
2	Time Based Maintenance		17.3%	3
3	Condition Based Maintenance		48.0%	1
4	Shutdown Maintenance		19.7%	2
5	0			
6	0			
7	0			
8	0			
9	0			
10	0			

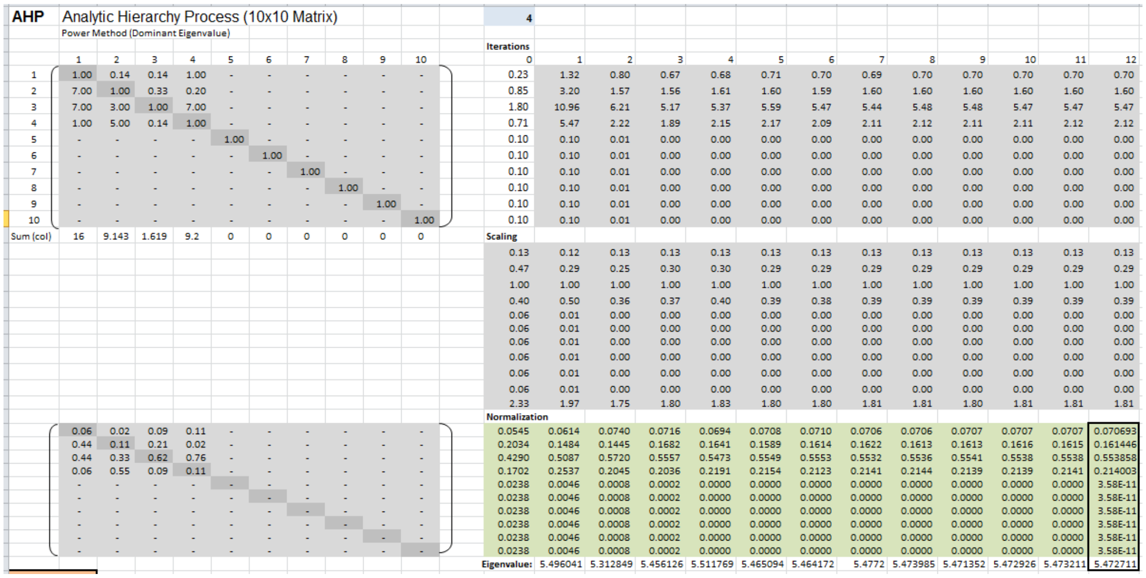
Figure 4.1.11: Results obtained from the tool

Table 4.1.3: Maintenance Policy Decision Result Comparison

Maintenance Policy Decision Result Comparison			
	Actual	**Using Tool**	**Difference**
Corrective Maintenance	14%	15%	1%
Time Based Maintenance	20%	17.3%	2.7%
Condition Based Maintenance	47%	48%	1%
Shutdown Maintenance	19%	19.7%	0.7%

The results differ ranging from zero to three percent because the tool actually calculate the data using the Eigenvector Method (EVM) to obtain the most accurate and consistent result. For every each of the pairwise comparison, they are being iterated and the Eigenvalue (λ_{max}), Consistency Index (CI), Consistency Ratio (CR) and Random Index (RI) are determined.

Below is the example of the worksheet for Risk Contribution Criteria using EVM:



AHP Analytic Hierarchy Process (10x10 Matrix)

Power Method (Dominant Eigenvalue)

4

	1	2	3	4	5	6	7	8	9	10
1	1.00	0.14	0.14	1.00	-	-	-	-	-	-
2	7.00	1.00	0.33	0.20	-	-	-	-	-	-
3	7.00	3.00	1.00	7.00	-	-	-	-	-	-
4	1.00	5.00	0.14	1.00	-	-	-	-	-	-
5	-	-	-	-	1.00	-	-	-	-	-
6	-	-	-	-	-	1.00	-	-	-	-
7	-	-	-	-	-	-	1.00	-	-	-
8	-	-	-	-	-	-	-	1.00	-	-
9	-	-	-	-	-	-	-	-	1.00	-
10	-	-	-	-	-	-	-	-	-	1.00
Sum (col)	16	9.143	1.619	9.2	0	0	0	0	0	0

Iterations

0	1	2	3	4	5	6	7	8	9	10	11	12
0.23	1.32	0.80	0.67	0.68	0.71	0.70	0.69	0.70	0.70	0.70	0.70	0.70
0.85	3.20	1.57	1.56	1.61	1.60	1.59	1.60	1.60	1.60	1.60	1.60	1.60
1.80	10.96	6.21	5.17	5.37	5.59	5.47	5.44	5.48	5.48	5.47	5.47	5.47
0.71	5.47	2.22	1.89	2.15	2.17	2.09	2.11	2.12	2.11	2.11	2.12	2.12
0.10	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Scaling

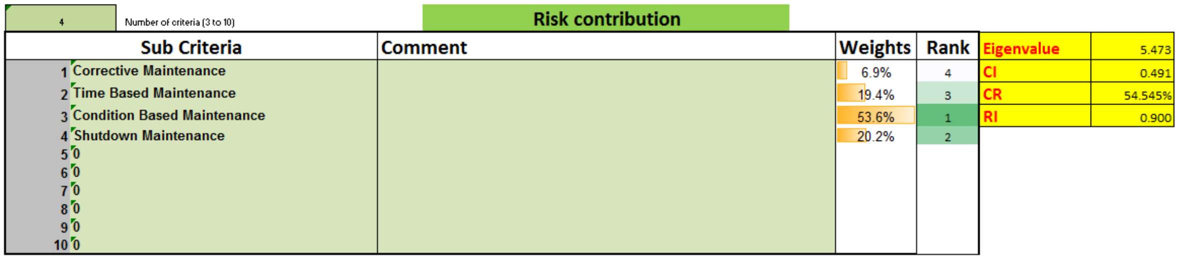
0.13	0.12	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
0.47	0.29	0.25	0.30	0.30	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.40	0.50	0.36	0.37	0.40	0.39	0.38	0.39	0.39	0.39	0.39	0.39	0.39
0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.33	1.97	1.75	1.80	1.83	1.80	1.80	1.81	1.81	1.80	1.81	1.81	1.81

0.06	0.02	0.09	0.11	-	-	-	-	-	-
0.44	0.11	0.21	0.02	-	-	-	-	-	-
0.44	0.33	0.62	0.76	-	-	-	-	-	-
0.06	0.55	0.09	0.11	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-

Normalization

0.0545	0.0614	0.0740	0.0716	0.0694	0.0708	0.0710	0.0706	0.0706	0.0707	0.0707	0.0707	0.070693
0.2034	0.1484	0.1445	0.1682	0.1641	0.1589	0.1614	0.1622	0.1613	0.1613	0.1616	0.1615	0.161446
0.4290	0.5087	0.5720	0.5557	0.5473	0.5549	0.5553	0.5532	0.5536	0.5541	0.5538	0.5538	0.553858
0.1702	0.2537	0.2045	0.2036	0.2191	0.2154	0.2123	0.2141	0.2144	0.2139	0.2139	0.2141	0.214003
0.0238	0.0046	0.0008	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	3.58E-11
0.0238	0.0046	0.0008	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	3.58E-11
0.0238	0.0046	0.0008	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	3.58E-11
0.0238	0.0046	0.0008	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	3.58E-11
0.0238	0.0046	0.0008	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	3.58E-11
0.0238	0.0046	0.0008	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	3.58E-11
Eigenvalue:	5.496041	5.312849	5.456126	5.511769	5.465094	5.464172	5.4772	5.473985	5.471352	5.472926	5.473211	5.472711

Figure 4.1.12: Eigenvector Section of the worksheet (Risk Contribution)



4 Number of criteria (3 to 10)

Risk contribution

	Sub Criteria	Comment	Weights	Rank
1	Corrective Maintenance		6.9%	4
2	Time Based Maintenance		19.4%	3
3	Condition Based Maintenance		53.6%	1
4	Shutdown Maintenance		20.2%	2
5	0			
6	0			
7	0			
8	0			
9	0			
10	0			

Eigenvalue	5.473
CI	0.491
CR	54.545%
RI	0.900

Figure 4.1.13: Eigenvalue, CI, CR, RI obtained from calculation for risk contribution

4.2: Case study 2: Using data from Reference [24] to test for λ max, CI, CR and global weight scores

Title: Application of Analytical Hierarchy Process in Selection of Desalination Plants

Introduction:

Seawater desalination plants have been utilized to supply fresh water to the Gulf Cooperation Council countries since the early 1950s. In spite of the fact that there are several types of desalination technology that can be used more efficiently and economically, one type of desalination technology, namely multi-stage flash, has been used extensively in the region. This work is an attempt to identify the most suitable technology for the specific use by soliciting expert opinions. Based on several relevant factors, the analytical hierarchy process (AHP) was utilized to select the most appropriate technology for seawater desalination. The selection process in this study was limited to seawater feed and seven factors and four commercially available desalination technologies, i.e., multi-stage flash, multi-effect desalination, vapor compression and reverse osmosis.

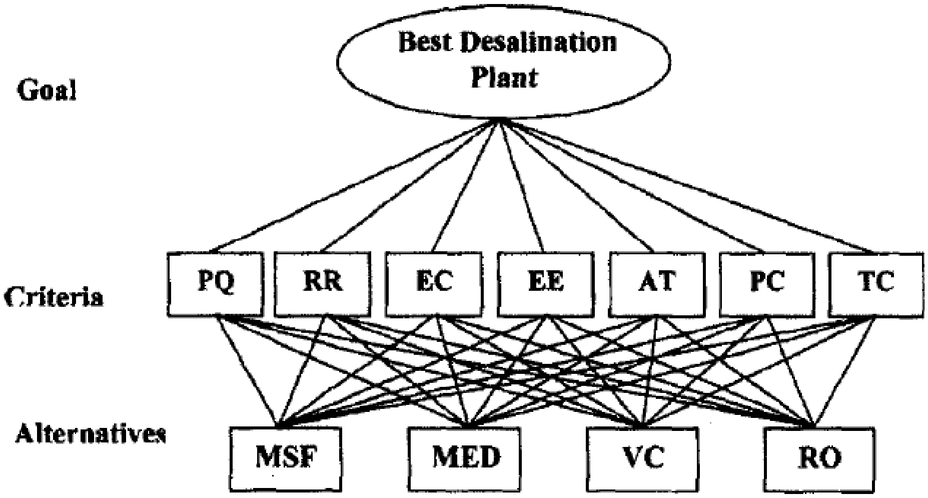
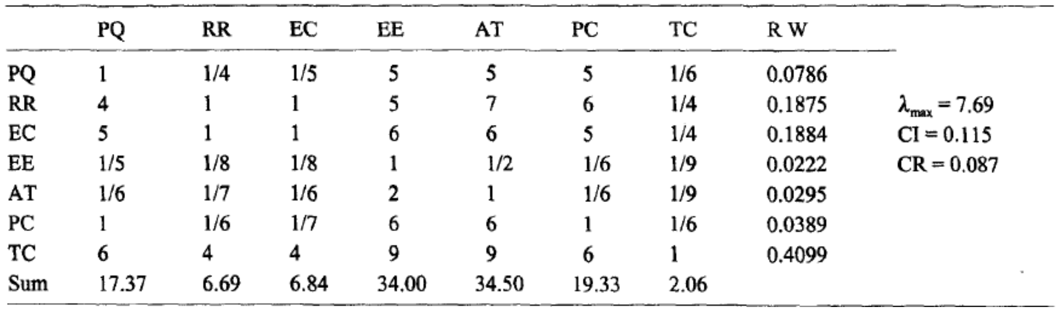


Figure 4.2.1: Hierarchical framework of choosing the best desalination plant

Table 4.2.1: Pair-wise comparison of the different criteria and their relative weights



	PQ	RR	EC	EE	AT	PC	TC	R W	
PQ	1	1/4	1/5	5	5	5	1/6	0.0786	
RR	4	1	1	5	7	6	1/4	0.1875	$\lambda_{max} = 7.69$
EC	5	1	1	6	6	5	1/4	0.1884	CI = 0.115
EE	1/5	1/8	1/8	1	1/2	1/6	1/9	0.0222	CR = 0.087
AT	1/6	1/7	1/6	2	1	1/6	1/9	0.0295	
PC	1	1/6	1/7	6	6	1	1/6	0.0389	
TC	6	4	4	9	9	6	1	0.4099	
Sum	17.37	6.69	6.84	34.00	34.50	19.33	2.06		

PQ = Product quality

RR = Recovery ratio

EC = Energy consumption

EE = Equipment efficiency

AT = Available technology

PC = Plant capacity

TC = Total cost

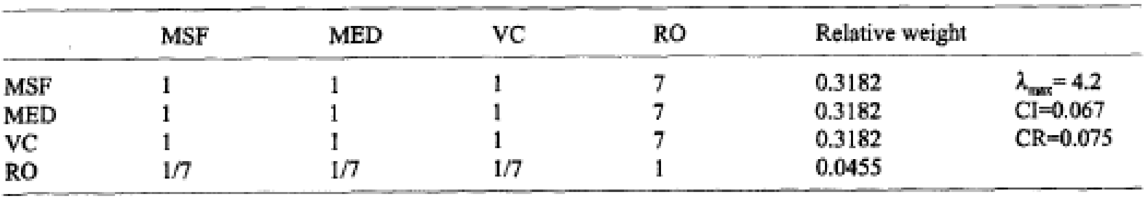
MSF = Multistage flash desalination

MED = Multi effect distillation

VC = Vapor compression

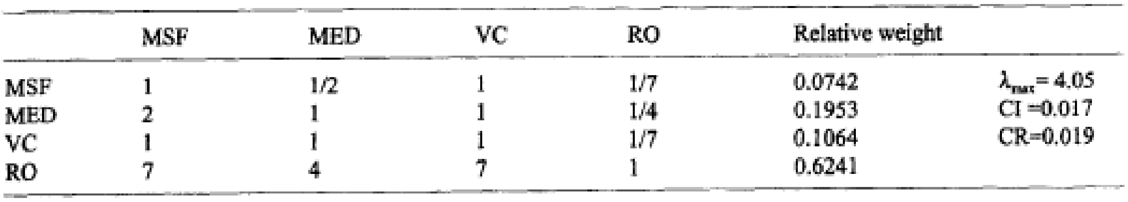
RO = Reverse osmosis

Table 4.2.2: Pair-wise comparison of the different technologies with respect to required product quality (PQ)



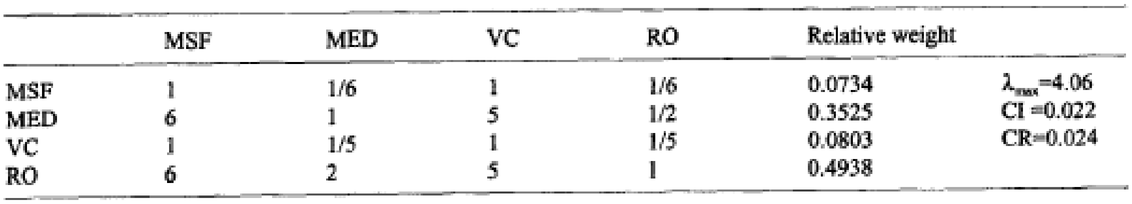
	MSF	MED	VC	RO	Relative weight	
MSF	1	1	1	7	0.3182	λ_{max}= 4.2
MED	1	1	1	7	0.3182	CI=0.067
VC	1	1	1	7	0.3182	CR=0.075
RO	1/7	1/7	1/7	1	0.0455	

Table 4.2.3: Pair-wise comparison of the different technologies with respect to recovery ratio (RR)



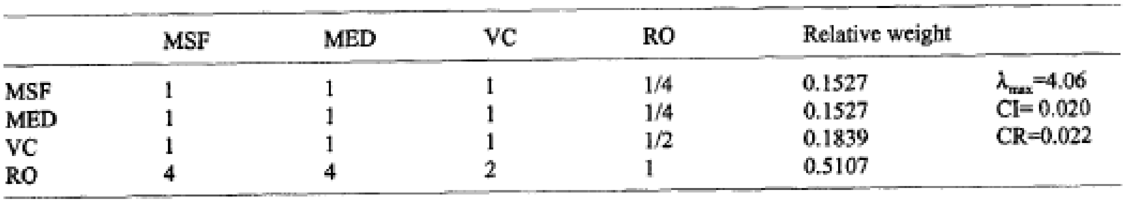
	MSF	MED	VC	RO	Relative weight	
MSF	1	1/2	1	1/7	0.0742	λ_{max}= 4.05
MED	2	1	1	1/4	0.1953	CI =0.017
VC	1	1	1	1/7	0.1064	CR=0.019
RO	7	4	7	1	0.6241	

Table 4.2.4: Pair-wise comparison of the different technologies with respect to energy consumption rate (EC)



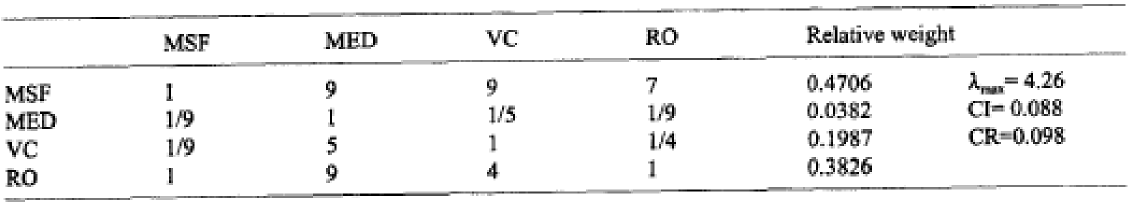
	MSF	MED	VC	RO	Relative weight	
MSF	1	1/6	1	1/6	0.0734	λ_{max}=4.06
MED	6	1	5	1/2	0.3525	CI =0.022
VC	1	1/5	1	1/5	0.0803	CR=0.024
RO	6	2	5	1	0.4938	

Table 4.2.5: Pair-wise comparison of the different technologies with respect to equipment efficiency and energy utilization (EE)



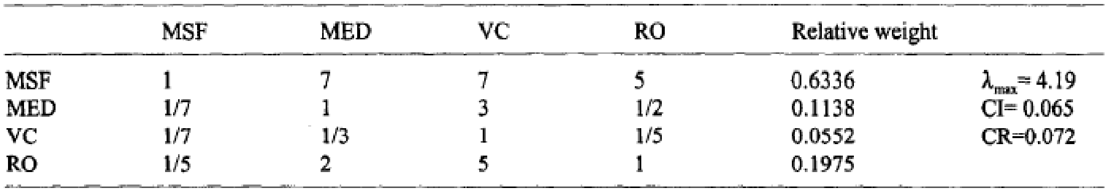
	MSF	MED	VC	RO	Relative weight	
MSF	1	1	1	1/4	0.1527	λ_{max}=4.06
MED	1	1	1	1/4	0.1527	CI= 0.020
VC	1	1	1	1/2	0.1839	CR=0.022
RO	4	4	2	1	0.5107	

Table 4.2.6: Pair-wise comparison of the different technologies with respect to available technology (AT)



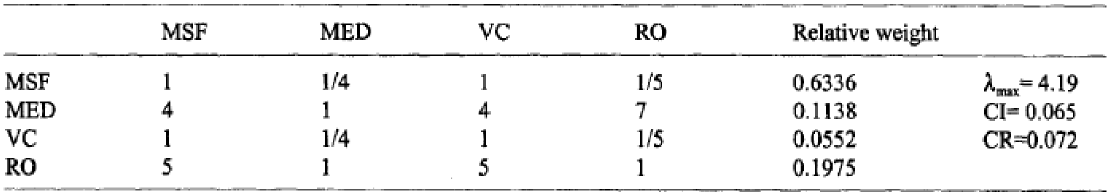
	MSF	MED	VC	RO	Relative weight	
MSF	1	9	9	7	0.4706	λ_{max}= 4.26
MED	1/9	1	1/5	1/9	0.0382	CI= 0.088
VC	1/9	5	1	1/4	0.1987	CR=0.098
RO	1	9	4	1	0.3826	

Table 4.2.7:Pair-wise comparison of the different technologies with respect to plant capacity (PC)



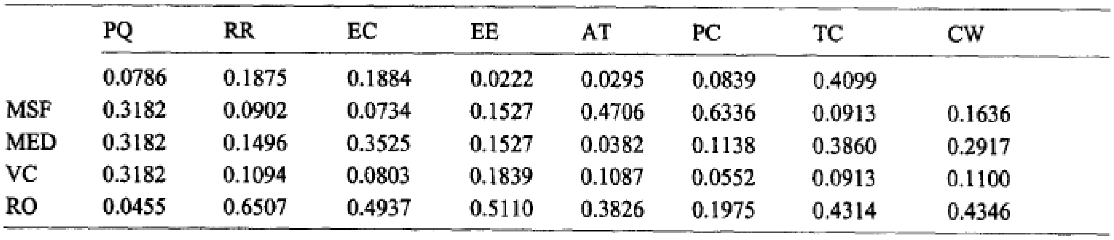
	MSF	MED	VC	RO	Relative weight	
MSF	1	7	7	5	0.6336	λ_{max}= 4.19
MED	1/7	1	3	1/2	0.1138	CI= 0.065
VC	1/7	1/3	1	1/5	0.0552	CR=0.072
RO	1/5	2	5	1	0.1975	

Table 4.2.8:Pair-wise comparison of the different technologies with respect to total cost (TC)

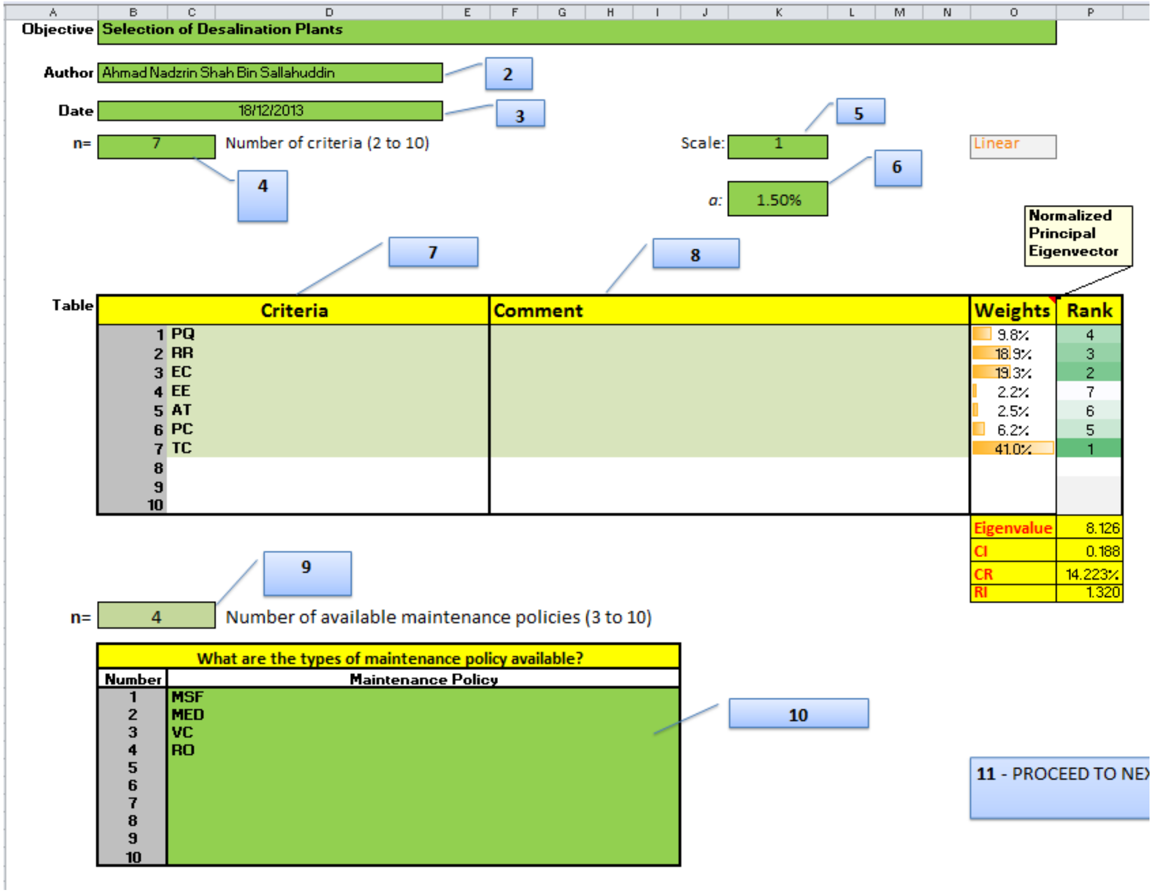


	MSF	MED	VC	RO	Relative weight	
MSF	1	1/4	1	1/5	0.6336	λ_{max}= 4.19
MED	4	1	4	7	0.1138	CI= 0.065
VC	1	1/4	1	1/5	0.0552	CR=0.072
RO	5	1	5	1	0.1975	

Table 4.2.9: Composite weight (CW) of the different desalination technologies



	PQ	RR	EC	EE	AT	PC	TC	CW
	0.0786	0.1875	0.1884	0.0222	0.0295	0.0839	0.4099	
MSF	0.3182	0.0902	0.0734	0.1527	0.4706	0.6336	0.0913	0.1636
MED	0.3182	0.1496	0.3525	0.1527	0.0382	0.1138	0.3860	0.2917
VC	0.3182	0.1094	0.0803	0.1839	0.1087	0.0552	0.0913	0.1100
RO	0.0455	0.6507	0.4937	0.5110	0.3826	0.1975	0.4314	0.4346



Objective Selection of Desalination Plants

Author Ahmad Nadzrin Shah Bin Sallahuddin

Date 18/12/2013

n= 7 Number of criteria (2 to 10)

Scale: 1 Linear

α: 1.50%

Table

	Criteria	Comment	Weights	Rank
1	PQ		9.8%	4
2	RR		18.9%	3
3	EC		19.3%	2
4	EE		2.2%	7
5	AT		2.5%	6
6	PC		6.2%	5
7	TC		41.0%	1
8				
9				
10				

Eigenvalue	8.126
CI	0.188
CR	14.223%
RI	1.320

n= 4 Number of available maintenance policies (3 to 10)

What are the types of maintenance policy available?	
Number	**Maintenance Policy**
1	MSF
2	MED
3	VC
4	RO
5	
6	
7	
8	
9	
10	

Figure 4.2.2: Summary page

Data is being inserted according to its numbering sequence of the blue callouts instructions:

1 Insert your objective here.

2 Insert your name here.

3 Insert date.

4 Input number of criteria. (From example above, the no. of criteria = 2)

5 Insert the scale of your evaluation.

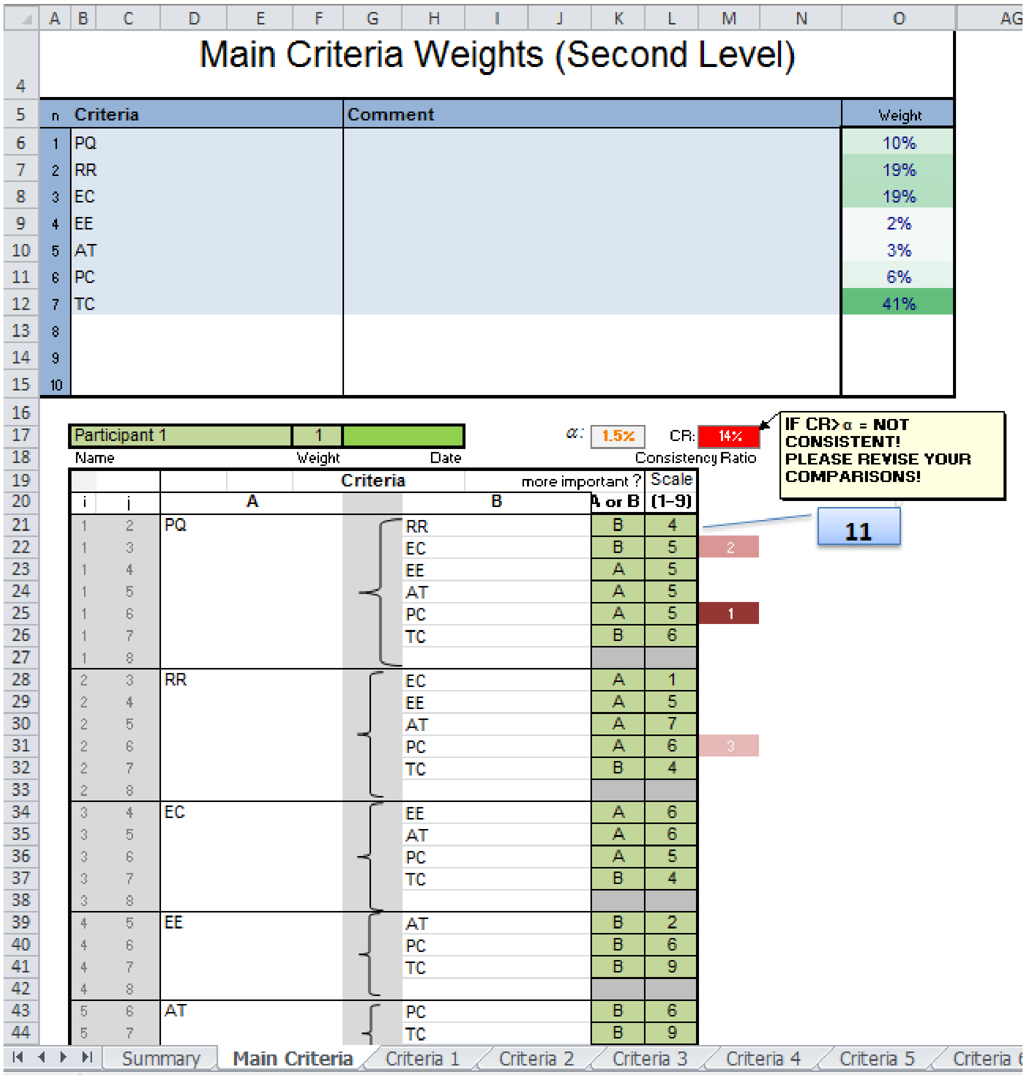
6 Enter your minimum consistency of acceptance (%)

7 Insert the criteria available for evaluation.

8 Insert any comments regarding the criteria chosen.

9 Insert the number of available maintenance policies. (From example above, the no. of available maintenance policy is 4.

10 Insert the types of maintenance policy available for this evaluation.



Main Criteria Weights (Second Level)

n	Criteria	Comment	Weight
1	PQ		10%
2	RR		19%
3	EC		19%
4	EE		2%
5	AT		3%
6	PC		6%
7	TC		41%
8			
9			
10			

Name: Participant 1
Weight: 1
Date:

α: 1.5%
CR: 14%
Consistency Ratio

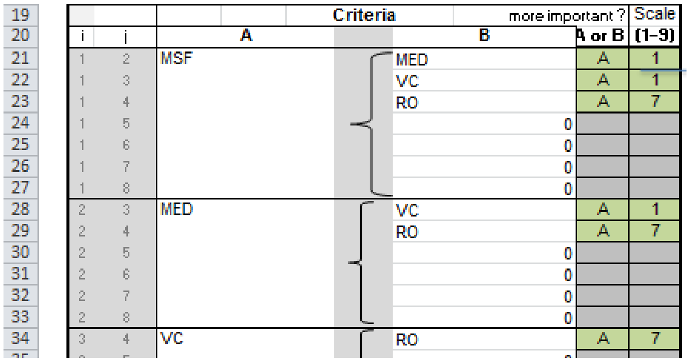
IF CR> α = NOT CONSISTENT! PLEASE REVISE YOUR COMPARISONS!

11

		Criteria		more important ?	Scale	
i	j	A	B	A or B	(1-9)	
1	2	PQ	RR	B	4	
1	3		EC	B	5	2
1	4		EE	A	5	
1	5		AT	A	5	
1	6		PC	A	5	1
1	7		TC	B	6	
1	8					
2	3	RR	EC	A	1	
2	4		EE	A	5	
2	5		AT	A	7	
2	6		PC	A	6	3
2	7		TC	B	4	
2	8					
3	4	EC	EE	A	6	
3	5		AT	A	6	
3	6		PC	A	5	
3	7		TC	B	4	
3	8					
4	5	EE	AT	B	2	
4	6		PC	B	6	
4	7		TC	B	9	
4	8					
5	6	AT	PC	B	6	
5	7		TC	B	9	

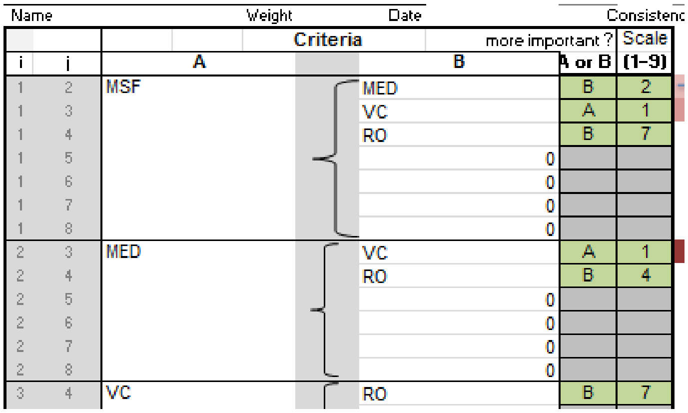
Figure 4.2.3: Second level criteria data input

From Figure 4.2.3, the importance of criteria are being measured and compared. For example, Cell K21 shows that the user has chosen B (RR) to be more important than A (PQ) and it is four times important than A.



19			Criteria		more important ?	Scale
20	i	j	A	B	A or B	(1-9)
21	1	2	MSF	MED	A	1
22	1	3		VC	A	1
23	1	4		RO	A	7
24	1	5		0		
25	1	6		0		
26	1	7		0		
27	1	8		0		
28	2	3	MED	VC	A	1
29	2	4		RO	A	7
30	2	5		0		
31	2	6		0		
32	2	7		0		
33	2	8		0		
34	3	4	VC	RO	A	7

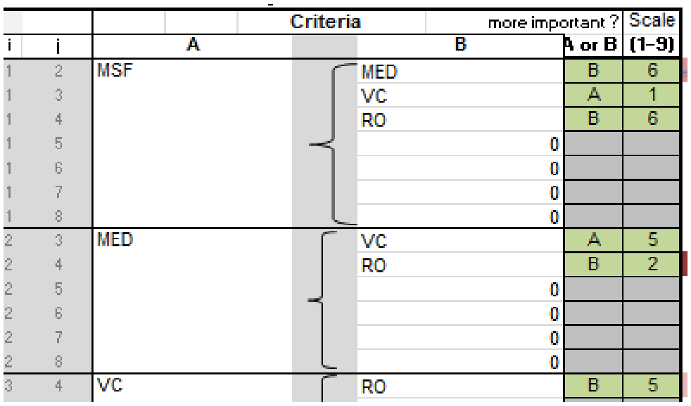
Figure 4.2.4: Product Quality (PQ) comparison worksheet



Name Weight Date Consistenc

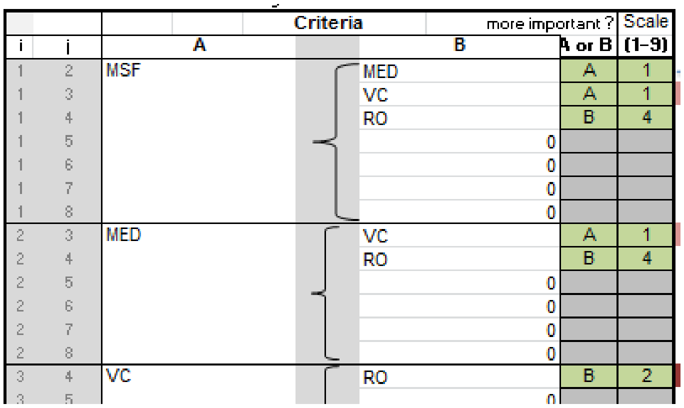
		Criteria		more important ?	Scale
i	j	A	B	A or B	(1-9)
1	2	MSF	MED	B	2
1	3		VC	A	1
1	4		RO	B	7
1	5		0		
1	6		0		
1	7		0		
1	8		0		
2	3	MED	VC	A	1
2	4		RO	B	4
2	5		0		
2	6		0		
2	7		0		
2	8		0		
3	4	VC	RO	B	7

Figure 4.2.5: Recovery Ratio (RR) comparison worksheet



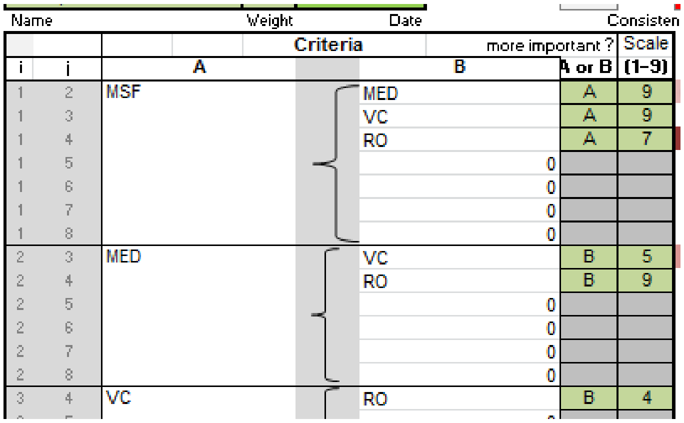
		Criteria		more important ?	Scale
i	j	A	B	A or B	(1-9)
1	2	MSF	MED	B	6
1	3		VC	A	1
1	4		RO	B	6
1	5		0		
1	6		0		
1	7		0		
1	8		0		
2	3	MED	VC	A	5
2	4		RO	B	2
2	5		0		
2	6		0		
2	7		0		
2	8		0		
3	4	VC	RO	B	5

Figure 4.2.6: Energy Consumption (EC) comparison worksheet



			Criteria	more important ?	Scale
i	j	A	B	A or B	(1-9)
1	2	MSF	MED	A	1
1	3		VC	A	1
1	4		RO	B	4
1	5		0		
1	6		0		
1	7		0		
1	8		0		
2	3	MED	VC	A	1
2	4		RO	B	4
2	5		0		
2	6		0		
2	7		0		
2	8		0		
3	4	VC	RO	B	2
3	5		0		

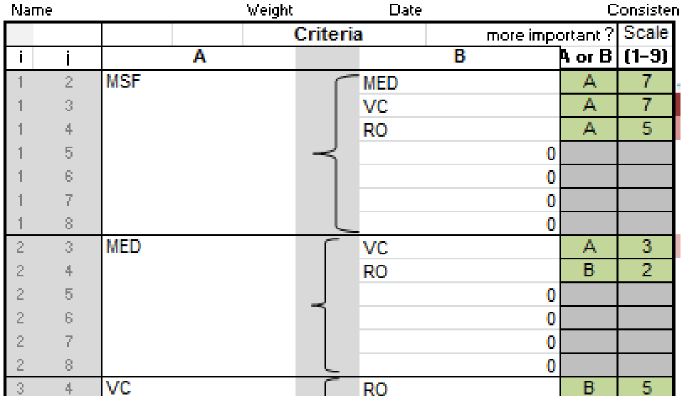
Figure 4.2.7: Equipment Efficiency (EE) comparison worksheet



Name Weight Date Consisten

			Criteria	more important ?	Scale
i	j	A	B	A or B	(1-9)
1	2	MSF	MED	A	9
1	3		VC	A	9
1	4		RO	A	7
1	5		0		
1	6		0		
1	7		0		
1	8		0		
2	3	MED	VC	B	5
2	4		RO	B	9
2	5		0		
2	6		0		
2	7		0		
2	8		0		
3	4	VC	RO	B	4

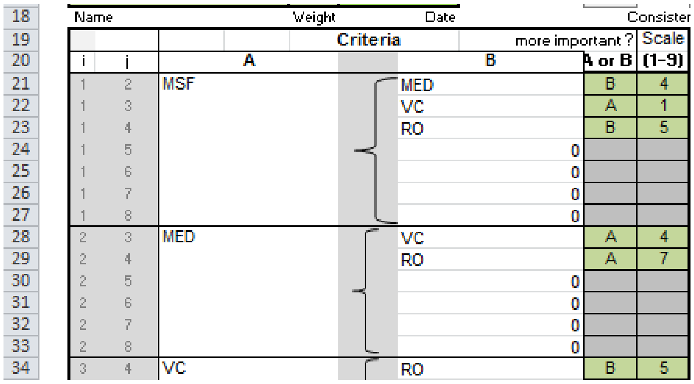
Figure 4.2.8: Available Technology comparison worksheet



Name Weight Date Consisten

		Criteria		more important ?	Scale
i	j	A	B	A or B	(1-9)
1	2	MSF	MED	A	7
1	3		VC	A	7
1	4		RO	A	5
1	5		0		
1	6		0		
1	7		0		
1	8		0		
2	3	MED	VC	A	3
2	4		RO	B	2
2	5		0		
2	6		0		
2	7		0		
2	8		0		
3	4	VC	RO	B	5

Figure 4.2.9: Plant Capacity (PC) comparison worksheet

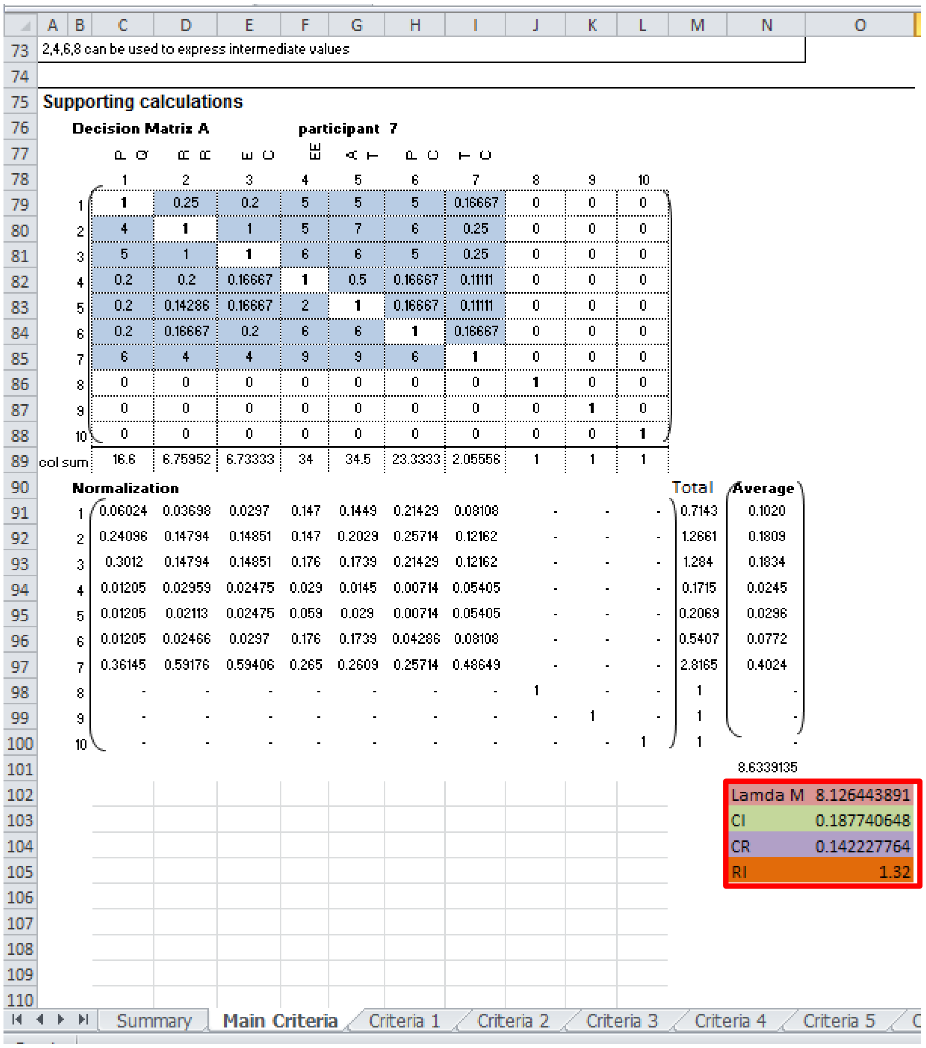


18 Name Weight Date Consister

			Criteria		more important ?	Scale
19						
20	i	j	A	B	A or B	(1-9)
21	1	2	MSF	MED	B	4
22	1	3		VC	A	1
23	1	4		RO	B	5
24	1	5		0		
25	1	6		0		
26	1	7		0		
27	1	8		0		
28	2	3	MED	VC	A	4
29	2	4		RO	A	7
30	2	5		0		
31	2	6		0		
32	2	7		0		
33	2	8		0		
34	3	4	VC	RO	B	5

Figure 4.2.10: Total Cost (TC) comparison worksheet

Figure 4.2.4 to 4.2.10 are the comparison worksheets for the alternatives of each criteria. For example, from Figure 4.2.10 which is under Total Cost criteria, it shows that MED is more important than MSF by a scale of four.



2,4,6,8 can be used to express intermediate values

Supporting calculations

Decision Matrix A **participant 7**

	1	2	3	4	5	6	7	8	9	10
1	**1**	0.25	0.2	5	5	5	0.16667	0	0	0
2	4	**1**	1	5	7	6	0.25	0	0	0
3	5	1	**1**	6	6	5	0.25	0	0	0
4	0.2	0.2	0.16667	**1**	0.5	0.16667	0.11111	0	0	0
5	0.2	0.14286	0.16667	2	**1**	0.16667	0.11111	0	0	0
6	0.2	0.16667	0.2	6	6	**1**	0.16667	0	0	0
7	6	4	4	9	9	6	**1**	0	0	0
8	0	0	0	0	0	0	0	**1**	0	0
9	0	0	0	0	0	0	0	0	**1**	0
10	0	0	0	0	0	0	0	0	0	**1**
col sum	16.6	6.75952	6.73333	34	34.5	23.3333	2.05556	1	1	1

Normalization

											Total	**Average**
1	0.06024	0.03698	0.0297	0.147	0.1449	0.21429	0.08108	-	-	-	0.7143	0.1020
2	0.24096	0.14794	0.14851	0.147	0.2029	0.25714	0.12162	-	-	-	1.2661	0.1809
3	0.3012	0.14794	0.14851	0.176	0.1739	0.21429	0.12162	-	-	-	1.284	0.1834
4	0.01205	0.02959	0.02475	0.029	0.0145	0.00714	0.05405	-	-	-	0.1715	0.0245
5	0.01205	0.02113	0.02475	0.059	0.029	0.00714	0.05405	-	-	-	0.2069	0.0296
6	0.01205	0.02466	0.0297	0.176	0.1739	0.04286	0.08108	-	-	-	0.5407	0.0772
7	0.36145	0.59176	0.59406	0.265	0.2609	0.25714	0.48649	-	-	-	2.8165	0.4024
8	-	-	-	-	-	-	-	1	-	-	1	-
9	-	-	-	-	-	-	-	-	1	-	1	-
10	-	-	-	-	-	-	-	-	-	1	1	-

8.6339135

Lamda M	8.126443891
CI	0.187740648
CR	0.142227764
RI	1.32

Figure 4.2.11: Second level (main criteria) weight calculations

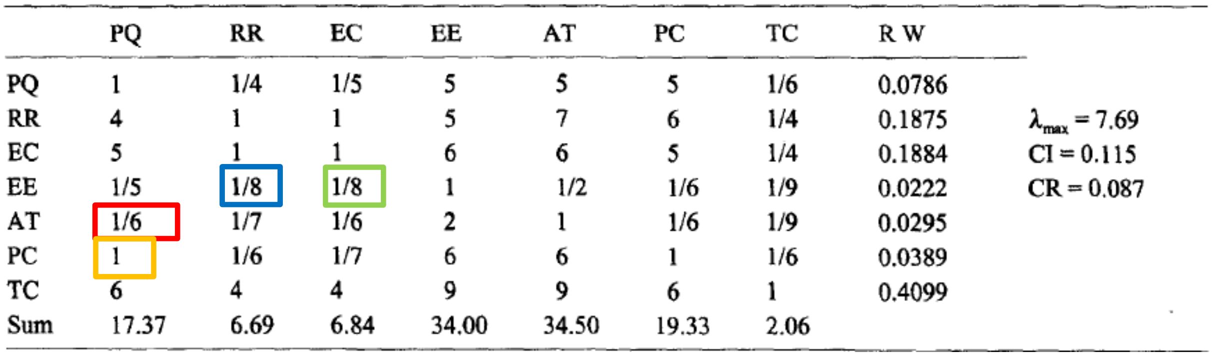
From Figure 4.2.11, the Consistency Ratio is bigger than 0.1 which make the data inconsistent. Since the data is taken from Reference [24], a comparison table is made to check whether the analysis is correct or not.

Table 4.2.10: Result comparison for Eigenvalue (lambda max), CI, CR

Result Comparison						
	λ max		CI		CR	
	Actual	Tool	Actual	Tool	Actual	Tool
Second level						
Main Criteria	7.69	8.13	0.115	0.187	8.7%	14.2%
Third level						
PQ	4.2	4.000	0.067	0.000	7.5%	0.000%
RR	4.05	4.051	0.017	0.017	1.9%	1.894%
EC	4.06	4.065	0.022	0.022	2.4%	2.400%
EE	4.06	4.061	0.02	0.020	2.2%	2.246%
AT	4.26	4.548	0.088	0.183	9.8%	20.279%
PC	4.19	4.192	0.065	0.064	7.2%	7.106%
TC	4.19	4.638	0.065	0.213	7.2%	23.635%

Why do the values of the main criteria, AT and TC are significantly different?

Table 4.2.11: Pairwise comparison of the different criteria and their relative weights



	PQ	RR	EC	EE	AT	PC	TC	R W	
PQ	1	1/4	1/5	5	5	5	1/6	0.0786	
RR	4	1	1	5	7	6	1/4	0.1875	$\lambda_{max} = 7.69$
EC	5	1	1	6	6	5	1/4	0.1884	CI = 0.115
EE	1/5	1/8	1/8	1	1/2	1/6	1/9	0.0222	CR = 0.087
AT	1/6	1/7	1/6	2	1	1/6	1/9	0.0295	
PC	1	1/6	1/7	6	6	1	1/6	0.0389	
TC	6	4	4	9	9	6	1	0.4099	
Sum	17.37	6.69	6.84	34.00	34.50	19.33	2.06		

The entries in a_{ij} are governed by the following rules:

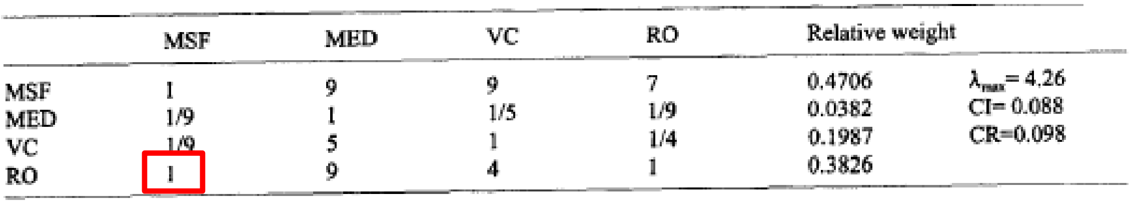
$$a_{ij}. > 0;\ a_{ii} = 1 \text{ for all } i$$

If a_{ij} is the element of row i column j of the matrix, then the lower diagonal is filled using this formula:

$$a_{ji} = 1/ a_{ij}$$

We know that the comparison matrix will be a positive reciprocal pair-wise comparison matrix because of the rules. From table 4.2.11, the red, orange, blue, and green highlighted frames show the incorrect reciprocals of the comparison. The value from the red framed number should be the reciprocal of the value 5, orange should be reciprocal of 5, blue should be reciprocal of 5, and green should be reciprocal of 6.

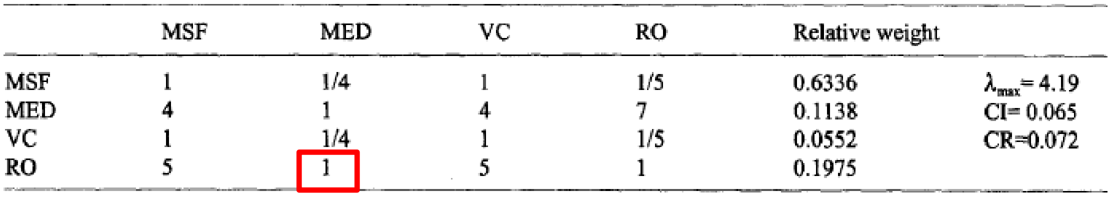
Table 4.2.12: Pairwise comparison of the different technologies with respect to the available technology (AT)



	MSF	MED	VC	RO	Relative weight	
MSF	1	9	9	7	0.4706	λ_{max}= 4.26
MED	1/9	1	1/5	1/9	0.0382	CI= 0.088
VC	1/9	5	1	1/4	0.1987	CR=0.098
RO	1	9	4	1	0.3826	

From Table 4.2.12, the red highlighted frame shows the incorrect reciprocals of the comparison. The value from the red framed number should be the reciprocal of the value 7.

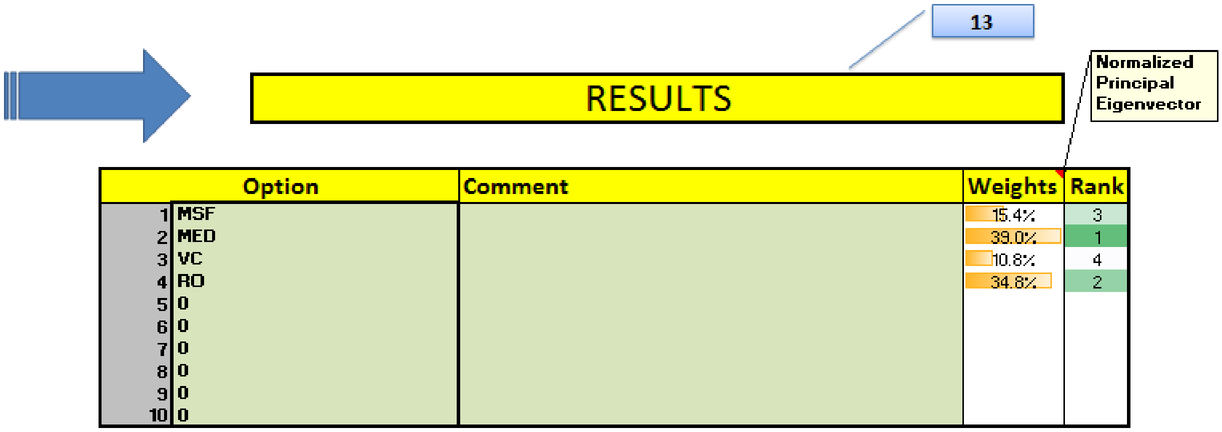
Table 4.2.13: Pairwise comparison of the different technologies with respect to total cost (TC)



	MSF	MED	VC	RO	Relative weight	
MSF	1	1/4	1	1/5	0.6336	λ_{max}= 4.19
MED	4	1	4	7	0.1138	CI= 0.065
VC	1	1/4	1	1/5	0.0552	CR=0.072
RO	5	1	5	1	0.1975	

From Table 4.2.13, the red highlighted frame shows the incorrect reciprocals of the comparison. The value from the red framed number should be the reciprocal of the value 7.

All of the numbers that are highlighted are the incorrect reciprocals of their respective pairwise comparisons. This shows that errors like these can be avoided if we are using **computerized calculation (this tool).**



13

Normalized Principal Eigenvector

RESULTS

	Option	Comment	Weights	Rank
1	MSF		15.4%	3
2	MED		39.0%	1
3	VC		10.8%	4
4	RO		34.8%	2
5	0			
6	0			
7	0			
8	0			
9	0			
10	0			

Desalination Plant Decision Result Comparison			
	Actual	**Proposed Tool**	**Difference**
MSF	16.4%	15.4%	1%
MED	29.17%	39.0%	9.83%
VC	11.00%	10.8%	0.2%
RO	43.46%	34.8%	8.66%

Since the pairwise comparisons from the actual data are wrongly calculated, the overall scores for each of the plants are significantly different.

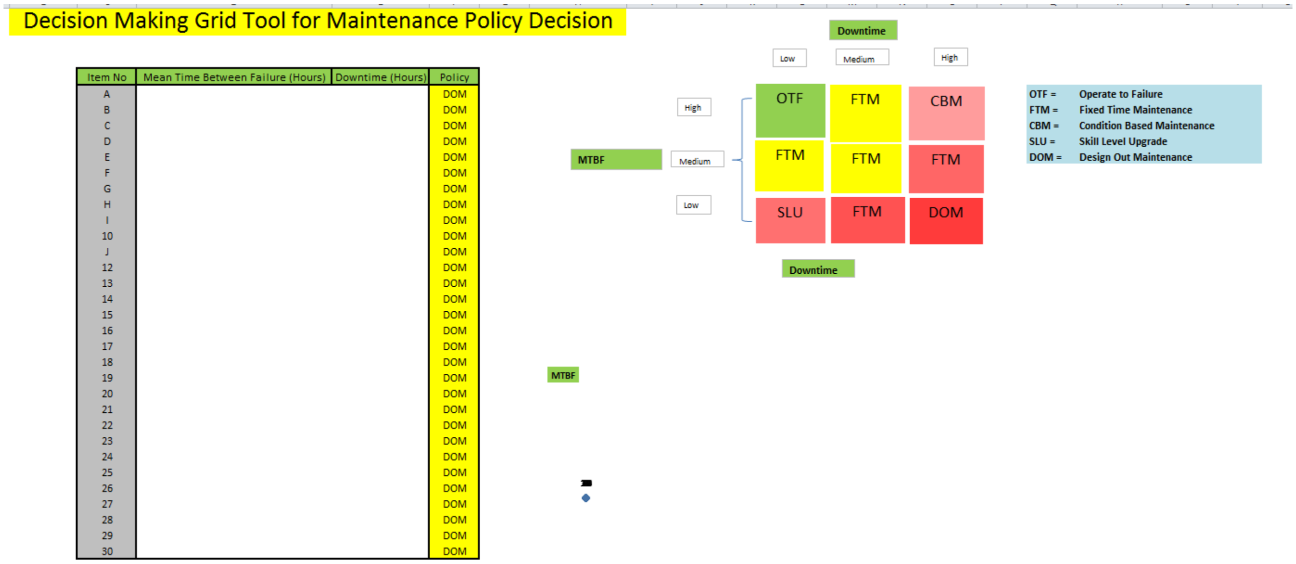
Case studies for DMG model spreadsheet

4.3: Case study 1: Using data from Reference [21] to obtain the decision making grid

Title: A decision analysis model for maintenance policy selection using a CMMS

Introduction:

In this paper, an investigation of the characteristics of computerised maintenance management systems (CMMSs) is carried out to highlight the need for them in industry and identify their current deficiencies. A proposed model provides a decision analysis capability that is often missing in existing CMMSs. The proposed model employs a hybrid of intelligent approaches. This hybrid system is analogous to the Holonic concept. The distinction between these two features is important. The rules function automatically. Practical implications. The main practical implication of this paper is the proposal of an intelligent model that can be linked to CMMSs to add value to data collected in the form of provision of decision support capabilities. A further implication is to identify the need for information to aid maintenance, followed by the provision of reasons for current deficiencies in existing off-the shelf CMMSs.



Decision Making Grid Tool for Maintenance Policy Decision

Item No	Mean Time Between Failure (Hours)	Downtime (Hours)	Policy
A			DOM
B			DOM
C			DOM
D			DOM
E			DOM
F			DOM
G			DOM
H			DOM
I			DOM
10			DOM
J			DOM
12			DOM
13			DOM
14			DOM
15			DOM
16			DOM
17			DOM
18			DOM
19			DOM
20			DOM
21			DOM
22			DOM
23			DOM
24			DOM
25			DOM
26			DOM
27			DOM
28			DOM
29			DOM
30			DOM

Downtime

MTBF	Low	Medium	High
High	OTF	FTM	CBM
Medium	FTM	FTM	FTM
Low	SLU	FTM	DOM

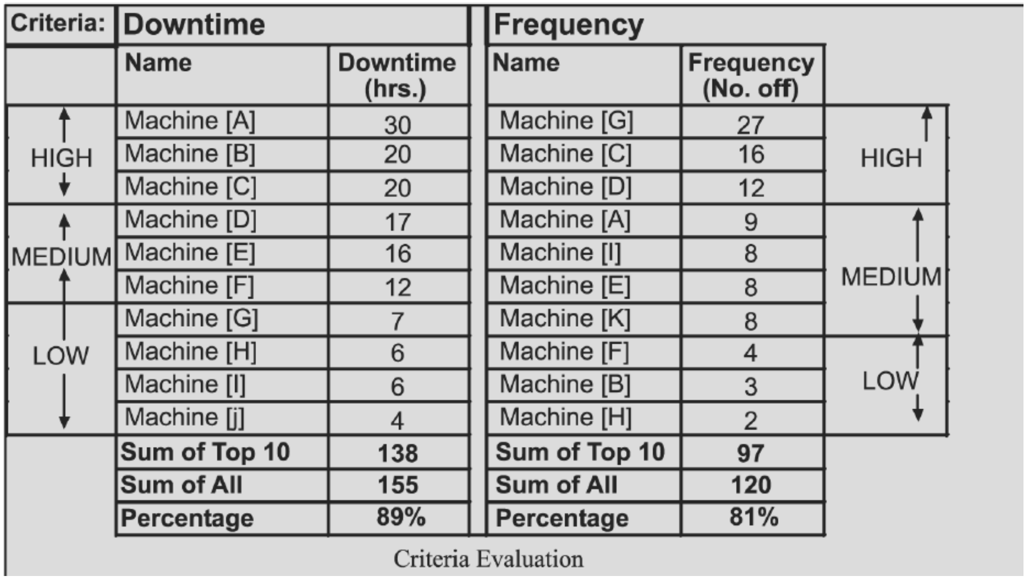
Downtime

OTF = Operate to Failure
FTM = Fixed Time Maintenance
CBM = Condition Based Maintenance
SLU = Skill Level Upgrade
DOM = Design Out Maintenance

Figure 4.3.1: Summary Input Page of the DMG Tool.

Procedure of using the tool:

1. Insert the item name/number on the first column of the table.
2. Choose the data type by selecting from the dropdown list. (Frequency of failure or MTBF)
3. Insert the Mean Time Between Failure (MTBF) or Frequency of failure on the second column.
4. Insert the downtime of the item on the third column.
5. The location of the item will then be shown in the grid along with the suitable maintenance policy.



Criteria:	**Downtime**		**Frequency**		
	Name	**Downtime (hrs.)**	**Name**	**Frequency (No. off)**	
HIGH	Machine [A]	30	Machine [G]	27	HIGH
	Machine [B]	20	Machine [C]	16	
	Machine [C]	20	Machine [D]	12	
MEDIUM	Machine [D]	17	Machine [A]	9	MEDIUM
	Machine [E]	16	Machine [I]	8	
	Machine [F]	12	Machine [E]	8	
LOW	Machine [G]	7	Machine [K]	8	
	Machine [H]	6	Machine [F]	4	LOW
	Machine [I]	6	Machine [B]	3	
	Machine [j]	4	Machine [H]	2	
	Sum of Top 10	**138**	**Sum of Top 10**	**97**	
	Sum of All	**155**	**Sum of All**	**120**	
	Percentage	**89%**	**Percentage**	**81%**	

Criteria Evaluation

Figure 4.3.2 Criteria Analysis from Reference [21]

From Figure 4.3.3, the author has set the range of frequencies to be in low, medium and high range. It is determined by assessing how bad the worst performing machines are for a certain period of time, say one month the worst performers as regards each criterion are sorted and placed into high, medium, and low sub-groups. This is definitely different from the method from Reference [23] which sets the level of frequencies by setting its range to be in incremental of one third from the highest value.

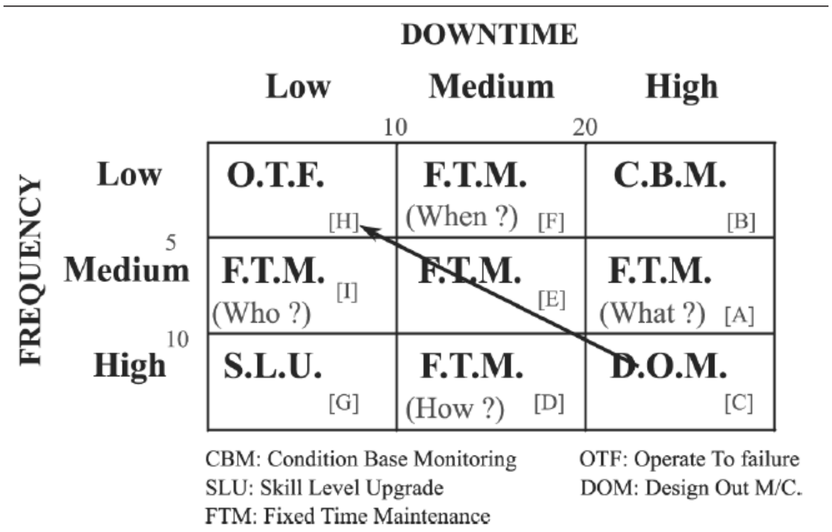
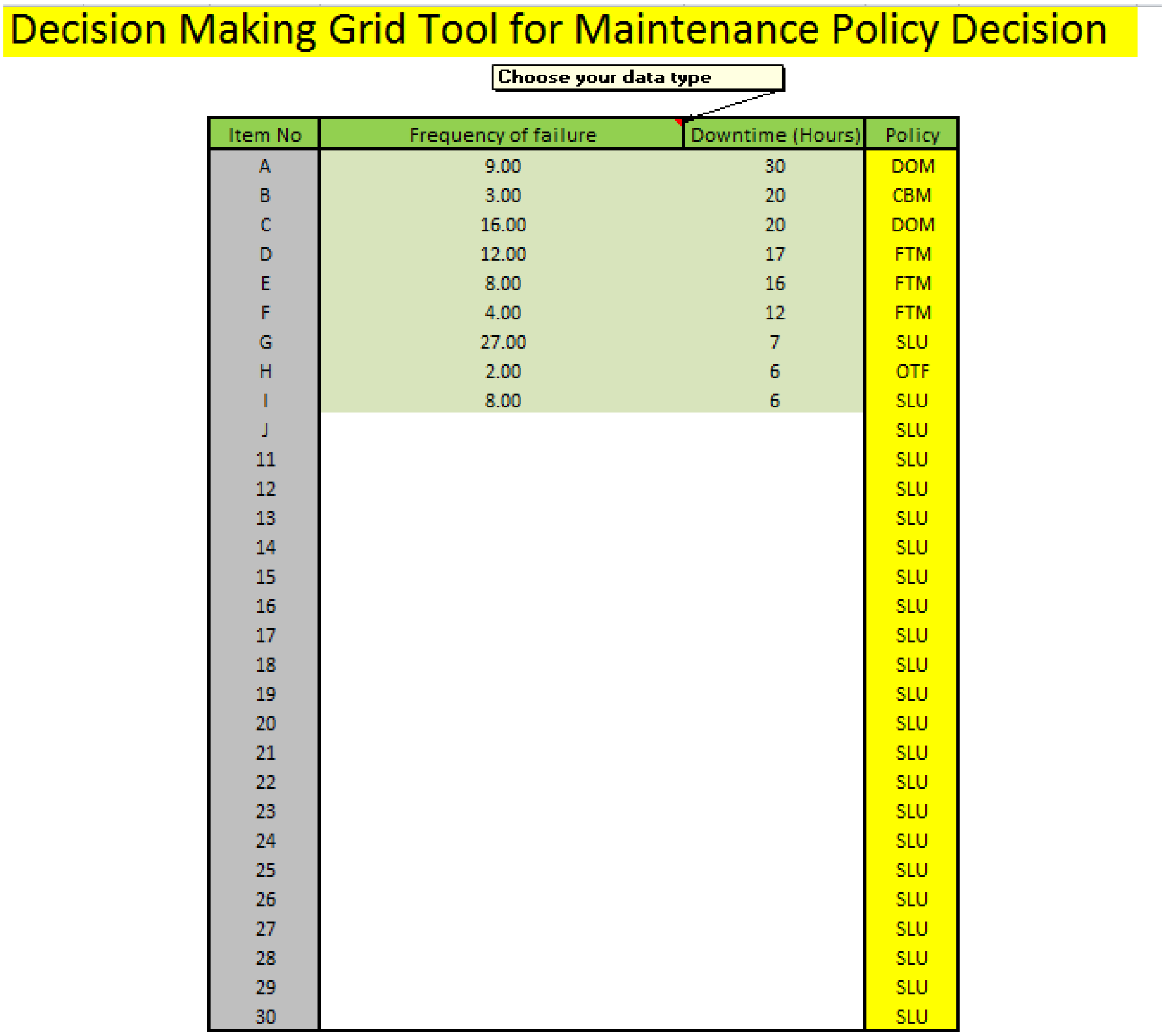


Figure 4.3.3: The Decision Making Grid from the Analysis [21]

From Reference [21] it is stated that for machine that is located at the top right region, it does not breakdown often (low frequency), but when it does it will lasts for a long time (high downtime). In this case the appropriate action to take is to analyze the breakdown events and closely monitor its condition, i.e. condition base monitoring (CBM). Machine in the bottom-right region is the worst performing machine on both criteria; a machine that maintenance engineers are used to seeing not working rather than performing normal duty such as Machine C. It needs to be structurally modified and major design out projects need to be considered, and hence the appropriate rule to implement will be design out maintenance (DOM). Preventive maintenance schedules are being ruled out for the medium downtime or a medium frequency. However, not all of the “medium” locations are the same. There are some that are near to the top left corner where the work is “easy” fixed time maintenance (FTM) – because the location is near to the OTF region – issues that need to be addressed include who will perform the work or when it will be carried out. For example, the performances of machine I is situated in the region between OTF and SLU and the question is about who will do the job – the operator, maintenance engineer, or subcontractor. Also, the position on the grid of a machine such as F has been shifted from the OTF region due to its relatively higher downtime and hence the timing of tasks needs to be addressed. Other preventive maintenance schedules need to be addressed in a different manner. The “difficult” FTM issues are the ones related to the contents of the job itself. It might be the case that the wrong problem is being solved or the right one is not being solved adequately. In this case machines such as A and D need to be investigated in terms of the contents of their preventive instructions and an expert advice is needed.



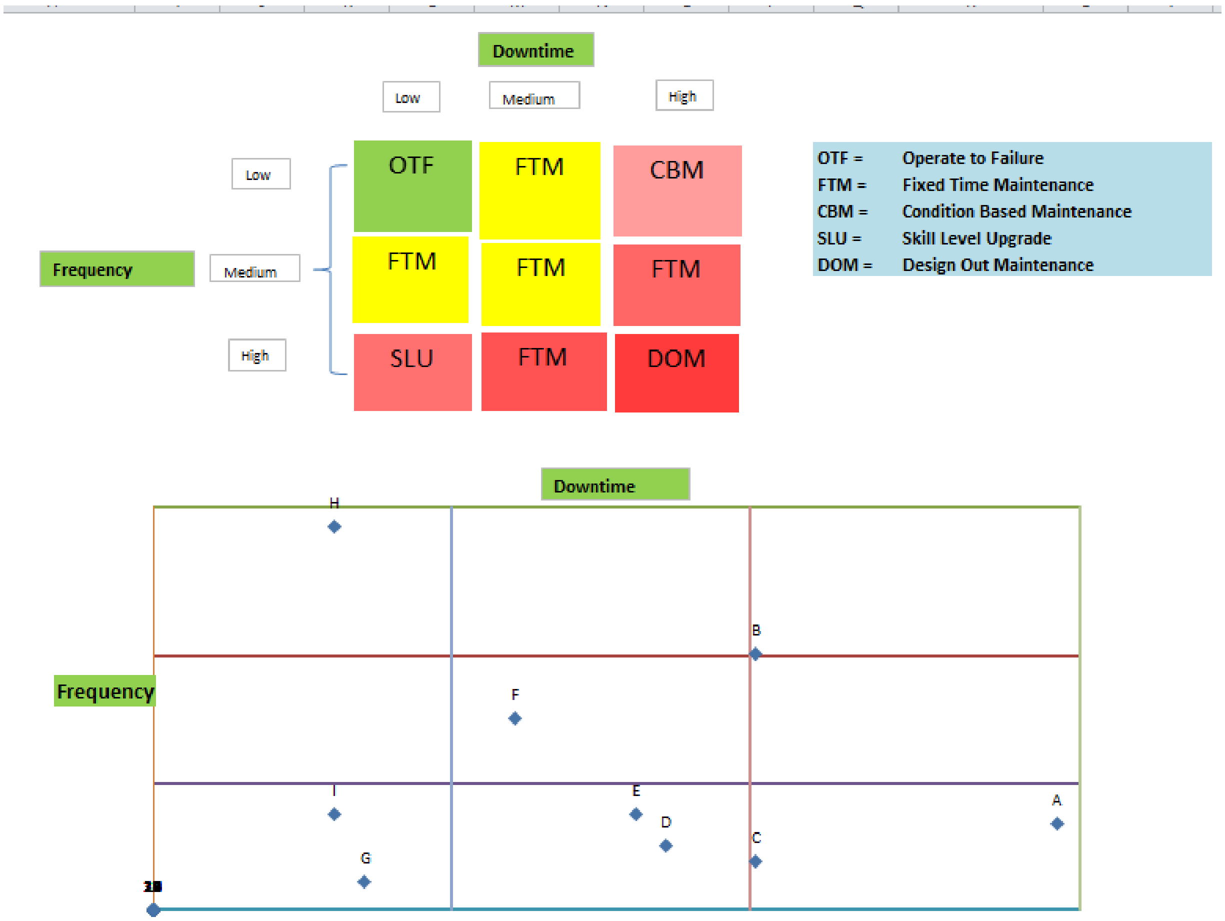
Decision Making Grid Tool for Maintenance Policy Decision

Choose your data type

Item No	Frequency of failure	Downtime (Hours)	Policy
A	9.00	30	DOM
B	3.00	20	CBM
C	16.00	20	DOM
D	12.00	17	FTM
E	8.00	16	FTM
F	4.00	12	FTM
G	27.00	7	SLU
H	2.00	6	OTF
I	8.00	6	SLU
J			SLU
11			SLU
12			SLU
13			SLU
14			SLU
15			SLU
16			SLU
17			SLU
18			SLU
19			SLU
20			SLU
21			SLU
22			SLU
23			SLU
24			SLU
25			SLU
26			SLU
27			SLU
28			SLU
29			SLU
30			SLU

Figure 4.3.4: Data input into DMG tool

The data type chosen is by frequency which is provided from Figure 4.3.3. Only data from Machine A to Machine I are used since Machine J and K have incomplete data. The frequency is taken from the figure.



	Low	Medium	High
Low	OTF	FTM	CBM
Medium	FTM	FTM	FTM
High	SLU	FTM	DOM

OTF = Operate to Failure
FTM = Fixed Time Maintenance
CBM = Condition Based Maintenance
SLU = Skill Level Upgrade
DOM = Design Out Maintenance

Figure 4.3.5: DMG obtained using the excel tool

Below are the comparison of Decision Making Grid from actual and the spreadsheet:

Table 4.3.1: Maintenance decision comparison

Maintenance Decision Comparison		
Machine	**Actual**	**From Spreadsheet**
A	**FTM**	**DOM**
B	**CBM**	**CBM**
C	**DOM**	**DOM**
D	**FTM**	**FTM**
E	**FTM**	**FTM**
F	**FTM**	**FTM**
G	**SLU**	**SLU**
H	**OTF**	**OTF**
I	**FTM**	**SLU**

From the table Machine A and Machine I have different maintenance decision when using the spreadsheet, this is due to the tool actually calculate the downtime and frequency/MTBF based from the following formula:

Let h be the highest value as stated in the list in Reference [23]:

$$\text{High value} = \text{Highest value} = h$$

$$\text{Highest value} = \text{Medium to high value} = h - 1/3$$

$$\text{Highest value} = \text{Medium to low value} = h - 2/3$$

$$\text{Low value} = \text{Lowest value} = 1$$

The result differs because the author from Reference [21] has set his own range of criteria whereas this tool set its range to be in incremental of one third from the highest value.

4.4: Case study 2: Using data from Reference [20]

Title: Developing Decision Making Grid for Maintenance Policy Making Based on Estimated Range of Overall Equipment Effectiveness

Introduction:

In today world of competition, one of critical success factors influencing survival, profitability, and competitive advantage of manufacturing organizations is to select appropriate maintenance policy. While decision making grid (DMG) provides a relatively comprehensive perspective to managers for policy making, its criteria does not include overall equipment effectiveness (OEE), perhaps since OEE is mostly used in one of the policies, i.e. total productive maintenance (TPM). In this article, the traditional DMG has been modified, in which the range of OEE has been estimated and replaced by one of the grid's criteria. A case study has been conducted in one of the steel manufacturing companies of Iran and data has been obtained and analyzed from 30 machines of the company. The major finding of this investigation is that although OEE is an indicator of TPM, its different values might suggest different policies in addition to TPM.

Table 4.4.1: Equipment Data from Reference [20]

Eq. No.	MTBF(Hr)	MTTR(Hr)	Availability(%)	Performance(%)	Quality(%)	OEE(%)
1	185.9	3.18	98.32	92.1	100	91
2	185.2	3.86	97.96	94.2	96.88	89
3	181.5	7.5	96.03	96.3	83.54	77
4	174.3	14.7	92.22	82	83.53	63
5	176.6	12.44	93.24	87	92.8	75
6	179.7	9.34	95.06	88	91	76
7	13	26	33	73	83.54	20
8	164.9	24.18	87.21	81	83	59
9	168.8	20.23	88.3	83	85	62
10	13	28	32	76	97	32
11	174.6	43.66	80	84	77	52
12	136	32	81	59	90	43
13	48	24	67	64	90	38
14	13.36	10.64	55.67	59.88	92	30.66
15	128.6	34	87	94	91	74
16	12.33	21	37	54	80	16
17	191.7	16.67	92	89	62.3	51
18	19.1	15	56	85	73.5	35
19	26.59	17	61	89	64.5	35
20	132.2	36	78.6	64.3	92.8	47
21	157	12	92.9	52.4	97.3	47.4
22	153.5	15	91.1	66.8	97.3	59.2
23	187	22	89.5	81	95	69
24	29	62	32	52	86	14
25	180	23	89	55	91	45
26	35	32	52	49	92	23
27	30	78	52	63	92	30
28	18	51	26	55	90	13
29	16	54	23	50	88	10
30	120	75	62	73	92	42

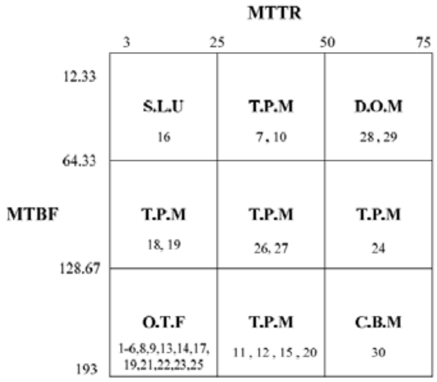
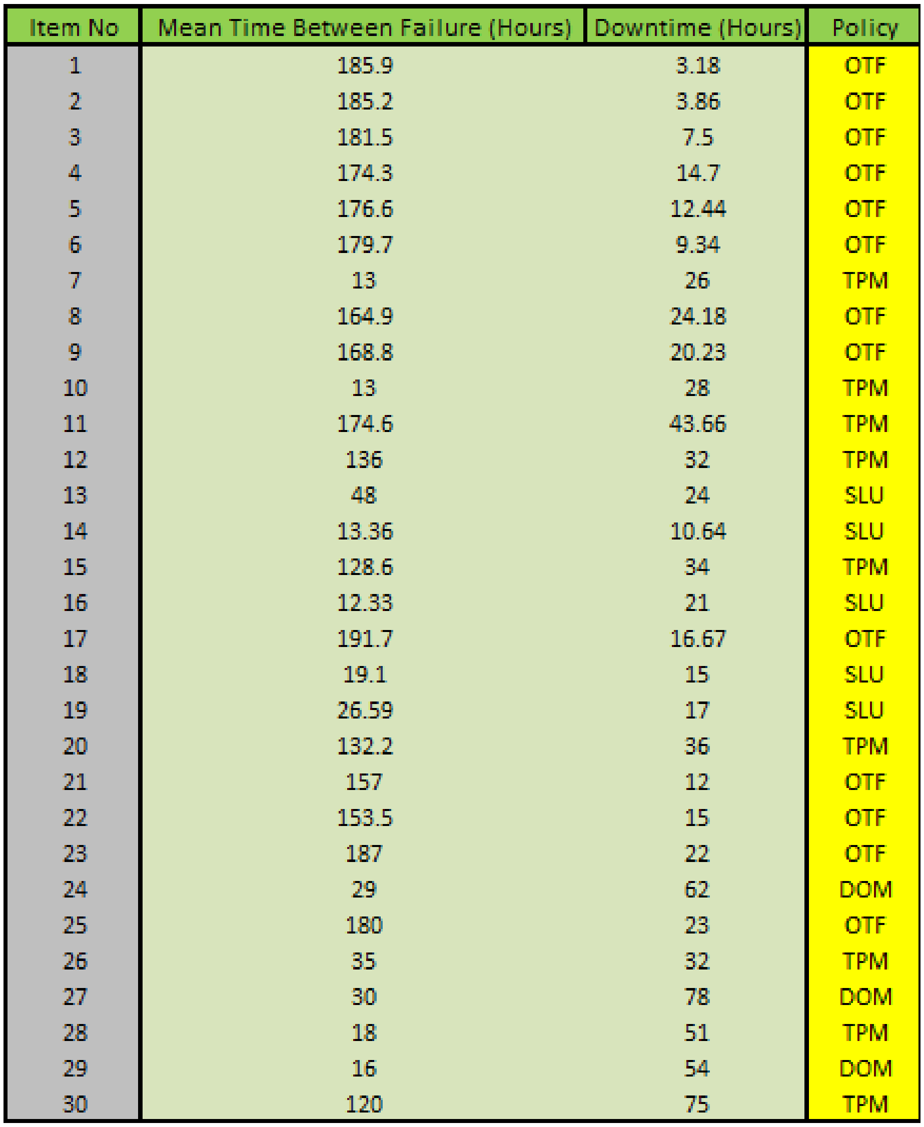
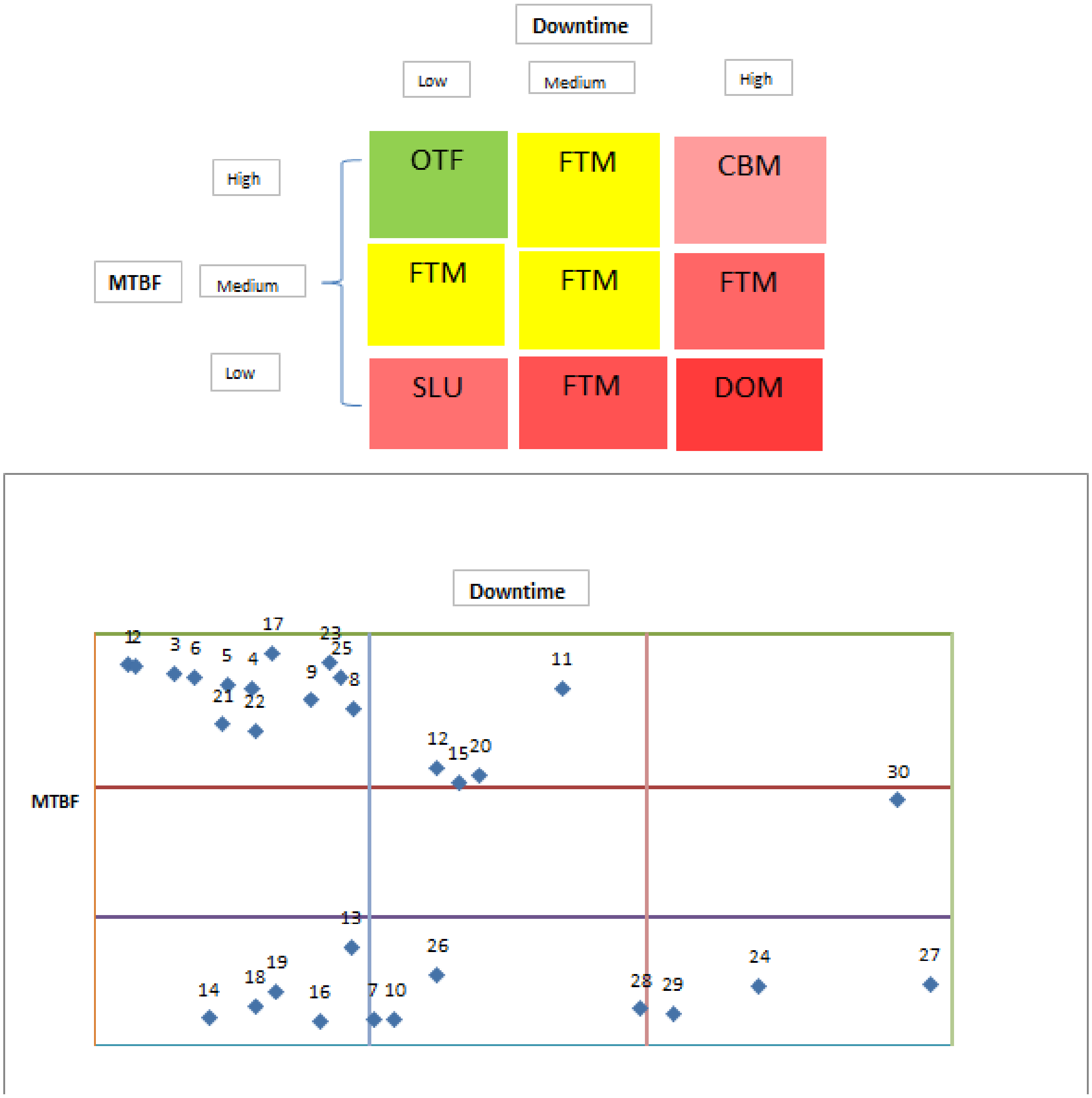


Figure 4.4.1: Decision Making Grid from Reference [20]



Item No	Mean Time Between Failure (Hours)	Downtime (Hours)	Policy
1	185.9	3.18	OTF
2	185.2	3.86	OTF
3	181.5	7.5	OTF
4	174.3	14.7	OTF
5	176.6	12.44	OTF
6	179.7	9.34	OTF
7	13	26	TPM
8	164.9	24.18	OTF
9	168.8	20.23	OTF
10	13	28	TPM
11	174.6	43.66	TPM
12	136	32	TPM
13	48	24	SLU
14	13.36	10.64	SLU
15	128.6	34	TPM
16	12.33	21	SLU
17	191.7	16.67	OTF
18	19.1	15	SLU
19	26.59	17	SLU
20	132.2	36	TPM
21	157	12	OTF
22	153.5	15	OTF
23	187	22	OTF
24	29	62	DOM
25	180	23	OTF
26	35	32	TPM
27	30	78	DOM
28	18	51	TPM
29	16	54	DOM
30	120	75	TPM

Figure 4.4.2: Data Input into DMG Tool



	Low	Medium	High
High	OTF	FTM	CBM
Medium	FTM	FTM	FTM
Low	SLU	FTM	DOM

Figure 4.4.3: Decision Making Grid obtained using the excel tool for Reference [20]

Table 4.4.2: Maintenance Decision Comparison

Maintenance Decision Comparison		
Equipment	**Actual**	**From Spreadsheet**
1	OTF	OTF
2	OTF	OTF
3	OTF	OTF
4	OTF	OTF
5	OTF	OTF
6	OTF	OTF
7	FTM	FTM
8	OTF	OTF
9	OTF	OTF
10	FTM	FTM
11	FTM	FTM
12	FTM	FTM
13	OTF	SLU
14	OTF	SLU
15	FTM	FTM
16	SLU	SLU
17	OTF	OTF
18	FTM	SLU
19	FTM	SLU
20	FTM	FTM
21	OTF	OTF
22	OTF	OTF
23	OTF	OTF
24	FTM	DOM
25	OTF	OTF
26	FTM	FTM
27	FTM	DOM
28	DOM	FTM
29	DOM	DOM
30	CBM	FTM

Equipment 18, 19, 24, 27, 28 and 30 from the tool have different maintenance decision from the actual data. After done checking for errors, the cause for the differences is the incorrect positioning of the equipment in the DMG of the case study. Equipment 18 which have MTBF of 26.59 hours should be in the SLU region whereas Equipment 19 with 132.2 hours should be in the OTF region. Same cases applied to Equipment 24, 27, 28 and 30.

Errors in positioning equipment in the DMG may cause in an increased cost for equipment that does not work best with the designated maintenance policy.

Key Milestone

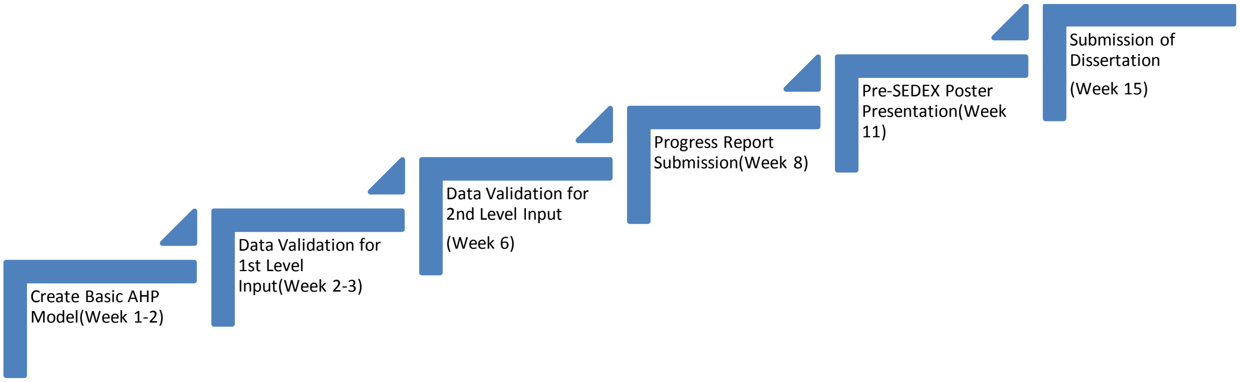
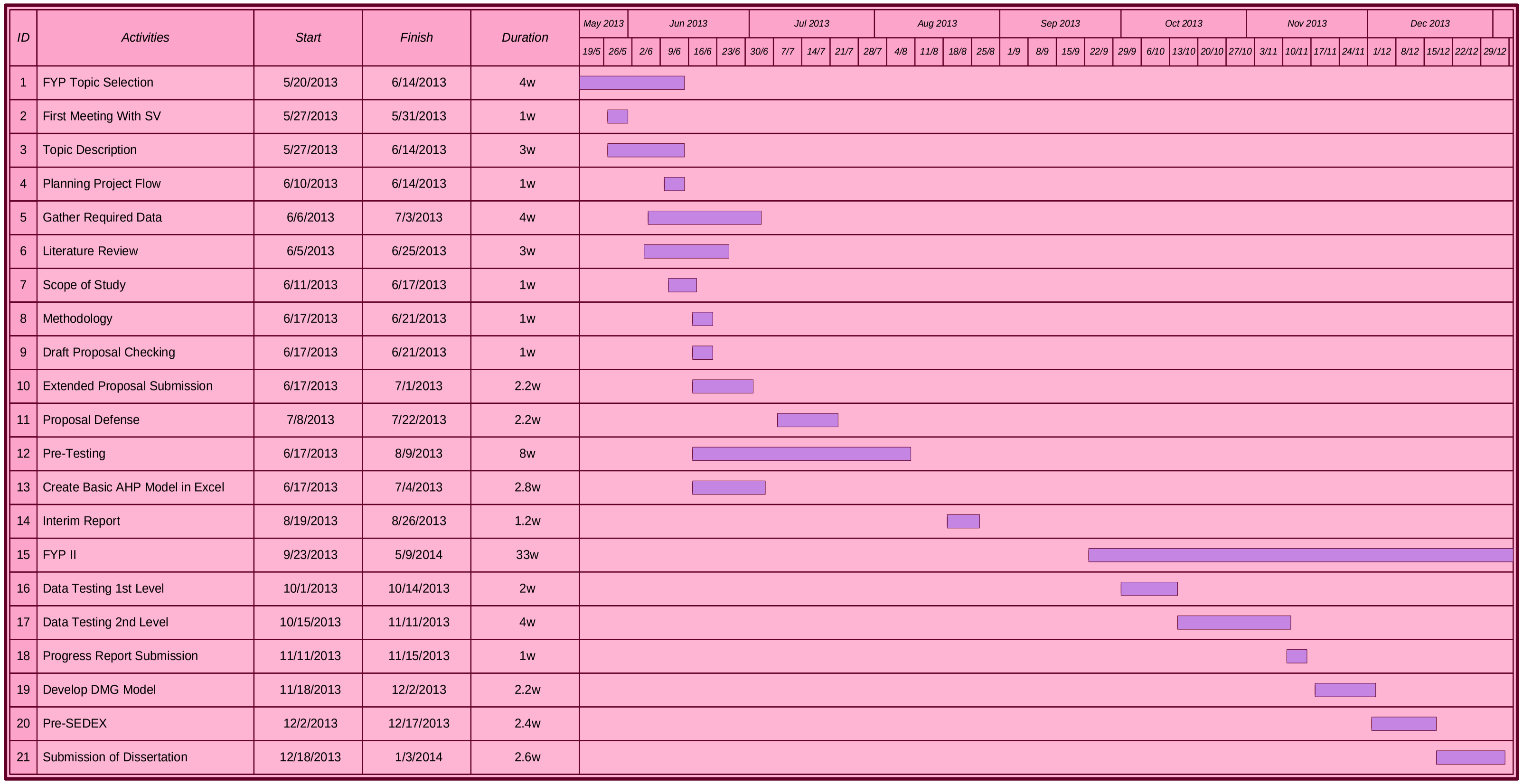


Figure 4.5.1: Key Milestone



ID	Activities	Start	Finish	Duration
1	FYP Topic Selection	5/20/2013	6/14/2013	4w
2	First Meeting With SV	5/27/2013	5/31/2013	1w
3	Topic Description	5/27/2013	6/14/2013	3w
4	Planning Project Flow	6/10/2013	6/14/2013	1w
5	Gather Required Data	6/6/2013	7/3/2013	4w
6	Literature Review	6/5/2013	6/25/2013	3w
7	Scope of Study	6/11/2013	6/17/2013	1w
8	Methodology	6/17/2013	6/21/2013	1w
9	Draft Proposal Checking	6/17/2013	6/21/2013	1w
10	Extended Proposal Submission	6/17/2013	7/1/2013	2.2w
11	Proposal Defense	7/8/2013	7/22/2013	2.2w
12	Pre-Testing	6/17/2013	8/9/2013	8w
13	Create Basic AHP Model in Excel	6/17/2013	7/4/2013	2.8w
14	Interim Report	8/19/2013	8/26/2013	1.2w
15	FYP II	9/23/2013	5/9/2014	33w
16	Data Testing 1st Level	10/1/2013	10/14/2013	2w
17	Data Testing 2nd Level	10/15/2013	11/11/2013	4w
18	Progress Report Submission	11/11/2013	11/15/2013	1w
19	Develop DMG Model	11/18/2013	12/2/2013	2.2w
20	Pre-SEDEX	12/2/2013	12/17/2013	2.4w
21	Submission of Dissertation	12/18/2013	1/3/2014	2.6w

Figure 4.5.2: Gantt

CHAPTER 5

CONLUSION AND RECOMMENDATION

As conclusion, if all of the steps for the development of the spread sheet are followed, the best maintenance policy can be selected by using both of these models. The user can select either to choose AHP or DMG as their decision making tool. The project can help those who want to decide the best alternative to be used. Furthermore, the advantages of using these tools are:

1) The hassle of calculating manually can be lifted.
2) The user can use the tool for other purposes not limited to maintenance policy selection.
3) The possibility of creating human error can be much less reduced.
4) By following the steps and guidelines stated in the worksheet, the user can easily get their result.

Since the work sheet is still limited to certain number of inputs, a lot of improvements can be made to make the tool more useful in the future.
Below are the improvement and activities that can be done:

- Simplifying user inputs for both AHP and DMG model.
- Adding more levels of criteria for the AHP tool.
- Implementing Visual Basic Applications to make the tool more user friendly.

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APPENDICES

<u>The guidelines provided for the user are as follows:</u>

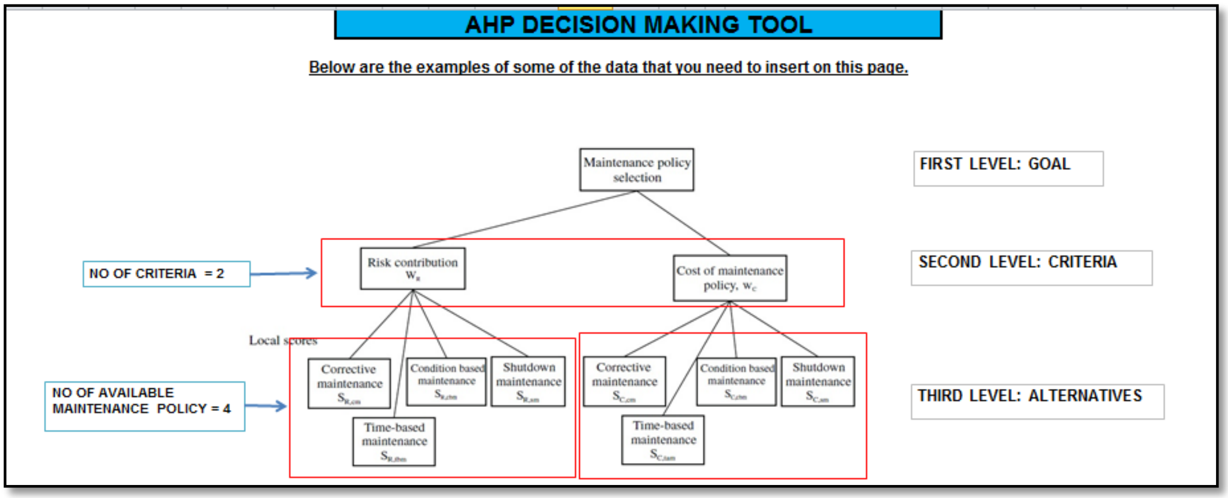
AHP Excel Template with Multiple Inputs for Maintenance Policy Decision

Introduction

The AHP template works under Windows OS and Excel version MS Excel 2010 (xlsx extension). The workbook consists of 11 input worksheets for pair-wise comparisons, a summary sheet to display the result, a sheet with reference tables (random index, judgment scales) and 10 sheets for solving the eigenvalue problem when using the eigenvector method (EVM).

Below are the limitations of this tool:

1. Maximum no of criteria as input: 10
2. Maximum no of available maintenance policy as input:10



AHP DECISION MAKING TOOL

Below are the examples of some of the data that you need to insert on this page.

Figure 1: Example- Hierarchical structure for maintenance policy decision of 5C-01 Rerun Column Equipment

On the summary sheet of the spread sheet, the example of the hierarchical structure for determining the maintenance policy is shown at the top of the worksheet. In order to use the template, we need to insert data for the following input:

1. The criteria which are located at the second level.
2. The alternatives available for each of the criteria chosen.
3. The measure of importance between criteria.
4. The measure of importance between alternatives of the criteria.

Please follow the blue callouts according to its numbering sequence and insert your data:

1 Insert your objective here.

2 Insert your name here.

3 Insert date.

4 Input number of criteria. (From example above, the no. of criteria = 2)

5 Insert the scale of your evaluation.

6 Enter your minimum consistency of acceptance (%)

7 Insert the criteria available for evaluation.

8 Insert any comments regarding the criteria chosen.

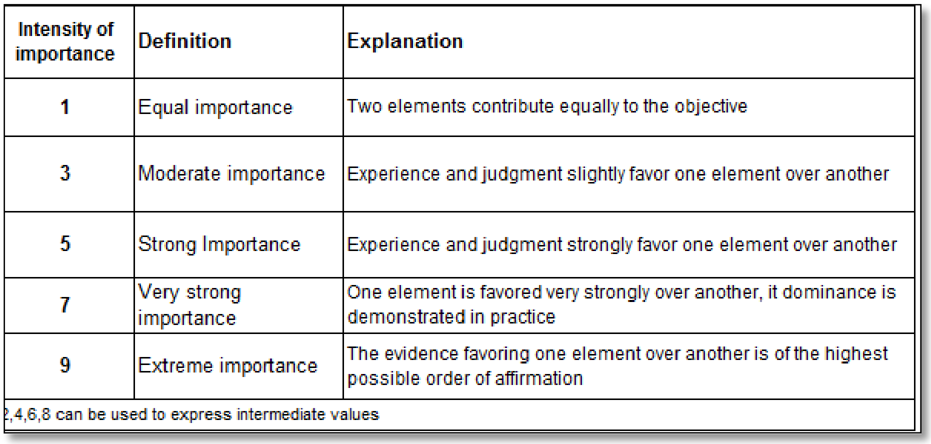
9 Insert the number of available maintenance policies. (From example above, the no. of available maintenance policy is 4.

10 Insert the types of maintenance policy available for this evaluation.

11

Click on the “Main Criteria” worksheet and find the green highlighted cells which are under the “A or B” and “(1-9)” column. Insert your evaluation into the cells.

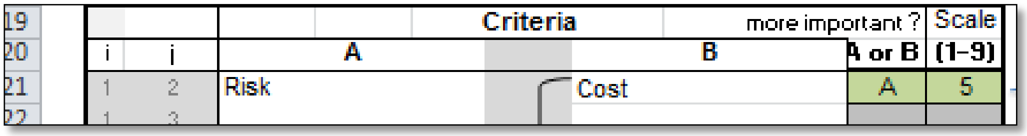
After done inputting the values, we can refer to the values of consistency ratio of our measurement, if it is bigger than α which is the minimum consistency of acceptance we need to adjust our measurement until it is within the value. At the bottom of the page the explanation of intensities (scale) is shown:



Intensity of importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

2,4,6,8 can be used to express intermediate values

Below are the example for Figure 1 which shows that Risk is 5 times more important than Cost:



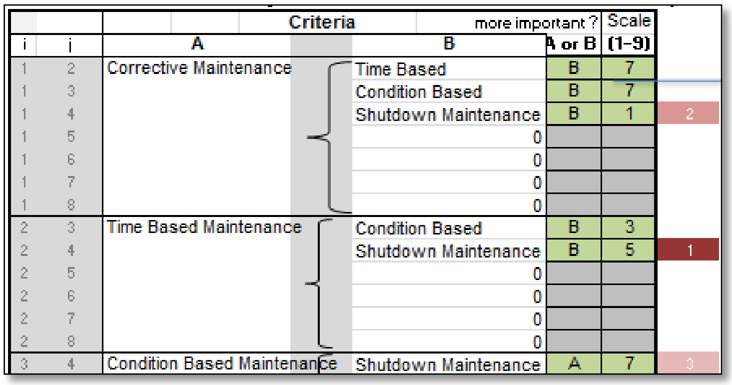
19			Criteria		more important ?	Scale
20	i	j	A	B	A or B	(1-9)
21	1	2	Risk	Cost	A	5
22	1	3				

12

Click on the “Criteria 1” worksheet and find the green highlighted cells which are under the “A or B” and “(1-9)” column.

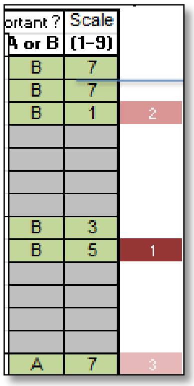
Insert your evaluation into the cells. After done inserting the values, we can refer to the values of consistency ratio of our measurement, if it is bigger than α which is the minimum consistency of acceptance, we need to adjust our measurement until it is within the value.

Below are the examples for Figure 1 which shows the measure of each of the available alternatives:



		Criteria		more important ?	Scale	
i	j	A	B	A or B	(1-9)	
1	2	Corrective Maintenance	Time Based	B	7	
1	3		Condition Based	B	7	
1	4		Shutdown Maintenance	B	1	2
1	5		0			
1	6		0			
1	7		0			
1	8		0			
2	3	Time Based Maintenance	Condition Based	B	3	
2	4		Shutdown Maintenance	B	5	1
2	5		0			
2	6		0			
2	7		0			
2	8		0			
3	4	Condition Based Maintenance	Shutdown Maintenance	A	7	3

Repeat the same step by choosing the next criteria worksheet (Criteria 2 until Criteria 10). From our example we currently have 2 criteria therefore we fill in the data until "Criteria 2" worksheet.



ortant ?	Scale	
A or B	(1-9)	
B	7	
B	7	
B	1	2
B	3	
B	5	1
A	7	3

This is an indication of inconsistent inputs.

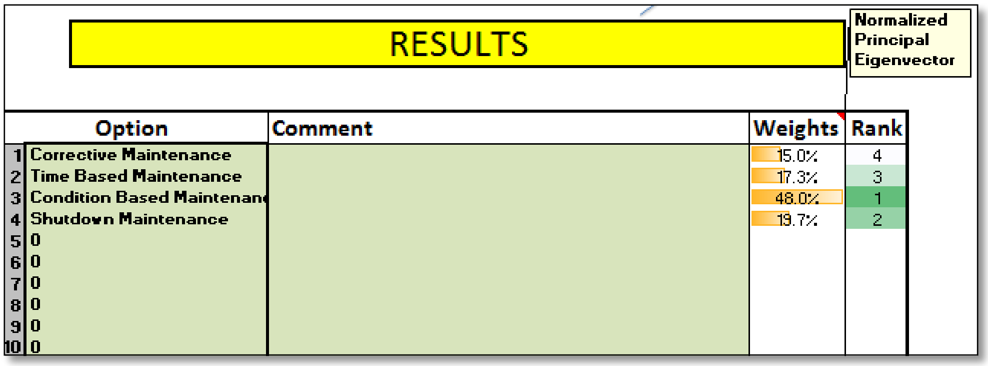
Note: Please complete all comparisons first.

When all comparisons are completed, and still some lines are highlighted, the user can slightly modify the highlighted judgments by modifying the intensities to achieve better consistency. The comparison with the highest inconsistency is marked with "1". Increase or decrease the intensity and observe the consistency ratio at the top of the table.

13

Finally the result will be shown on the summary sheet. They are calculated using the normalized principal eigenvector method. All the weights and rank for each criterion are shown on the same worksheet.

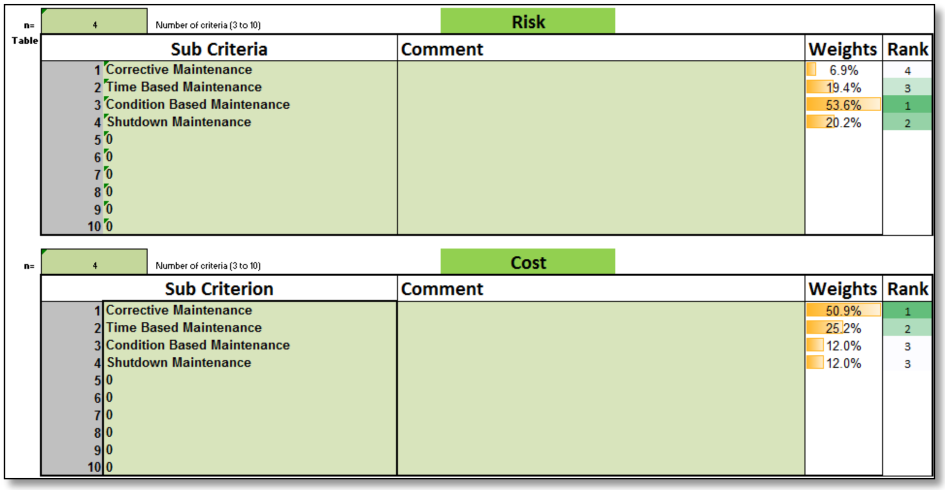
Below are the examples of the result from Figure 1:



RESULTS

Normalized Principal Eigenvector

	Option	Comment	Weights	Rank
1	Corrective Maintenance		15.0%	4
2	Time Based Maintenance		17.3%	3
3	Condition Based Maintenanc		48.0%	1
4	Shutdown Maintenance		19.7%	2
5	0			
6	0			
7	0			
8	0			
9	0			
10	0			



n= 4 Number of criteria (3 to 10)

Risk

Table

	Sub Criteria	Comment	Weights	Rank
1	Corrective Maintenance		6.9%	4
2	Time Based Maintenance		19.4%	3
3	Condition Based Maintenance		53.6%	1
4	Shutdown Maintenance		20.2%	2
5	0			
6	0			
7	0			
8	0			
9	0			
10	0			

n= 4 Number of criteria (3 to 10)

Cost

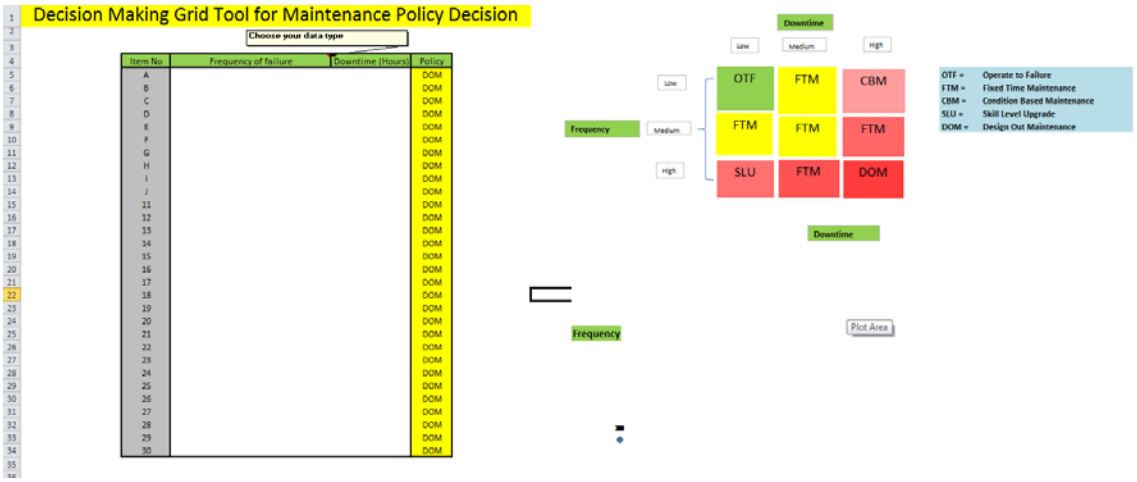
	Sub Criterion	Comment	Weights	Rank
1	Corrective Maintenance		50.9%	1
2	Time Based Maintenance		25.2%	2
3	Condition Based Maintenance		12.0%	3
4	Shutdown Maintenance		12.0%	3
5	0			
6	0			
7	0			
8	0			
9	0			
10	0			

Decision Making Grid Excel Template with multiple Inputs

The DMG template works under Windows OS and Excel version MS Excel 2010 (xlsx extension). The workbook consists of one input worksheet which displays the input cells and results on the Decision Making Grid for maintenance policies.

Limitations:

1. Maximum number of items/equipment: 30
2. Mean Time Between Failure (MTBF) and Downtime should be of the same unit.
3. Only 5 maintenance policies are available for this tool.



Decision Making Grid Tool for Maintenance Policy Decision

Choose your data type

Item No	Frequency of failure	Downtime (Hours)	Policy
A			DOM
B			DOM
C			DOM
D			DOM
E			DOM
F			DOM
G			DOM
H			DOM
I			DOM
J			DOM
11			DOM
12			DOM
13			DOM
14			DOM
15			DOM
16			DOM
17			DOM
18			DOM
19			DOM
20			DOM
21			DOM
22			DOM
23			DOM
24			DOM
25			DOM
26			DOM
27			DOM
28			DOM
29			DOM
30			DOM

	Low	Medium	High
Low	OTF	FTM	CBM
Medium	FTM	FTM	FTM
High	SLU	FTM	DOM

OTF = Operate to Failure
FTM = Fixed Time Maintenance
CBM = Condition Based Maintenance
SLU = Skill Level Upgrade
DOM = Design Out Maintenance

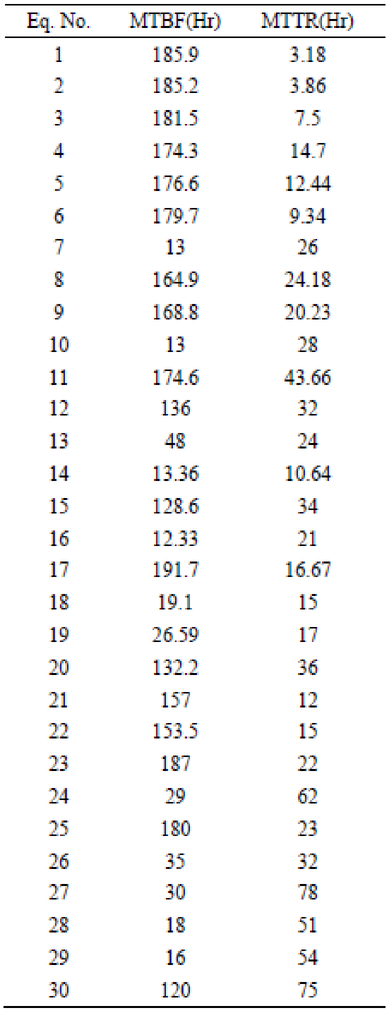
Figure 1: Decision Making Grid (Labib, 1998)

Procedure of using the tool:

1. Insert the item name/number on the first column of the table.
2. Choose the data type by selecting from the dropdown list. (Frequency of failure or MTBF)
3. Insert the Mean Time Between Failure (MTBF) or Frequency of failure on the second column.
4. Insert the downtime of the item on the third column.
5. The location of the item will then be shown in the grid along with the suitable maintenance policy.

Below is the example of the grid obtained based on the following data:

Table 1: Data obtained from equipments



Eq. No.	MTBF(Hr)	MTTR(Hr)
1	185.9	3.18
2	185.2	3.86
3	181.5	7.5
4	174.3	14.7
5	176.6	12.44
6	179.7	9.34
7	13	26
8	164.9	24.18
9	168.8	20.23
10	13	28
11	174.6	43.66
12	136	32
13	48	24
14	13.36	10.64
15	128.6	34
16	12.33	21
17	191.7	16.67
18	19.1	15
19	26.59	17
20	132.2	36
21	157	12
22	153.5	15
23	187	22
24	29	62
25	180	23
26	35	32
27	30	78
28	18	51
29	16	54
30	120	75

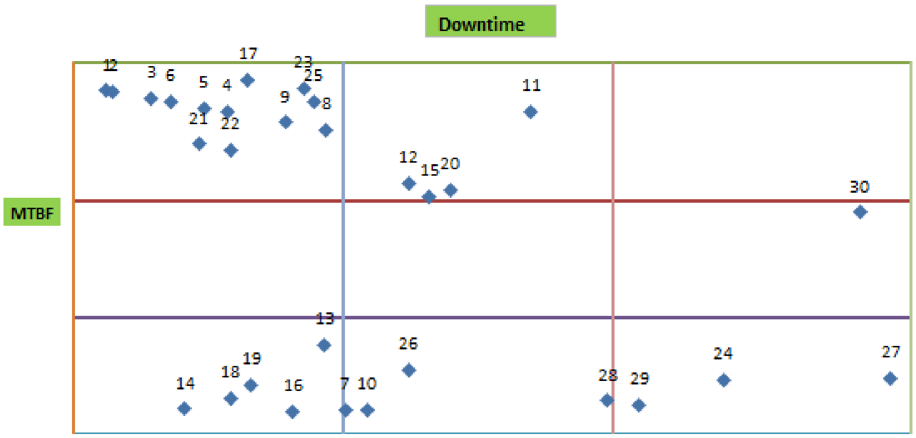
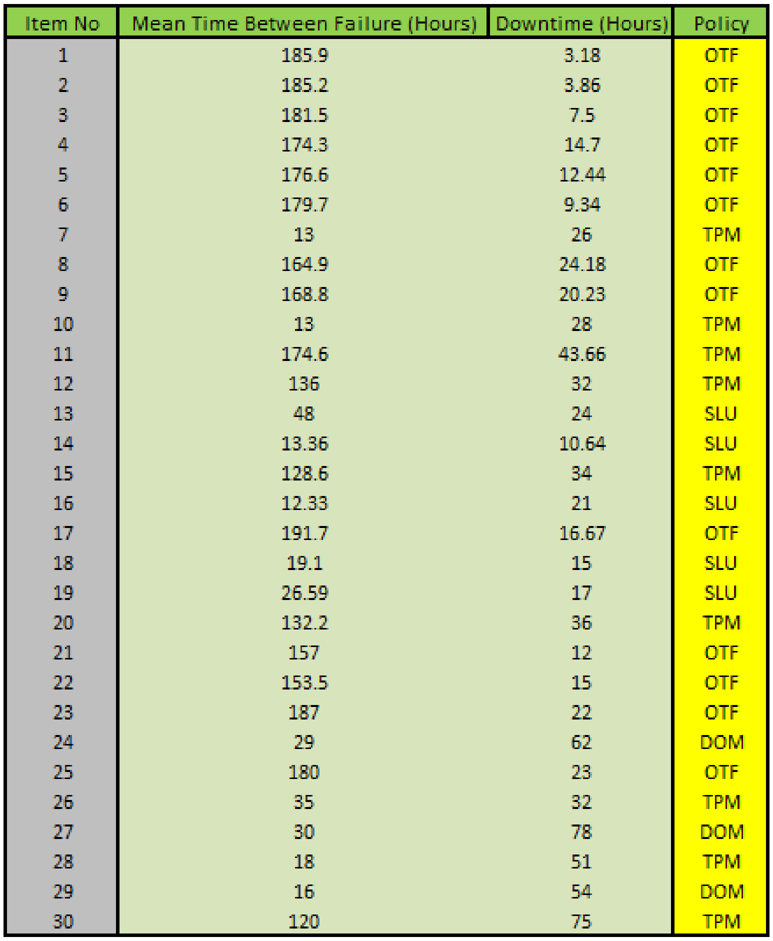


Figure 2: Grid obtained based on user input

The grid follows the arrangement from **Figure 1**. For example, the grid shows that item no 11, 12, 15 and 20 are best to be maintained using the Fixed Time Maintenance. We can also get the results from the fourth column of the table located in the worksheet.



Item No	Mean Time Between Failure (Hours)	Downtime (Hours)	Policy
1	185.9	3.18	OTF
2	185.2	3.86	OTF
3	181.5	7.5	OTF
4	174.3	14.7	OTF
5	176.6	12.44	OTF
6	179.7	9.34	OTF
7	13	26	TPM
8	164.9	24.18	OTF
9	168.8	20.23	OTF
10	13	28	TPM
11	174.6	43.66	TPM
12	136	32	TPM
13	48	24	SLU
14	13.36	10.64	SLU
15	128.6	34	TPM
16	12.33	21	SLU
17	191.7	16.67	OTF
18	19.1	15	SLU
19	26.59	17	SLU
20	132.2	36	TPM
21	157	12	OTF
22	153.5	15	OTF
23	187	22	OTF
24	29	62	DOM
25	180	23	OTF
26	35	32	TPM
27	30	78	DOM
28	18	51	TPM
29	16	54	DOM
30	120	75	TPM