ANALYTIC HIERARCHY PROCESS APPROACH FOR SELECTION AND EVALUATION OF MAINTENANCE STRATEGY

by

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12262

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons.)
(Mechanical Engineering)

MAY 2013

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
In partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

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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 acknowledgments, and that the original work contained herein have not been undertaken nor done unspecified sources or persons.

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ABSTRACT

Selection of suitable maintenance strategy has always been vital for the industries. The selection deals with the large number of tangible and intangible attributes. Estimation of the optimal maintenance strategies for the different failure modes represents the main complexity of the selection process. Equipment, as well as the available maintenance facilities, tools and capabilities delimit the selection of the type of maintenance. In many cases, the selection requires the knowledge of various factors such as safety aspects, environmental problems, costs and budget constraints, manpower utilization and etc.

This project presents Analytic Hierarchy Process (AHP) approach to define the best strategies for maintenance of mechanical systems or equipment. The main objective is to develop an application, which would assist in quick selection of maintenance strategy using AHP. User friendly application is developed to assist the user in selection, and weighting the criterions and alternatives. The final output is the scores of each maintenance strategy that will aid in ranking. However, the user is also offered predetermined sets of weightings of criterions and alternatives that are dependent on risk analysis results. Since risk contributes towards decision making by affecting the weighting considerations, the classic definition of risk that accounts both the probability and consequence of accident or failure is also considered, and equipment can be categorized into four risk zones based user's judgment or assessment results, if any conducted. The developed decision framework is tested for validity of results with help of two case studies. The results obtained prove the validity of developed framework.

ACKNOWLEDGEMENT

I would like to deliver my utmost gratitude and appreciation to all those, who provided me the possibility to complete my Final Year Project and the report. Sincere appreciation is dedicated to my Supervisor Dr. Ainul Akmar Binti Mokhtar, who have helped me in selection of the project title and guided me throughout the whole final year project with handful advices and dedicative monitoring.

A special thanks goes to my friends, who helped me in the areas I needed guidance in. I thank my family for helping me mentally and emotionally in hard times. Lastly, I would like to show gratitude to GOD for giving me the courage and strength to go through this task and for keeping me in pink of health through this journey.

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ABBREVIATIONS

AHP – Analytic Hierarchy Process

CM – Corrective Maintenance

CBM – Condition-based Maintenance

PM - Preventive Maintenance

RBM – Reliability-Centered Maintenance

TBM – Time-Based Maintenance

RBI – Risk-Based Inspection

IR – Inconsistency Ratio

CI – Consistency Index

VBA – Visual Basic Application

NOMECLATURE

λ_{max} – Principal Eigenvalue

A_w – Largest Eigenvalue

CHAPTER 1
INTRODUCTION

1.1 PROJECT BACKGROUND

In the era of high competitiveness, companies decide on competing in the market based on worthwhile priorities like cost, quality, flexibility and etc. Equipment maintenance, as an integral part of industrial business or manufacturing, can influence these competitive priorities and hence the business strategy directly in a negative or positive way (Srinivas , Pintelona, & Vereeckeb, 2006). The unforeseen failures, the down time associated and loss of production with these failures, as well as the higher maintenance costs are major problems in any process plant (Krishnasamy & Khan, 2005). In this regard, making use of the knowledge of failures and accidents to achieve the potential safety with the lowest possible cost is the universal objective of the maintenance process (Arunraj & Maiti, 2007). In addition, maintenance plays an important role in keeping availability and reliability at requited levels, maintaining product quality and adhering to safety requirements. Consequently, many companies develop or implement various kinds of maintenance strategies, depending on type of industry they are involved in, product output or equipment in use, processes involved, operational conditions (risk and hazard level) and etc. The variety of maintenance strategies has increased drastically over past few decades. Corrective Maintenance, Predictive Maintenance, Preventive maintenance, Reliability- Centered Maintenance and the most recent Risk-Based Maintenance are some of the examples of the variety of strategies available.

Based on above, it is not a matter of doubt that selection of proper maintenance plan and strategy for a plant, system or equipment significantly reduces the total operating cost and at the same time retains the productivity. Significance of maintenance policy selection may shrink, when it brought down to applications, where risk and hazard associated with mechanical systems or equipment is low and not considerable. So, it is important to consider the prominence of risk state, at which the equipment is.

Risk associated with equipment has a lot to do with type of maintenance policy to be selected. Therefore, it carries validity for implementation of thorough approach for selection, and risk state of equipment or system is deemed to be integral part of it.

1.2 PROBLEM STATEMENT

Unfortunately, in the past, different from production and manufacturing problems, which have received tremendous interest from researchers and practitioners, maintenance received a petite attention. This is one of the reasons that results in low maintenance efficiency in some of the industries at present (Ling Wanga , Jian Chua, & Jun Wub, 2007). As indicated by Ling Wanga (2007), one third of all maintenance costs are wasted as the result of unnecessary or improper maintenance activities. This again stresses on importance of selection of proper maintenance strategy.

The managers or maintenance engineers, in charge, are responsible for selection of the best maintenance strategy for each piece of equipment or system from a set of potential alternatives. Dealing with the large number of tangible and intangible attributes, as well as estimating the optimal maintenance strategies for the different failure modes represents the main complexity of the problem for them (Bertolini & Bevilacqua, 2005). Equipment, as well as the available maintenance facilities, tools and capabilities delimit the selection of the type of maintenance. In many cases, the selection requires the knowledge of various factors such as safety aspects, environmental problems, costs and budget constraints, manpower utilization and etc. Various kinds of maintenance strategies can be defined both at a system level and at a component level. Examples of those are given in the literature review chapter. A common practice for any systems is to group the components with similar operating conditions that can be treated uniformly during maintenance (Arunraj & Maiti, 2007). Oil refineries can serve as an example for such complex systems. Proposed selection framework also requires such classification tool. These sorts of systems require an outsized amount of quantitative data. Simplifying the method of selection for such structures could end in less accurate result.

Many authors have developed frameworks for classification of components of complex systems, which enables easy selection of maintenance policy. Whether for complex systems or not, the selection process involves multipart decision making, where no unique or the best approach exists. Analytic Hierarchy Process is one the most popular tools that deal with complex decision making and applied in selection of maintenance strategy. This project also adopts AHP for selection of maintenance strategy for mechanical systems.

According to Khan & Haddara (2003), maximizing availability and efficiency of the equipment, controlling the rate of equipment deterioration, ensuring the safe and environmentally friendly operation and minimizing the total cost of the operation are the main challenges of the maintenance engineer in selection and implementation of the maintenance strategy. As stated by Bertolini & Bevilacqua (2000), there are not many studies that deal with the analysis and development of maintenance policy selection. Most of the decision-making techniques that are available for selections of maintenance strategy are too complex, time consuming or in some cases, even, unreasonable for implementation for small systems of component. So challenge was to simplify selection decision making process based on the existing techniques, and to adapt it to complex systems, where classification of components is required, as well as their component level or single equipment.

1.3 OBJECTIVES

Objectives of the project are as follows:

- To develop a decision making framework for selection of suitable maintenance strategy using AHP, which is relatively simple in structure and quick in obtaining the results
- To develop user friendly windows application using Visual Basic Application (VBA) based on the framework developed
- To test correct functioning and valid outputs of application using case study by S.O. Odeyale et al (2013).
- To assess and identify the feasibility of the approach, suitable application areas, conditions and constraints related to combined approach

1.4 SCOPE OF STUDY

Several complex combinations of AHP with lexicographic goal programming and other variations of decision making frameworks were developed over the past decades. After thorough analysis of existing techniques, it was decided to narrow down the studies on combined risk assessment and AHP method that could be simplified and redeveloped according to the objective. Preventive Maintenance (PM), Condition-Based Maintenance (CBM), Corrective Maintenance (CM) and Reliability-Centered Maintenance are the set of maintenance policy alternatives chosen for selection. As mentioned before, whether the application is functioning correctly or not, as well the validity of the output results will be tested by a case study of S.O. Odeyale and his colleagues.

To aid the decision maker in his decision making, the application should make it available to load preset values of pairwise comparison that are derived from the risk assessment and analysis results or just by experienced personnel, who is able to categorize the risk associated with particular equipment under study.

CHAPTER 2
LITERATURE REVIEW

A variety complex multi-criteria decision making approaches have been proposed and developed for maintenance strategy selection. Example of those would be Analytic Hierarchy Process (AHP), Genetic Algorithm (GA), fuzzy set theory, mathematical programming, factor analysis, simple multi-attribute rating technique (SMART) and etc. AHP has gained a huge popularity as a multi-criteria tool by most of the authors. In the process of optimization of maintenance strategy selection, many authors have utilized it either independently or in the combination with other approaches (Gandhare & Akarte, 2012). Multi-criteria approach consists of finite set of alternatives and criteria among which a decision maker has to rank or select. AHP, multi-criteria approach, is briefly described in the next paragraph.

2.1 ANALYTIC HIERARCHY PROCESS

Developed in 1970s by professor Thomas L. Saaty, AHP is a powerful and flexible multi-criteria decision making tool for complex problems where both qualitative and quantitative aspects need to be considered (Bevilacqua & Braglia, 2000). The AHP makes use of hierarchical structure similar to a family tree, which helps the analysts to organize the critical aspects and link them. The main idea of AHP is to make use of simple pairwise comparison and ranking, which allows reduction of complex decision making and enables synthesizing the results. It does not only help the analysts to arrive at the best decision, but also provides a clear rationale for the choices made. The author of technique T. L Saalty explains steps in making a decision in an organized way to generate priorities (Odeyale, Alamu, & Odeyale, 2013). The decision is decomposed into the following steps in Table1.

Table 1- Steps in generating priority in AHP

1.	Problems and type of knowledge sought is to be defined
2.	Build up the decision hierarchy from top to bottom. It starts with setting the goal of decision and objective from a broad perspective. Criterion are identified at the intermediate level, sub-criteria is set, if needed. Lowest levels are the alternatives involved.
3.	Next, comparison matrices constructed for a set of pairwise comparison. Each element in an upper level is used to compare the elements in the level immediately below with respect to it.
4.	Use the priorities obtained from the comparisons to weigh the priorities in the level immediately below. Do this for every element. Then for each element in the level below add its weighed values and obtain its overall or global priority. Continue this process of weighing and adding until the final priorities of the alternatives in the bottom most level are obtained.

When step 2 is completed, hierarchical tree similar to Figure 1 should be generated. Figure 1 represents the simplest case, where 3x3 matrix is created.

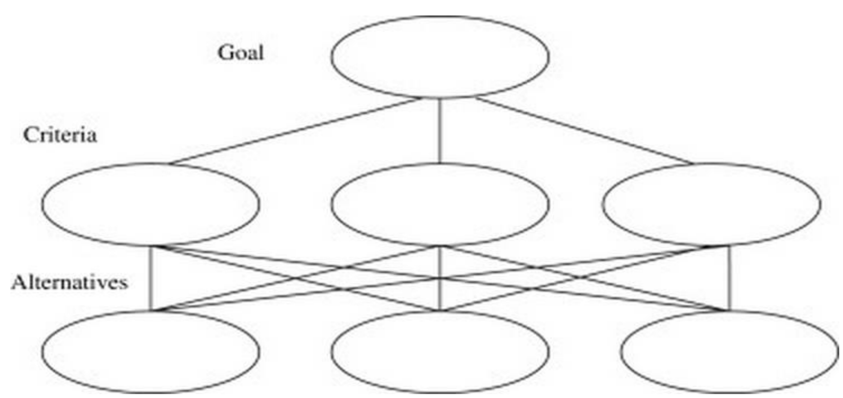

Figure 1 - Typical AHP hierarchical tree

In the third step, relative priorities of elements in each level of the hierarchy are determined using pairwise comparison matrix with respect of the elements at the next higher level. Comparison is based on Saaty's 1-9 scale displayed in Table 2. This scaling allows only integer values to be used in pairwise comparison.

Table 2 - Saaty's 1-9 scale for pairwise comparison

Value of rating judgments	**Verbal judgments**
$a_{ij} = 1$	The two parameters are equally important
3	Parameter *i* is weakly more important than parameter *j*
5	Parameter *i* is strongly more important than parameter *j*
7	Parameter *i* is very strongly more important than parameter *j*
9	Parameter *i* is absolutely more important than parameter *j*
2, 4, 6, 8	Interval values between two adjacent choices

In the comparison matrix, *aij* can be interpreted as the degree of preference of *i*th criteria over *j*th criteria. If n (n − 1)/2 comparisons are consistent with n is the number of criteria, then the elements {*aij*} will satisfy the following conditions $aij=wi/wj=1/aji$ and $aij = 1$ with $i, j, k = 1,\cdots, n$.

The relative weights are given by the right eigenvector (w) corresponding to the largest eigenvalue (λ_{max}), as (Delice & Güngör, 2012)

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

The AHP enables the analyst/user to evaluate the consistency of his judgments with the inconsistency ratio IR.

$$RI= (\lambda_{max}-n)/(n-1)$$

Generally, the judgments can be considered acceptable/consistent, if IR<0:1. In case of inconsistency, the assessment process for the inconsistent matrix is immediately repeated, by revaluating the pairwise comparison. As mentioned earlier, an inconsistency ratio of 0.1 or more may warrant further investigation (Bevilacqua & Braglia, 2000). This general practice is also implemented in this project. Developed framework will check consistency of entered comparison values, and in case of IR being more than 0.1, will immediately ask user to reevaluate judgment.

2.2 SELECTED CRITERIA AND ALTERNATIVES

As mentioned earlier, only four maintenance strategies are considered in this project. Most common maintenance policies, which are implemented in in complex mechanical systems and as well as in this selection framework, are as following:

Table 3 - Description of maintenance strategies used as alternatives. Adapted from Bevilacqua & Braglia (2000)

Breakdown Maintenance **(Corrective)**	The main feature of corrective maintenance is that actions are only performed when a machine breaks down. There are no interventions until a failure has occurred.
Time-Based Maintenance **(Preventive)**	Preventive maintenance is based on component reliability characteristics. This data makes it possible to analyze the behavior of the element in question and allows the maintenance engineer to define a periodic maintenance program for the machine. The preventive maintenance policy tries to determine a series of checks, replacements and/or component revisions with a frequency related to the failure rate. In other words, preventive (periodic) maintenance is effective in overcoming the problems associated with the wearing of components. It is evident that, after a check, it is not always necessary to substitute the component: maintenance is often sufficient
Condition-Based Maintenance **(Predictive)**	A requisite for the application of condition-based maintenance is the availability of a set of measurements and data acquisition systems to monitor the machine performance in real time. The continuous survey of working conditions can easily and clearly point out an abnormal situation (e.g. the exceeding of a controlled parameter threshold level), allowing the process administrator to punctually perform the necessary controls and, if necessary, stop the machine before a failure can occur.
Reliability-Centered Maintenance	Basically, RCM methodology deals with some key issues not dealt with by other maintenance programs. It recognizes that all equipment in a facility is not of equal importance to either the process or facility safety. It recognizes that equipment design and operation differs and that different equipment will have a higher probability to undergo failures from different degradation mechanisms than others. It also approaches the structuring of a maintenance program recognizing that a facility does not have unlimited financial and personnel resources and that the use of both need to be prioritized and optimized. In a nutshell, RCM is a systematic approach to evaluate a facility's equipment and resources to best mate the two and result in a high degree of facility reliability and cost-effectiveness.

As for criteria, there are also four predetermined criteria, namely, cost, added value, safety and feasibility. All of these 4 criteria, in general, reflects sum of many sub-criteria. There were many criteria more than above, but most of them overlapped on each other. In addition numerous criteria need more calculation and time consuming (Tan Zhaoyang et al, 2010). These factors affected the choices made regarding criteria selection. Brief description of criteria is given in Table 4 below:

Table 4 - Description of selected criteria

Cost	Cost can include crew cost, spare part cost (minimum inventory requirement), basically all the costs that might incur.
Safety	Sums safety for personnel, equipment, facilities, environment
Added value	Accounts for loss production arising from failure affect added value, maintaining high product quality.
Feasibility	Each maintenance policy must be feasible to implement. Return on investment enhanced, area of business the company is in and etc.

2.3 RISK ASSESSMENT

Risk assessment is a complex activity because it is not only bounded with statistical and mathematical calculations. It also implies a certain vision and an attempt to predict the future, to assess possible dangers (Radu, 2009). Rephrasing what was stated above risk assessment is process that involves estimation of the likelihood of occurrence for specific undesirable event, and at the same time the severity of the possible damage or consequence of it. Assessment of risk comes together with a value judgment concerning the significance of the results. It combines both the likelihood of failure and the consequence of failure. Risk is computed or estimated by analyzing probability and consequence of failure, and multiplying it to each other (Selvik, Scarf , & Aven , 2011).

Risk = Like hood of failure * Consequence

Based on the outcome, to achieve tolerable risk criteria, the high-risk components are prioritized, greater frequency and thoroughness of inspection and maintenance activities is implemented (Brown & May , 2003). So consequently, risk assessment is a tool that aids in decision making. In the case this report, risk assessment utilized to group equipment according to risk it carries. Risk assessment is also an integral part of risk-based inspection (RBI). It is the first step comprising in it, allows classification according to risk and enables the further analysis of action to be taken (how often to inspect?). In several works RBI was utilized in decision making for selection of maintenance strategy (Arunraj & Maiti , 2009) , (Tan Zhaoyang et al, 2010).

To make the decision making process of the maintenance strategy more accurate, it is required to know the level of risk associated with the equipment or component under study. Many authors had different approaches regarding the risk assessment and estimation, yet how it is achieved is of a lesser concern in our case. We presume that user is knowledgeable enough to estimate risk and categorize it accordingly, in case if no risk assessment was conducted previously. However, if risk assessment is to be conducted, the degree of intensity of risk assessment is not much of concern as well. Out of many authors, who combined risk assessment/RBI with AHP in selection of maintenance strategy, many selected qualitative and semi-qualitative risk assessment methods. One of those authors was Patel (2005), who briefly describes the types of RBI and their effect on AHP decision making. He covers three levels of risk based inspection that have been developed by API for prioritizing risk levels associated with individual pieces of pressure equipment. Accordingly, RBI processes can be qualitative and quantitative or combination of both. Again the sole purpose is to rank the equipment on the basis of risk associated with them. So consequently, categorization of RBI is nothing, but a risk assessment categorization.

The framework developed in this project requires only the result of that risk assessment. Result should clearly tell at which risk zone the equipment is. The standard risk matrix is utilized as a categorization tool (see Figure 2). The risk zone, at which the equipment is, will provide the predetermined set of priority weights. This is the most critical feature of the framework being developed.

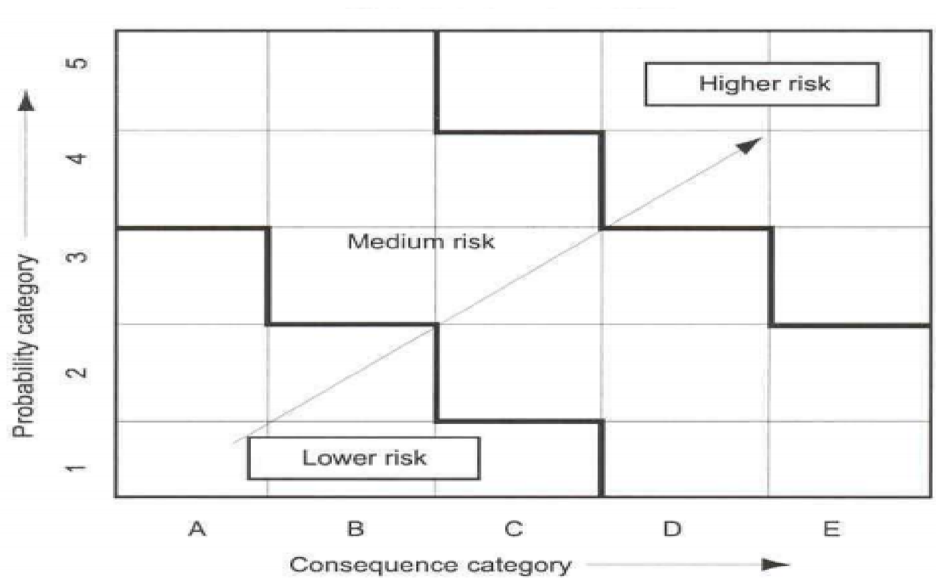

Figure 2 - Typical risk matrix (Patel, 2005)

2.4 AHP IN SELECTION OF MAINTENANCE STRATEGY

Many AHP combinations were used in selection of maintenance strategy. Arunraj & Maiti (2009) presented an approach of maintenance selection based on risk of equipment failure and cost of maintenance. RBI, AHP and goal programming (GP) were implemented for maintenance policy selection. To support the combined technique a case study in a benzene extraction unit of a chemical plant was done. CM, CBM, SM (shut down maintenance) and TBM (time-based maintenance) were among the alternatives considered in selection. The combined approach was applied in two subsequent stages: the first part of the analysis provided the priority levels for the different maintenance policies with respect to risk contribution, and cost of maintenance policy. The second step, with the formulation of the goal programming model, has led to the identification of the best set of maintenance type for the equipment considered. A criterion of risk contribution was evaluated using RBI. Before Arunraj & Maiti similar hybrid selection technique was developed by Bertolini & Bevilaqua (2005). In fact Arunaj & Maiti referenced and followed the technique of Bartolini & Maiti extensively. They have presented "Lexicographic" Goal Programming (LGP) approach to define the best strategies for the maintenance of critical centrifugal pumps in an oil refinery. For each pump failure mode, the model developed allowed to take into account the maintenance policy burden in terms of inspection or repair and in terms of the manpower involved, linking them to efficiency-risk aspects quantified as in FMECA methodology through the use of the classic parameters occurrence, severity and detectability, were evaluated through an adequate application of the AHP technique.

Another application of the AHP for selecting the best maintenance strategy was used for important Italian oil refinery. Bevilacqua & Braglia (2000) listed five possible alternatives for consideration: preventive, predictive, condition-based, corrective and opportunistic maintenance. With AHP technique, several aspects, which characterize each of the above-mentioned maintenance strategies, are arranged in a hierarchic structure and evaluated using only a series of pairwise judgments. The internal methodology developed by the company to solve the maintenance strategy selection problem for the new plant was based on a "criticality analysis", which may be considered as an extension of the FMECA technique. This analysis took into account the following six parameters: safety; machine importance for the process; maintenance costs; failure frequency; downtime length; machine access difficulty. AHP with Fuzzy

Logic control has also been proposed to provide flexible strategies to support the decision maker in issue of how assets should be maintained. That is, whether to run until failure, to maintain on a fixed time basis, or to design out the causes of failures, based on the prioritized focus (A.W. Libib, 2004). Author further proposed a FuzzyDMG approach to determine what type and when a maintenance strategy has to be implemented to facilitate the responsiveness of a manufacturing system to the changing environment (A.W. Libib, 2008). In addition to the AHP, other tools are also reported in evaluating and selecting the maintenance strategy. For example, the use of Genetic Algorithm for different situations has been proposed to address the least-cost part replacement problem (Dragan A. Savic, 1995), and a case study of a power station coal transportation system (Yu Liu, 2010).

Different maintenance strategies - corrective, time-based, condition-based, and predictive - for different equipment have been evaluated by using a fuzzy-AHP method

(Wang, Chua, & Jun, 2007). Similarly, Shyjith proposed a combination of AHP and TOPSIS to select suitable maintenance policy for a textile spinning mill ring frame unit (K. Shyjit, 2008). Recently, Anhua Peng and Zhiming Wang compared fuzzy approach with TOPSIS (Technique for Order Preference by Similarities to Ideal Solution) and commented that fuzzy approach is better suited to address the ambiguity and uncertainty part of the decision making (Peng & Wang, 2011). A combination of AHP, TOPSIS, and VIKOR methodologies was used to select the most effective maintenance strategy for non-safety category of failures in aircraft systems (Alirza Ahmadi, 2011). Similarly, Sunil Dutta proposed a fuzzy logic and AHP multi-criteria approach to select maintenance strategy for transmission system of military vehicle (Dutta, Kumar, & Kumar, 2011)

Tan Zhaoyang et al (2010) had briefly explained another hybrid technique of selection of maintenance plan, which is based on RBI and AHP. Risk based inspection (RBI) methodology was proposed to evaluate the maintenance strategy in industrial process which was constructed in one of the units of Fujian Oil Refinery ISOMAX unit. Using classic definition of risk, both the probability and consequence of accident or failure were investigated respectively under the support of risk-specific code. All equipment in this unit was evaluated and categorized into five risk zone based on the RBI, result which covered five levels. In addition, an application of the analytical hierarchy process (AHP) to select the most practicable maintenance strategy for equipment, which was located in each risk rating scale, was described. To arrange the hierarchic structure and evaluation, four main criteria were defined for pairwise judgments. Finally, four possible alternative strategies were proposed for administrators. RBI used in this hybrid system was quantitative, required extensive data of failures and maintenance record, and also used RISKWISE software.

A very general case study was conducted by Odeyale et al (2011), where aim was to select best maintenance strategy for manufacturing plant (Odeyale, Alamu, & Odeyale, 2013). Authors include Corrective maintenance, Preventive maintenance and Predictive maintenance as alternatives. Criteria is as wide as 8, namely: Low maintenance cost, Improved reliability, Improved safety, High Product Quality, Minimum Inventory, Return on investment, Acceptance by Labor, enhanced competitiveness. As mentioned earlier, this paper is taken as a validation case study for the project.

CHAPTER 3
METHODOLOGY

3.1 MAINTENANCE SELECTION METHODOLOGY

Selection framework: The main maintenance strategy selection method incorporates combined AHP and risk assessment method, where the weights for pairwise comparison are predetermined by developer based on Tan Zhaoyang et al (2010) research. However, the user may not follow the predetermined framework. The user is free to assign own weights for each of them. Choice of alternatives is fixed for AHP and risk assessment combined method. However, the user will not have predetermined set of priority weights like in case of criteria. Weights of alternatives vs. criteria comparison is purely based on the judgment of the user. Once the weights are assigned and priorities and known, the application will calculate the scores and show the rankings.

In general proposed AHP and risk assessment combination model for selection of suitable maintenance strategy can be divided into two main steps that are similar to method by Tan Zhaoyang et al (2010):

1. Risk assessment must be fulfilled on selected mechanical system or equipment, probability and consequence must be analyzed and risk value assigned (either by actually conducting it or if the user is experienced by direct assignment). Evaluated risk is then classified into one of the risk groups in the risk matrix (see Figure 3) Note favorable and acceptable risk zones are to be considered as one, since they risk almost equally negligible. So all together, we would have only 4 risk zones, namely, favorable & acceptable =>tolerable =>unsatisfactory =>critical.
2. Once equipment is risk-classified, AHP decision model takes turn. Objective, criteria and alternatives in AHP hierarchy are as discussed earlier:
   - Objective - to select suitable maintenance strategy;
   - Criteria – Cost, Safety, Added Value and Feasibility;

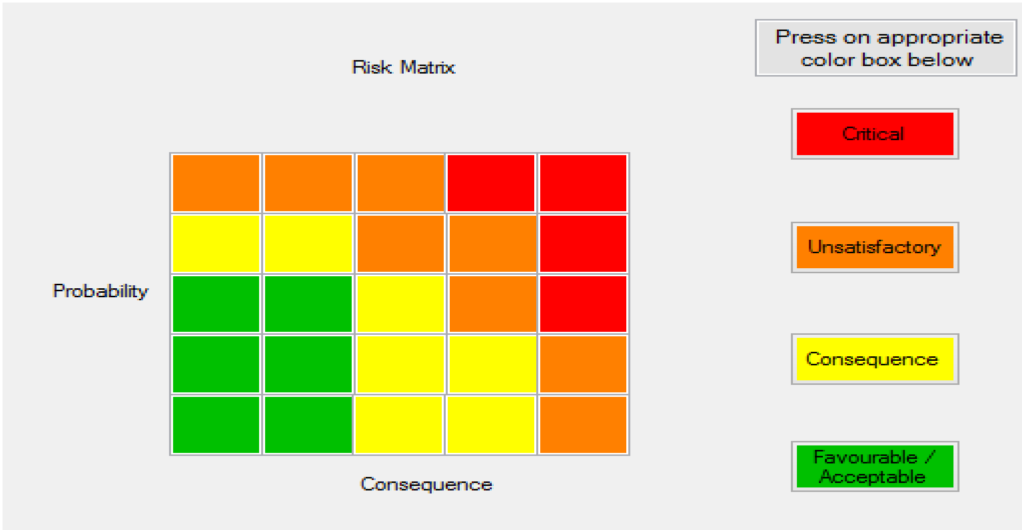

Figure 3 - Risk matrix used in AHP and Risk Assessment framework

- Alternatives – Breakdown Maintenance, Condition-Based Maintenance, Time-Based Maintenance and Reliability-Centered Maintenance.

For ease of analysis, we select the criteria to be similar to Tan Zhaoyang et al (2010). In the selection of the criteria Tan Zhanyang et al (2010) implement sophisticated ten step approach commonly used procedure for building a criterion metadata. So the outcome the selection of criterion is safety, cost, feasibility and added value. The AHP hierarchy would have final look like in Figure 4.

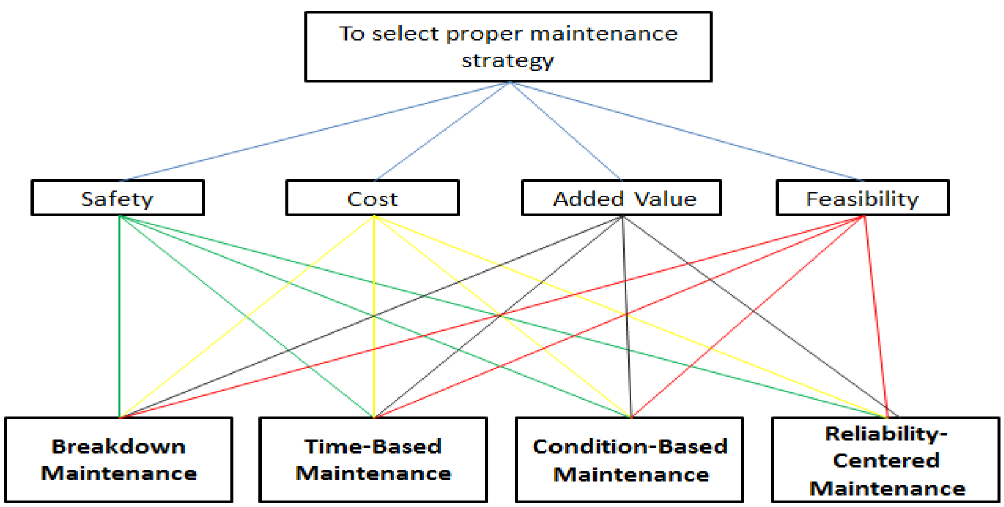

Figure 4 - Hierarchal tree for combined AHP and risk assessment method

As mentioned before, risk matrix output consists of four main risk rating scales. Suitable maintenance policy must be assign to each area by calculating each policy priority by means of pair wise comparison matrixes. The most important point is that the ranking of criteria is different for each risk rating scale, so pair wise comparison matrix must be calculated in each risk rating scale. Ranking judgment is made according Saaty's ranking table that was discussed in introduction part of this report (Table 2).

3.2 SOFTWARE AND TOOLS

As mentioned earlier, VBA is used to develop windows based application. Generally there are three components to consider in VBA:

1. **Visual Basic:** It is simply one programming language that speaks to the Microsoft .NET Framework, which is the next term in the list.
2. **.NET Framework:** The layer that sits between the language (in this case, Visual Basic) and the operating system. Framework layer serves to provide functionality based on the operation of the Windows system on which it resides, as well as to provide libraries for other functionality (such as math computations and database access)
3. **Visual Studio:** The tool that you use to create any kind of application using any compatible programming language. When you go to write a new program in the .NET environment, you run Visual Studio and select the kind of program you want to write in the programming language you want to use.

3.3 RESEARCH METHODOLOGY

Research methodology is based on following algorithm:

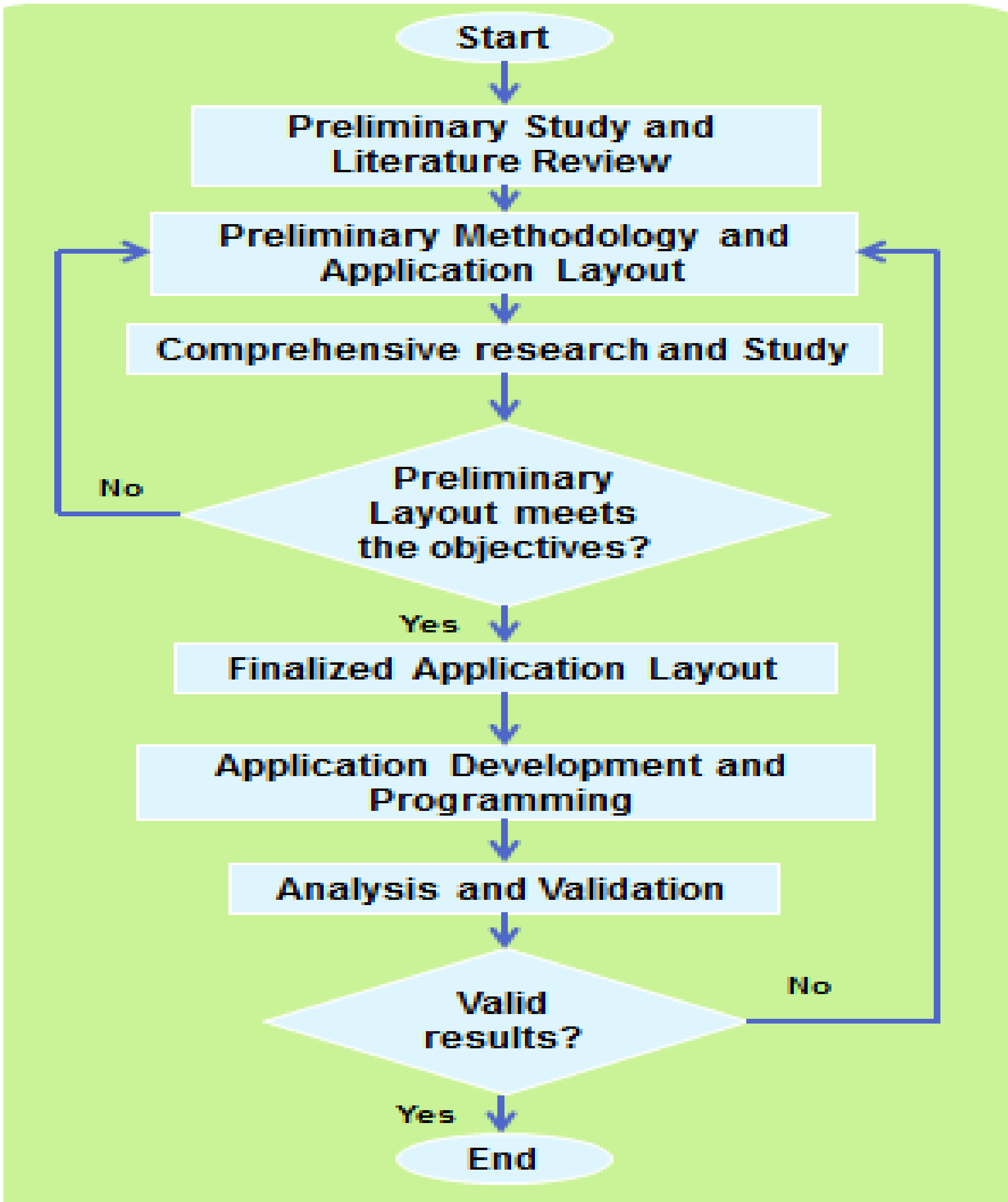

Figure 5 - Research Methodology

3.4 GANTT CHART

Project activities and key milestones are highlighted in the following figures.

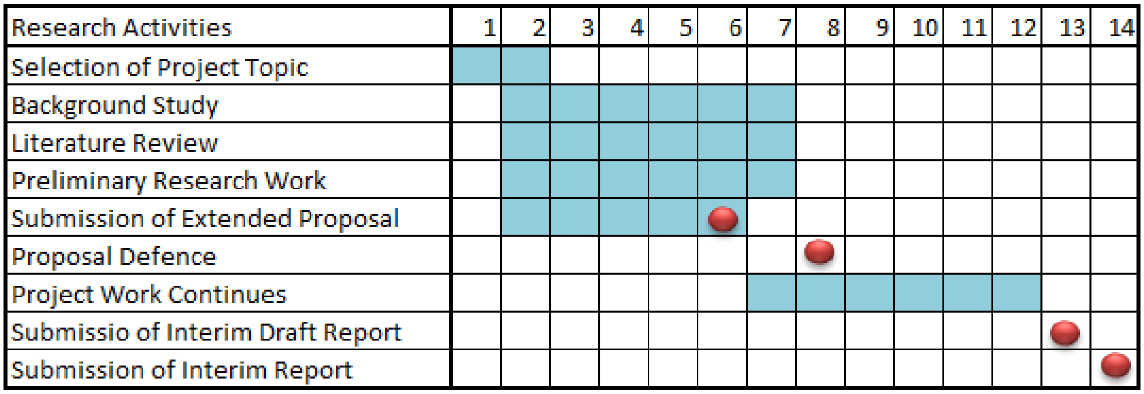

Figure 6 - FYP1 Gantt chart

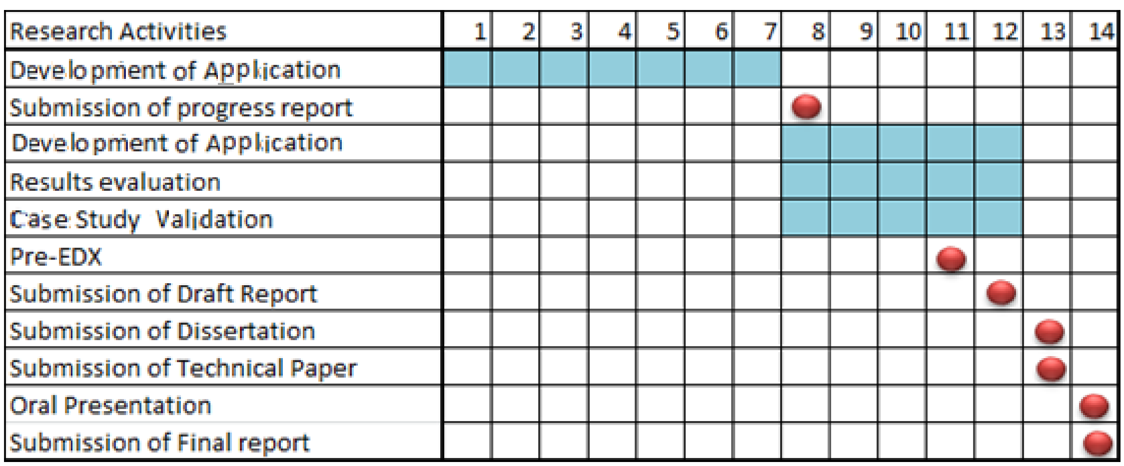

Figure 7 - FYP2 Gantt chart

CHAPTER 4
RESULTS AND DISCUSSION

4.1 FINALIZED DECISION MAKING FRAMEWORK

After following all the steps in Figure 5, the finalized working algorithm of the decision framework and application have shaped into following:

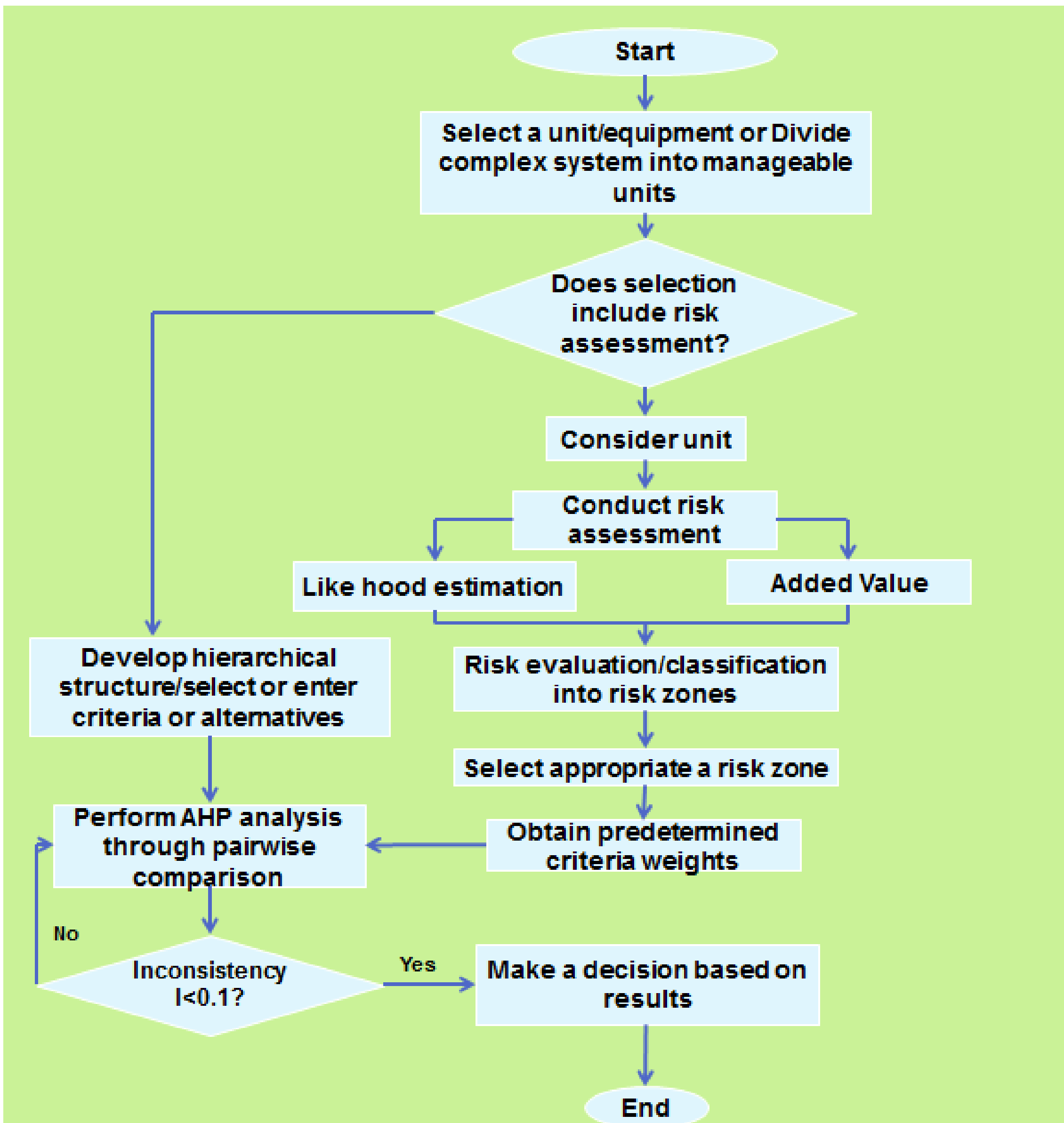

Figure 8 - Working principle of Decision Framework

As it can be seen from the algorithm, after dividing the complex system in to manageable components, user is offered to choose between methods of decision making. Option number one is using simple AHP without risk assessment, and two is the combined decision framework that accounts for both risk assessment and AHP. A print screen from the application programmed in VB is shown in Figure 9. It illustrates both of the choices that were highlighted above.

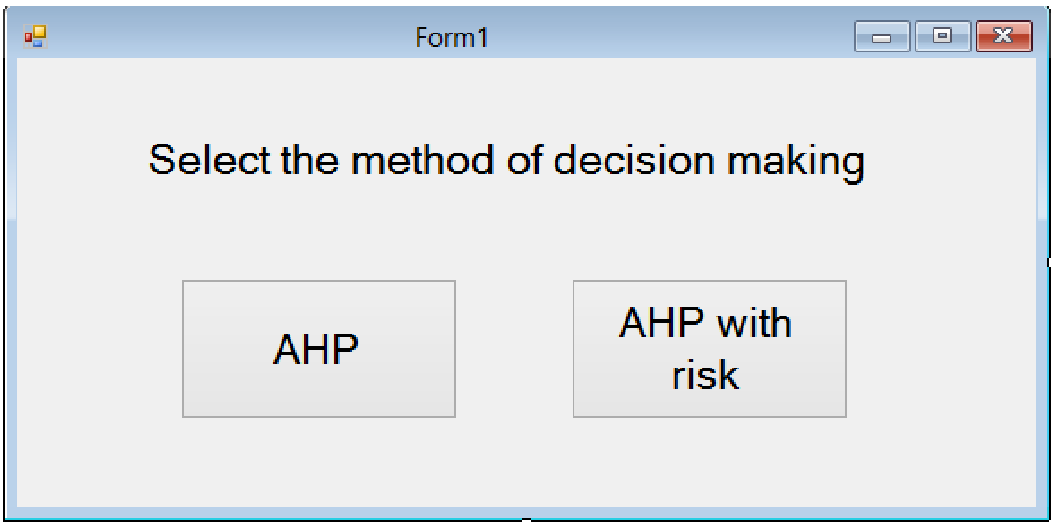

Figure 9 - Options of available decision making methods in the framework

So as repeated several times before, AHP option leads to simple decision making framework, where decision making is performed using AHP solely, whereas the combined AHP and risk assessment option requires risk zone categorization as in Figure 3 before utilizing AHP for selection. Both options have a lower limit (minimum) of the matrix size to be 3x3. And upper limit of matrix size is also same for both options; 4x4 Figure 10 illustrates the maximum allowable number of alternatives and criteria.

Number of alternatives does not change for both options. However, user is allowed to enter 2 additional criteria in pure AHP mode. User also has option of selecting alternatives out of predefined 4 alternatives and criteria in pure AHP mode.

Before proceeding with description of the validation of the framework, it is important to mention another critical decision made while developing and programming the framework. Once pairwise comparison is over, to compute the priority numbers eigenvectors principle is used. To follow conventional eigenvector calculation,

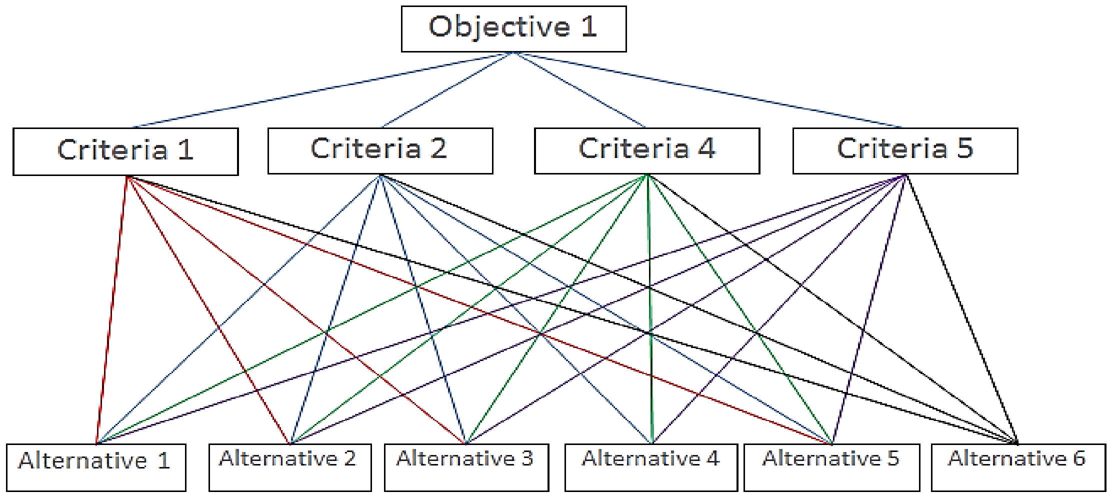

Figure 10 - Maximum limit of criteria and alternatives in pure AHP mode

MATLAB was required to be outsourced. Due to time constraint and to keep the application simple, it was decided to only use an approximation of Eigenvector of reciprocal matrix. This approximation is actually very accurate and works well with small matrix sizes 3x3 and higher (Kardi, 2006).

To illustrate the insignificance of the between conventional eigenvector calculation and approximation method, following example by T. Cardi (2006) is provided. Imagine a 3x3 matrix, where 3 alternatives are evaluated using pairwise comparison with respect to some goal. The priority values, which are found through priority vector (also known as eigenvector), are to be found. Pairwise comparison values are transferred to 3x3 matrix, and this is shown in Table 5.

Table 5 - Priority Matrix by T. Cardi (2006)

A=

	Alt1	Alt2	Alt3
Alt1	1	1/3	5
Alt2	3	1	7
Alt3	1/5	1/7	1

Next step is to sum the values in each column separately as in Table 6.

Table 6 - Summation of columns

A=		Alt1	Alt2	Alt3
	Alt1	1	1/3	5
	Alt2	3	1	7
	Alt3	1/5	1/7	1
	Sum	21/5	31/21	13

Then we divide each element of the matrix with the sum of its column to obtain normalized relative weights. After this division is performed, the sum of each column must be equal to 1.

Table 7 - Normalized priority matrix

A=		Alt1	Alt2	Alt3
	Alt1	5/21	7/31	5/13
	Alt2	15/21	21/31	7/13
	Alt3	1/21	3/31	1/13
	Sum	1	1	1

Normalized principal eigenvector can be obtained by averaging across the rows. This step is summarized in Table 8.

Table 8 - Normalized principal eigenvector

W= 1/3*	Alt1	Alt2	Alt3	=	
	5/21	7/31	5/13		0.2828
	15/21	21/31	7/13		0.6434
	1/21	3/31	1/13		0.0738

Now, using eigenvector values we can find out maximum eigenvalue for the case above. Principle Eigenvalue is obtained from the summation of products between each element of Eigen vector and the sum of columns of the reciprocal matrix.

$$\lambda_{max} = \frac{21}{5}(0.2828) + \frac{31}{21}\ (0.6434) + 13(0.0738) = 3.0967$$

If were to solve this vector in MATLAB using the conventional method, Principle Eigenvalue λ_{max} would have yield to 3.0649. Calculating the percent error, we get 1% error:

$$\% \, Error = \frac{3.0967 - 3.0649}{3.0649} = 0.0103$$

Summaries of eigenvalues, IR and percent error is provided in the table below:

Table 9 - Comparison between Approximation and Conventional method of Eigenvalue and Eigenvector

Parameters / Matrix size	Eigenvalue		IR	Percent Error
	Conv.	Approx.		
3x3	3.0649	3.0967	0.048	1.03%
4x4	4.0805	4.131	0.043	1.23%

For above reason, it was decided to use Eigenvector and Eigenvalue approximation method. The results insignificantly deviate from conventional way of calculation. The percent errors are negligible. Appendix A proves that developed application yields to same results as shown above. Inconsistency Ratio (IR) is equals to 0.048 (see Appendix A).

4.2 CASE STUDY AND VALIDATION

There are many reasons behind choosing Odeyale et al (2011) case study for validation. Firstly, and most importantly he provides all the information about his pairwise judgment of both criteria and alternatives. Second of all, the alternatives and criteria he chose for his case study are very much close to the ones selected for decision framework of this project. The summary of alternatives and criteria used in Odeyale's ease study are provided in Table 10.

Table 10 - List of Alternatives and Criteria Comparison

Combined AHP and Risk Assessment Method		Case study by Odeyale	
Alternative	Criteria	Alternative	Criteria
Corrective	Cost	Corrective	Low Maintenance cost
Predictive	Safety	Predictive	Improved reliability
Preventive	Added value	Preventive	Improved safety
Reliability-Centered	Feasibility		High Product quality
			Minimum inventory
			Return on investment
			Acceptance by labor
			Enhanced competitiveness

As it can be seen from the table, the alternatives' list in case study by Odeyale did not include reliability centered maintenance, whereas first three alternatives (Corrective, Predictive and Preventive) are identical with the developed AHP and risk assessment framework. Case study of Odeyle included 8 criteria, whereas combined method encountered just 4. However, finding similar trends amongst these criteria is not that problematic. The low maintenance cost criterion in Odeyale's case is absolutely same as cost criteria of combined method. The improved safety and safety are identical as well. Return on investment can be assumed to be equal to feasibility, whereas improved reliability is same as added value. To match other parameters and variables, make following arrangements are made:

1. Validation study is run in combined AHP and risk assessment mode of the developed application
2. All 4 alternatives from developed framework are included in validation (Corrective, Preventive and predictive, Reliability-Centered Maintenance)
3. Criteria's pairwise comparison is based on Zhaoyang's case study that was adopted in combined AHP and risk assessment method.

4. In combined AHP and risk assessment mode of developed application maximum of 4 criteria are allowed to be entered into decision making process. The challenge here was to select four criteria from Odeyale's case study that are closely identical to combined method. As mentioned earlier, the four criteria from Odeyale's case study that are closely identical to combined method's criteria are improved safety, low maintenance cost, return on investment and improved reliability. Enhanced competitiveness, high product quality, acceptance by labor and minimum inventory are excluded from validation run. It can be observed that these criteria have the lowest priority scores (see Table 11) in Odeyale's pairwise comparison. So consequently, their elimination should not affect the decision making process outcomes significantly.

Table 11 - Priority scores in Odeyale's case study (low maintenance cost (*C*1), improved reliability (*C*2), improved safety (*C*3), High Product Quality (C4), Minimum Inventory (*C*5), return on investment (*C*6), Acceptance by Labor (C7) enhanced competitiveness (*C*8

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	$\sqrt[n]{}$	W
C_1	1	1/2	1/3	4	5	4	6	3	1.984	0.166
C_2	2	1	1/4	3	8	4	9	4	2.539	0.213
C_3	3	4	1	4	7	6	8	5	4.105	0.344
C_4	1/4	1/3	1/4	1	4	3	8	3	1.251	0.105
C_5	1/5	1/8	1/7	1/4	1	1	5	1/6	0.406	0.034
C_6	1/4	1/4	1/6	1/3	1	1	4	1/3	0.511	0.043
C_7	1/6	1/9	1/8	1/8	1/5	1/4	1	1/6	0.199	0.017
C_8	1/3	1/4	1/5	1/3	6	3	6	1	0.938	0.079
	7.20	6.57	2.47	13.04	32.20	22.25	47.00	16.67	11.93	1.00

5. Priority scores and pairwise comparison of selected alternatives respect to criteria are based on Odeyale's case study.

So, in the end it was decided to have 4 alternatives and 4 criteria for validation run. How it will look on a hierarchal tree is illustrated in Figure 11, which is basically a snapshot of the AHP hierarchal tree that was developed for validation run in the combined AHP and risk assessment mode of the developed application.

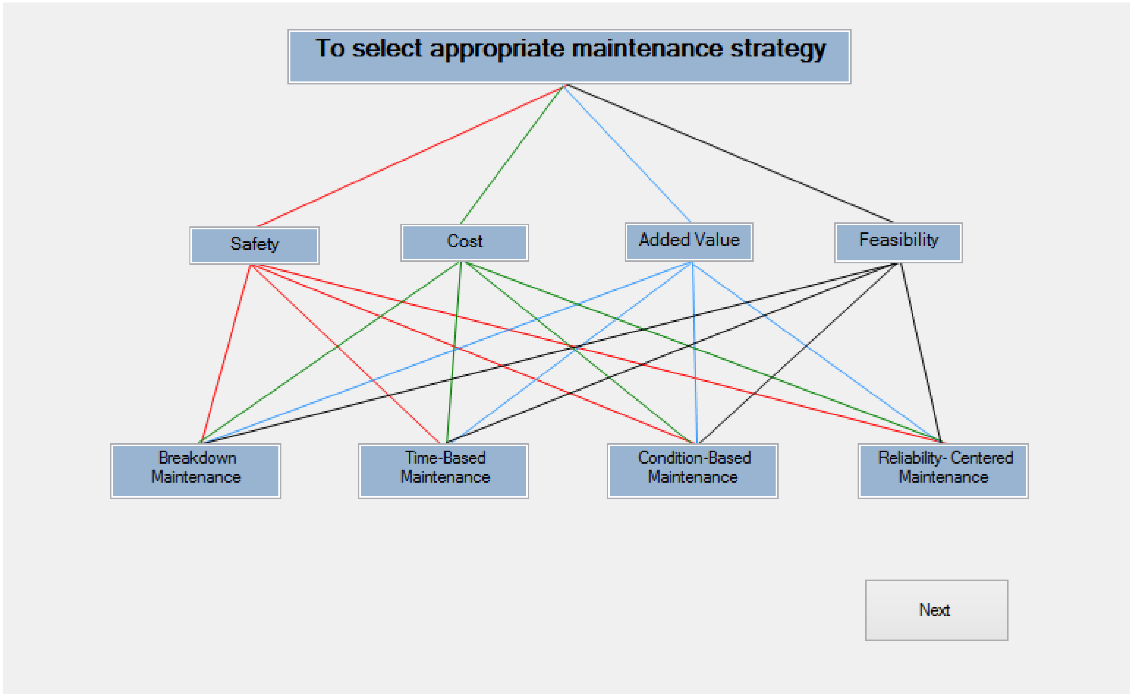

Figure 11 - Hierarchal Tree of validation run

For ease of analysis, following labeling is used in further parts of this report and a few of the tables: Breakdown Maintenance (A1), Time-Based Maintenance (A2), Condition-Based Maintenance (A3), Reliability-Centered Maintenance (A4); Safety (C1), Cost (C2), Added Value (C3) and Feasibility (C4).

The validation run is run for all four regions of the risk matrix. We start with analysis of the lowest risk zone, which is favorable/acceptable zone. The pairwise comparison of criteria with respect to achieving the goal (To select appropriate maintenance strategy) and the priority score of each criterion in favorable/acceptable region is shown in Table 12.

In the lowest risk zone, safety has the highest priority number 0.3667, followed by added value 0.2810, feasibility 0.2012 and cost 0.1507. This arrangement does not change in other risk zones, however, the scores vary. Table 13, 14 and 15 illustrate the scores for tolerable, unsatisfactory and critical zones.

Table 12 - Pairwise comparison and priority scores in favorable/acceptable risk region

Calculation wieghts in criteria level-favourable / accaptable area

	Safety	Cost	Added Value	Feasibility	Priority
Safety	0.3529	0.4285	0.2857	0.4000	0.3667
Cost	0.1175	0.1428	0.1428	0.2000	0.1507
Added Value	0.3529	0.2857	0.2857	0.2000	0.2810
Feasibility	0.1764	0.1428	0.2857	0.2000	0.2012

Table 13 - Pairwise comparison and priority scores in tolerable risk region

Calculation of wieghts in criteria level-tolerable area

	Safety	Cost	Added Value	Feasibility	Priority
Safety	0.4800	0.4000	0.5217	0.4615	0.4658
Cost	0.1200	0.1000	0.0868	0.0769	0.0959
Added Value	0.2400	0.3000	0.2608	0.3076	0.2771
Feasibility	0.1598	0.2000	0.1304	0.1538	0.1610

Table 14 - Pairwise comparison and priority scores in unsatisfactory risk region

Calculation wieghts in criteria level-unsatisfactory area

	Safety	Cost	Added Value	Feasibility	Priority
Safety	0.5607	0.3846	0.6545	0.4800	0.5199
Cost	0.1121	0.0769	0.0545	0.0399	0.0708
Added Value	0.1869	0.3076	0.2181	0.3600	0.2681
Feasibility	0.1401	0.2307	0.0726	0.1200	0.1408

Table 15 - Pairwise comparison and priority scores in critical risk region

Calculation wieghts in criteria level-critical area

	Safety	Cost	Added Value	Feasibility	Priority
Safety	0.6278	0.4666	0.7594	0.4800	0.5834
Cost	0.0896	0.0666	0.0379	0.0399	0.0585
Added Value	0.1255	0.2666	0.1518	0.3600	0.2259
Feasibility	0.1569	0.2000	0.0506	0.1200	0.1318

Second, step in validation run is comparing the alternatives respect to each criterion on pairwise basis. As mentioned many times before, this pairwise comparison values are based on Odeyale's case study. Summary of comparison entries and respective priorities are given in Table 16.

Table 16 - Alternatives pairwise comparison and local priorities with respect to each criterion

Comparison based on safety						Comparison based on cost					
	A1	A2	A3	A4	Local priority		A1	A2	A3	A4	Local priority
A1	1	1/3	1	1/2	0.1411	A1	1	8	6	4	0.6343
A2	3	1	3	2	0.4546	A2	1/8	1	1/2	1/3	0.0655
A3	1	1/3	1	1/2	0.1411	A3	1/6	2	1	1/2	0.1104
A4	2	1/2	2	1	0.2630	A4	1/4	3	2	1	0.1896
Comparison based on added value						Comparison based on feasibility					
	A1	A2	A3	A4	Local priority		A1	A2	A3	A4	Local priority
A1	1	5	3	2	0.4396	A1	1	5	4	3	0.5323
A2	1/5	1	1/2	1/6	0.0679	A2	1/5	1	1/4	1/4	0.0677
A3	1/3	2	1	1/5	0.1178	A3	1/4	4	1	1	0.1940
A4	1/2	6	5	1	0.3744	A4	1/3	4	1	1	0.2057

Due to relatively low cost and labor cost involved with breakdown maintenance it has the highest local priority with respect to cost criterion. Also easy application and again relative low cost puts breakdown maintenance in advantage with respect feasibility. However, with respect to the most important criteria safety, breakdown maintenance has the lowest score. Time-based maintenance and reliability-centered maintenance obtained highest priority at this criterion comparison.

Now that alternative and criteria priorities are obtained, final global priorities of each alternative with respect to goal can be obtained. The summaries of global priorities for each risk zone are highlighted in Table 17.

Table 17 - Summaries of global priorities for each risk zone

Risk zone / Maintenance type	**Accept./Favor**	**Tolerable**	**Unsatisfactory**	**Critical**
Breakdown maintenance	0.3663	0.3193	0.2945	0.2703
Time-based maintenance	0.1712	0.1994	0.2147	0.2327
Condition-based maintenance	0.1582	0.1626	0.1651	0.1690
Reliability-centered maintenance	0.3038	0.3184	0.3251	0.3274

4.3 RESULTS ANALYSIS AND DISCUSSION

As it was prognosed and proved by other authors, the level of risk associated with any equipment significantly affects the type of maintenance strategy that needs to be implemented for that particular equipment. Similary to the results of Zhaoyang Tan et al (2011), Acceptable/Favorable and Tolerable risk zones favor Breakdown maintenance (see Table 17). Acceptable/Favorable and Tolerable risk zones with low risk involved do not require advance and complicating maintenance strategies to be implemented on them. Simple “wait until breaks” maintenance strategy has the highest overall global priority in these risk regions. The reason for above scenarios can be related to low cost, low complexity and less amount of work involved with Breakdown Maintenance. The owners and maintenance engineers deem the effort and cost associated with other maintenance strategies to be irrelevant, when it comes to equipment, the failure of which does not sum up to significant amount of money, does not affect the overall production or operation, or simply has very low probability of failure in addition to that.

Once the risk associated with equipment escalates, “wait until breaks” can no more be implemented, since all owners and maintenance engineers prioritize safety, and escalating risk is a threat to safety. In the regions of high criticality and high risk, maintenance strategies that offer predictive and preventive measures dominate over corrective maintenance. The importance or priorities of criteria that are chosen before selection of the maintenance strategy, as a framework and basis of selection, significantly vary for low and high risk zones. (See Tables 12 to 15). The results obtained from the simulation run, proves that maintenance strategies such as Reliability-centered and Time-based maintenance have higher priority in high risk zones.

Obtained results clearly show the importance of risk categorization in the first place, because as risk varies and escalates priorities involved with criteria for selection also change accordingly. Apart from good results and better performance of overall plant or system, the owners and maintenance engineers can significantly reduce the amount of time, effort and money associated with maintenance.

However, for the developed application with combined AHP and risk analysis method it is essential to realize that reliability-centered maintenance or breakdown maintenance that have obtained high priority scores in high risk and low risk regions respectively, may be replaced by other maintenance strategies depending on alternatives comparison with respect to criterion. Even though specific criteria priorities are set to be constant but different for different risk zones, one must realize that alternative comparison is different from case to case. The alternative priorities should not be set constant as it was with criteria, since alternative pairwise comparison and priority number has high dependency on various factors. The factors that affect the outcome of alternative pairwise comparison can account to the amount of available resources, time, the type of industry and business the owner involved in, complexity and reliability of the equipment and mechanical systems, governmental rules, regulations, enforcements and many more. These factors above dictate a need for careful and thorough approach in evaluation of alternatives with respect to the criteria selected and prioritized. Alternative evaluation cannot be limited and arranged into a framework. Zhaoyang Tan et al (2011) also stress on this matter large amount of times in his work.

As a clear example of why the alternative cannot be set into framework can be viewed from the results of the validation run. The case study by Zhaoyang Tan et al

(2011), has led to similar but not identical results. Appendix C with a table summary of his work shows that for unsatisfactory risk zone the highest global priority was obtained by Time-based maintenance (predictive maintenance), whereas in validation run of proposed framework, the selection is Reliability-Centered Maintenance. It again demonstrates that alternatives' comparison is significant, and as it varies the outcome of selection will vary as well.

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The developed decision framework has met the requirements set as target at the beginning of project. It can be used as a handful decision making tool that assists in selection of a maintenance strategy. In addition to utilization of AHP as decision tool, the developed framework has successfully integrated risk assessment into decision making process. Based on the results of the risk assessments, each system components or single equipment can be categorized into risk zones according to risk level associated with it. The application provides framework for thorough evaluation and selection of maintenance policy.

Case study by Odeyale et al (2013) has served as a validation input data and results obtained from validation run have successfully proved validity of the developed framework and application, since the results obtained are closely similar to another reference case study by Zhaoyang Tan et all (2013).

The validation has again highlighted the importance of risk state of equipment in selection of maintenance strategy. The risk level of the equipment significantly affects the results of decision making.

5.2 RECOMMENDATION

The developed framework and application can be improved further in following ways. One is to use conventional eigenvector and eigenvalue calculation by outsourcing MATLAB or any other relevant software. This will decrease the insignificant, but yet present error between conventional and approximation method of eigenvector and eigenvalue calculation. The second method is related to software itself. To make it more user friendly and diversify function, the input option should not only involve qualitative inputs, but quantitative as well. The user should be allowed to directly enter his quantitative data input without having thought of converting data into qualitative.

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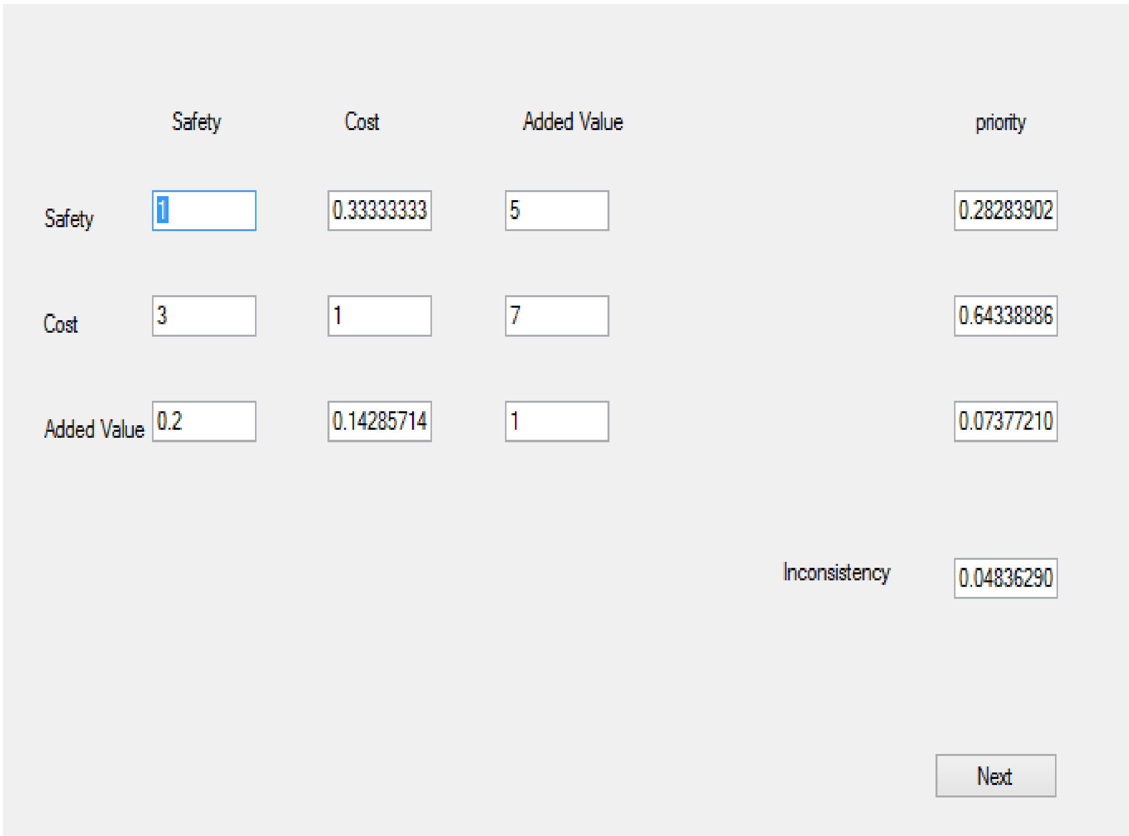
APPENDICES

APPENDIX A: Calculation of Normalized eigenvector via approximation method in the developed application.



APPENDIX B: Coding in developed framework that calculates principle Eigenvalue, IR and priorities.

```
Private Sub Forward1_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles Forward1.Click
    TabControl1.SelectedIndex = 5

    Box411.Text = 1
    Box412.Text = Val(val41.Text) / Val(val42.Text)
    Box413.Text = Val(val43.Text) / Val(val44.Text)
    Box414.Text = Val(val45.Text) / Val(val46.Text)
    Box421.Text = Val(val42.Text) / Val(val41.Text)
    Box422.Text = 1
    Box423.Text = Val(val47.Text) / Val(val48.Text)
    Box424.Text = Val(val49.Text) / Val(val410.Text)
    Box431.Text = Val(val44.Text) / Val(val43.Text)
    Box432.Text = Val(val48.Text) / Val(val47.Text)
    Box433.Text = 1
    Box434.Text = Val(val411.Text) / Val(val412.Text)
    Box441.Text = Val(val46.Text) / Val(val45.Text)
    Box442.Text = Val(val410.Text) / Val(val49.Text)
    Box443.Text = Val(val412.Text) / Val(val411.Text)
    Box444.Text = 1

    '/////////////////////////////
    Dim sum41 = Val(Box411.Text) + Val(Box421.Text) + Val(Box431.Text) + Val(Box441.Text)
    Dim sum42 = Val(Box412.Text) + Val(Box422.Text) + Val(Box432.Text) + Val(Box442.Text)
    Dim sum43 = Val(Box413.Text) + Val(Box423.Text) + Val(Box433.Text) + Val(Box443.Text)
    Dim sum44 = Val(Box414.Text) + Val(Box424.Text) + Val(Box434.Text) + Val(Box444.Text)

    '/////////////////////////////

    pri41.Text = ((Val(Box411.Text) / sum41) + (Val(Box412.Text) / sum42) + (Val(Box413.Text) / sum43) + (Val(Box414.Text) / sum44)) / 4
    pri42.Text = ((Val(Box421.Text) / sum41) + (Val(Box422.Text) / sum42) + (Val(Box423.Text) / sum43) + (Val(Box424.Text) / sum44)) / 4
    Pri43.Text = ((Val(Box431.Text) / sum41) + (Val(Box432.Text) / sum42) + (Val(Box433.Text) / sum43) + (Val(Box434.Text) / sum44)) / 4
    pri44.Text = ((Val(Box441.Text) / sum41) + (Val(Box442.Text) / sum42) + (Val(Box443.Text) / sum43) + (Val(Box444.Text) / sum44)) / 4

End Sub
```

APPENDIX C: Results of Zhaoyang Tan et al (2011) case study

Risk Area / Maintenance Policy	Unsatisfactory	Critical	Tolerable	Acceptable Favorable
PM	0.2678	0.2905	0.2483	0.2124
CBM	0.1546	0.1531	0.1561	0.1590
CM	0.2891	0.2740	0.3032	.3294
RCM	0.2932	0.2877	0.2965	.3023
Maintenance Selection	RCM	PM	CM	CM