RISK-BASED INSPECTION MODEL FOR HEAT EXCHANGER TUBE BUNDLES

BY

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CERTIFICATION OF APPROVAL

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Approved by,

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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 acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(Muhammad Hisyamuddin bin Basir)

ABSTRACT

Heat exchangers are widely used by many industries such as petrochemical, power generation, and oil and gas industries. The safety while operating heat exchanger is heavily concerned. Hazard of heat exchanger especially in those industries may end up with risk related issues. Many companies nowadays apply the condition-based inspection programs whereby the bundle life is predicted by analyzing the history of each exchanger bundle since the service start date. As the result, the financial consequences will not be considered associated with the bundle life while analyzing the reliability of the exchanger. Thus, an effective risk assessment model is required to assess failures associated with heat exchanger and to achieve plant availability and efficiency. This study presents the development of a risk-based inspection model for heat exchanger. The project is carried out to assist operator/user that operates heat exchanger to develop a customized maintenance optimization tool for selecting cost effective and appropriate maintenance and inspection tasks and techniques in determining the risk level of mode of failures associated with the heat exchanger. A comprehensive literature review related to the project topic is carried out from several journals and books available and being analyzed which consist of the overview of the Risk-Based Inspection (RBI) model, analysis of some of the existing RBI model, the overview of heat exchanger, description and analysis of currently used semi-quantitative risk assessment matrix method and the application of Microsoft Excel and Visual Basic Applications (VBA) in developing RBI model. Apart from that, Weibull distribution will be discussed further to understand its use in determining the probability of failure through life data analysis. The application of Microsoft Excel is proposed to ease the process of inspection by using the developed RBI model. Then, the program built will be validated with several available software in the market such as Weibull++ and RBI developed by Reliasoft Corp. The sample of validated historical data of inspection of heat exchanger from API RBI will be used to justify the risk level for each failures associated by applying the life data analysis. The scope of study for this research include establish the life data analysis by using Weibull analysis, analyze the risk value associated with several modes of failure and propose the inspection plan based on the result of analysis.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

On February 4, 2010, an explosion and fire led to the fatal injury of seven employees happened when a nearly forty-year-old heat exchanger catastrophically failed during a maintenance operation to switch a process stream between two parallel banks of exchangers at the Tesoro Refinery in Anacortes, Washington. On the other case, on June 11, 2008, one worker was killed and approximately seven others were injured during a maintenance operation on a heat exchanger at Goodyear Rubber and Tire Company in Houston, Texas. According to the investigation report, ammonia over-pressured inside the exchanger has caused it to rupture. The US Chemical Safety Board (CSB) which in their investigation report released on May 2014 under section 6.2 stated that API RP 581, the API standard for implementing a Risk-Based Inspection (RBI) program lacks of specific direction to ensure that users employ appropriate actual operating conditions. As a result, the CSB found that using the Tesoro design operating conditions and 38 years of operating yields a result that the B and E heat exchangers of the refinery have a "Low Susceptibility" to High Temperature Hydrogen Attack (HTHA).

By definition, RBI is the process of developing an inspection plan based on the knowledge of the risk of failure of the equipment. Nowadays, RBI has become one of the crucial aspects in engineering industries, predominantly in oil and gas industry. RBI is an ideal maintenance commercial process used to inspect equipment such as heat exchangers, pressure vessels and piping in industrial plants. It examines the business risk and Health, Safety and Environment (HSE) of active and potential Damage Mechanisms (DMs) to evaluate and rank failure probability and consequence. This ranking is used to enhance inspection intervals based on site-acceptable risk levels and operating limits, while mitigating risks as appropriate. RBI assessment can be qualitative, quantitative or semi-quantitative in nature. RBI is a means of using inspection resources more cost effectively and with confidence. RBI ensures that the company or the user fulfil the current safety procedures and also

allow them to make inspection decisions based on sufficient information and expertise, thereby saving time and money.

There are several risk assessment models which has been developed and used by most of the pressurized equipment's operator. These include Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Failure Mode and Effect Analysis (FMEA), Hazard and Operating studies (HAZOP), Risk Matrix and etc. Different technique has different approach. FMEA for instance assumes a failure mode arises in a system or component through some failure mechanism then the possibility of failure of the equipment or system as a whole will be calculated.

Risk-Based Inspection recommendations and guidelines have been established by several technical societies, most notably the American Society of Mechanical Engineers (ASME) and American Petroleum Institute (API). The API began the RBI Project in May 1993. The intention of API RBI is to be a practical and comprehensible tool at a plant inspection level by simplification of complex models using a practical procedure standardized for petrochemical plants. The API RP 581 which focusing on Risk-Based Inspection Technology is used in conjunction with the API RP 580. API RP 580 is the API standard for developing an RBI model or program while API RP 581 is the API standard for executing an RBI program.

1.2 Problem Statement

Risk based inspection model for heat exchanger is required due to the following issues:

- Most inspection codes and standards in general, are developed based on probability of failure instead of the cost of failure, e.g. Condition-based Inspection.
- Expensive commercial RBI software purchased from the market which in some cases, less suited with the equipment used in the operator's plant may lead to inaccurate result of analysis as compared to customized ones.
- Assessment of risk is required to identify the best frequency or time interval between inspections by taking into account the cost of inspection and the cost associated with lost opportunity due to bundle failure.
- Developments are necessary in the cost effectiveness of inspection programs by shifting capitals to solve the vital few issues.

1.3 Objectives

The objectives of this project are as follows:

- To develop a Risk-Based Inspection (RBI) model for heat exchanger tube bundles.
- To apply Microsoft Excel and VBA in developing RBI application to perform calculation, analyze information and visualize data for RBI model.

1.4 Scope of Study

The scope of the project covers the following:

- Main components of heat exchanger, which are shell, tube bundles and baffle that are critical and usually exposed to failures.
- Life data analysis by applying the use of Weibull distribution.
- Input data for the FMECA of a heat exchanger tube bundles used in industry, mostly on thickness data and corrosion.
- Comparison between quantitative and semi-quantitative risk analysis of bundles that combines both advantages of qualitative and quantitative analysis.
- The application of Microsoft Excel and VBA to perform life data analysis, evaluate the risk level and propose the next inspection date of bundles.

1.5 Relevancy and Feasibility

In order to develop an RBI model for exchangers, all necessary relevance key points are taken into consideration. This involves all stages which include the life data analysis of exchanger tube bundles, risk assessment of mode of failure of exchangers and the next inspection plan based on the result of assessment. Weibull distribution will be used in order to accomplish the life data analysis whereby the dataset of age-to-fail will be used as the raw data for the model. As for the risk assessment, quantitative method will be used to evaluate the risk value by taking into account the probability of failure and the associated financial consequences. Then, based on the risk assessment, the next inspection plan which consists of the date of next inspection can be proposed.

CHAPTER 2

LITERATURE REVIEW

2.1 Chapter Introduction

In this chapter, there will be discussion and analysis of a number of literatures related to this case study. As described in earlier chapters, this project involves several key points that need further justification and analysis to be understood before being implemented into this project. The key points that will be described and analysed further in this chapter include the background theory of RBI for tube bundles, overview of Weibull distribution and its application in RBI as the method of quantitative assessment, risk analysis based on the risk matrix, the inspection planning, the overview of TEMA code used in heat exchanger fabrication and the inspection codes used to inspect the tube bundles. A number of literatures consists of past research papers and available books will be used as the reference. In this literature analysis, the terms *heat exchanger*, *exchanger*, *tubular* and *tube bundles* are interchangeably used to refer to shell-and-tube heat exchangers.

2.2 Background of RBI

Risk-based inspection (RBI) is defined as the process of developing an inspection plan based on the knowledge of the risk of failure of the equipment (Bertolini, 2009). Most people sometimes mistakenly understand that the RBI as the methodology of the inspection process rather than the inspection planning or program developed for the facility or the equipment in the plant. There are a number of guidance documents published from several institutions serve as the guidelines to implement RBI technology for the tube bundles used in industry. Among the notable ones are API 580, API RP 581 and ASME PCC-3.

Ralph (2015) in his book titled Reliable Maintenance Planning, Estimating and Scheduling under Chapter 14: Understanding Risk-Based Maintenance by Using Risked-Based Planning with Risk-Based Inspections describes the evolution of Maintenance strategies from 1950 until 1995. According to him, maintenance strategies have been evolved from event-based response in 1950, followed by time-based in 1960, condition based in 1980, reliability based in 1990 and lastly the risk-based in 1995. This development of maintenance strategy is illustrated in Figure 2.1 (Ralph 2015).
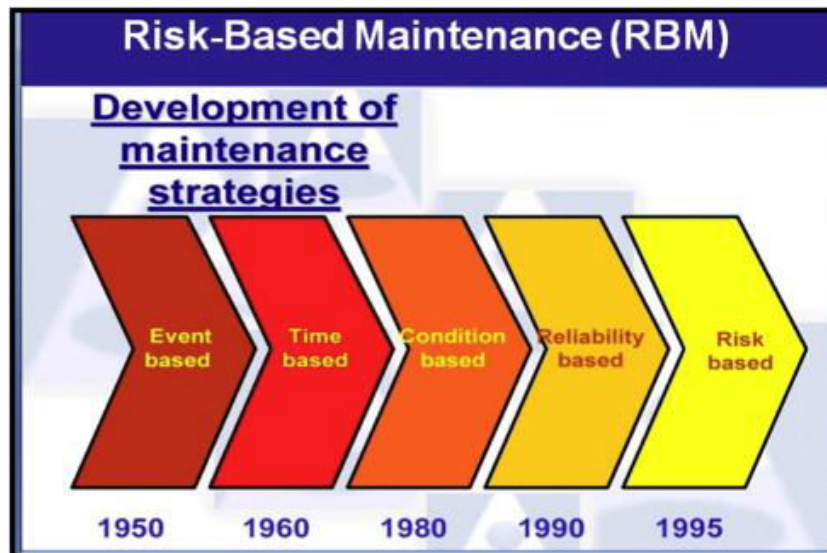
Figure 2.1: The Development of Maintenance Strategies.
(Reliable Maintenance Planning, Estimating and
Scheduling, 2015)

Maintenance strategies have evolved from primitive breakdown maintenance to more sophisticated strategies like condition monitoring and reliability-centred maintenance over the past few decades (Khan & Haddara, 2004). Another approach in this chain of development has recently been added by the introduction of a risk-based methodology to maintenance. This approach has been recommended as a new vision for asset integrity management (ASME, 2000). Some authors (Krishnasamy et al., 2005, Kumar, 1998 and Van Heel et al., 1999) developed Risk-based maintenance strategies by taking both the reliability of a system and the risk that would result as a consequence of an unexpected failure into consideration to provide an inspection planning program which involves in making decisions regarding the type and the time for maintenance actions. Mostly, either quantitative or semi-quantitative is used in the previous studies as the method of risk assessment to develop RBI for a system.

Complete methodology and guidance has been described intensively for RBI of heat exchanger tube bundles in API 581 published in 2008. Generally, there are 5 key steps being emphasized to implement the RBI tube bundles proposed in the publication. These are identification of POF, calculating the COF, carry out the risk analysis, inspection planning based on the risk analysis and the bundle inspect/ replacement decision using the Cost Benefit Analysis (CBA). Two-parameter Weibull distribution is recommended by API 581 in calculating the POF of bundle

failure as a function of service duration time of the exchanger. A reliability database or Weibull library is essential in assessing the reliability of the exchanger to be evaluated as this can provide the additional data of Time To Failure (TTF) of the similar exchanger in the database. A Weibayes approach can be used if the assumption is made that similar designed bundles in similar service will have the same failure mechanism. Basic data required for the database in obtaining the identical designed bundle is provided in Table 8.1 in the API 581. Appendix A shows a copy of the basic data for the exchanger bundle risk analysis. One of the matching criteria or the cut-set proposed is the failure mechanism. Several different failure mechanisms that a heat exchanger tube bundle can experience include corrosion, pitting, cracking, erosion/corrosion, vibration damage, mechanical failure and tube end thinning. A Weibull probability plot will be done based on the age-to-fail data obtained after filtering the bundle reliability database using the parameters listed in the Appendix A. Goodness of fit test is necessary to be be carried out to examine whether or not the subset of data filtered in the reliability database is correct.

2.3 Weibull Distribution

Weibull distribution was invented by Waloddi Weibull in 1937. He claimed that his distribution applied to a wide range of problems. Weibull distribution is widely used in life data analysis. It is the leading method in the world for fitting and analyzing life data. Dr. Robert B. Abernethy in his book The New Weibull Handbook found that the Weibull method works with extremely small samples, even two or three failures for engineering analysis. He also states that the scope of the Weibull analysis may include plotting the data and interpreting the plot, failure forecasting and prediction, evaluating corrective action plans, test substantiation for new designs with minimum cost, maintenance planning and cost effective replacement strategies, space parts forecasting, warranty analysis and support cost predictions. This project will implement Weibull distribution in determining the POF by identifying the two parameters and obtaining the Mean Time To Failure, MTTF for failure forecasting and inspection plans.

2.3.1 Probability of Failure from the Weibull Plot

The Weibull Data Plot
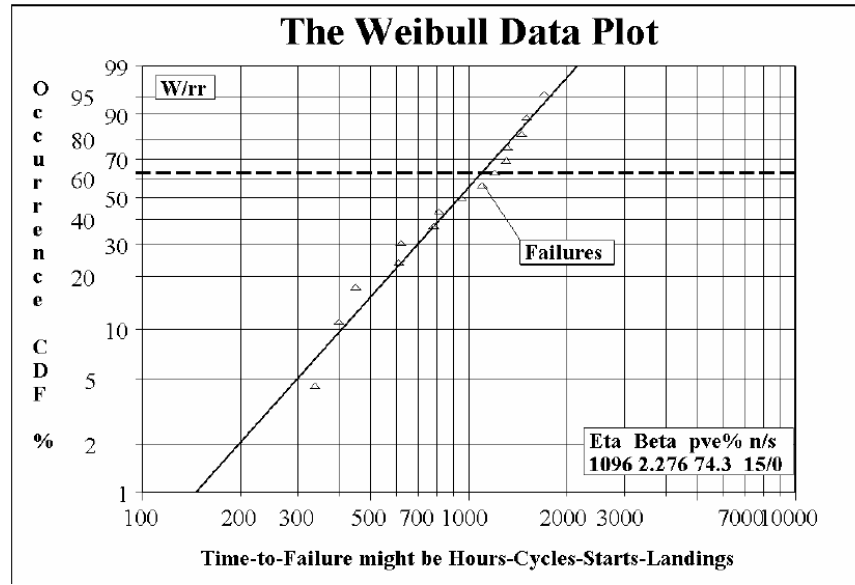
Figure 2.2: Typical Weibull Probability Plot. (The New Weibull Handbook, 1998)

Figure 2.2 shows a typical Weibull plot. The horizontal axis is a measure of life-to-failure or aging. The examples of aging parameters are start-stop cycle, operating time, mileage and landings or mission cycle. The cumulative percentage failed scale is presented by the vertical axis. The line slope, β and the characteristic life, η are the two defining parameters of the Weibull line. The typical time to failure or the mean time to failure is related to the characteristic life, η. For this project, the age of each part which is the tube bundle is required, both failed and unfailed (suspensions). According to (Robert, 2006), the slope, β indicates which class of failure is present:

- β < 1.0 : infant mortality
- β = 1.0 : random failures (independent of age)
- β > 1.0 : wear out failures

Sometimes, it may be necessary to determine the time at which 1% of the tube population will have failed. Weibull called this as B1 life. In the case of more serious and may lead to catastrophic failure, a lower risk may be required, B.1 which means the age at which 0.1% of the tubes population would fail. The age-to-failure can be read form the Weibull plot. For instance, by referring to

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Figure 2.2, B1 life is approximately equal to 160 and B30 is 700. Equation 2.1 and Equation 2.2, which are the Bernard's median rank and Drew Auth's correction, will be used for Weibull plotting. Mischke in his ASME paper titled A Distribution-Independent Plotting Rule for Ordered Failures explains the use and derivation of Drew Auths's correction for adjusted rank algorithm (involving suspension data) (Robert, 2006).

$$MR = \frac{i - 0.3}{N + 0.4}$$ ……………….…………… (2.1)

where,   MR = median rank

i   = failure order number

N   = total number of failure / data

$$AR = \frac{(IR)(PAR) + (N+1)}{(IR+1)}$$ ………………….……… (2.2)

where,   AR = adjusted rank

IR = inverse rank

PAR = previous adjusted rank

N = total number of failure / data

Since the RBI model developed in this project involves the incomplete or censored data, both of the Equation 2.1 and Equation 2.2 will be used in determining the POF of the bundle failure. Chapter 3 (Methodology) will explain the steps in plotting the Weibull line by using these equations.

2.3.2 Advantages of Weibull Analysis

According to (Robert, 2006), the main advantage of Weibull analysis is the capability of the distribution to provide failure forecast and analysis even with extremely small available samples. This would enable the operator or engineer to plan the solution of the damage mechanism without having to wait for additional damage to happen. This would accelerate the process to mitigate the risk level for the risk involved.

Furthermore, Weibull analysis provides a simple yet useful graphical plot of the failure data. The plot is informative and useful to the engineer and

manager. From the plot, engineers can obtain the value of the characteristics life, η and the shape factor, β. These two parameters will enable the engineer to calculate the probability of failure of the exchangers (Robert, 2006).

2.3.3 Probability of Failure using Weibull Distribution

According to API RBI, the probability of failure for a tabular heat exchanger bundle can be expressed using two parameters of Weibull distribution as shown in the Equation 2.3.

$$P_f^{tube} = 1 - R(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \dots\dots\dots\dots (2.3)$$

where, P_f^{tube} = probability of failure

t = independent variable time in years

η = Weibull characteristic life in years

β = Weibull shape factor

By rearrange Equation 2.3 into Equation 2.4, the time to reach a desired probability of failure can be calculated.

$$t = \eta(-\ln[1 - P_f{}^{tube}])^{\frac{1}{\beta}} \dots\dots\dots\dots\dots\dots (2.4)$$

Equation 2.4 is very important and useful as it will be used to calculate the duration to failure in a given POF thus capable to calculate the next inspection date. Equation 2.4 will be used in Chapter 3 (Methodology) to calculate the time to reach a desired probability given the risk target stated by the owner-user.

According to API RBI, there are four methods that can be used to calculate the probability of failure as a function of in-service duration. The four methods are as follow:

- Method 1: Using matching criteria to filter on the reliability library
- Method 2: Using Weibull parameters, β and η specified by owner-user
- Method 3: Using Mean Time to Failure, MTTF specified by owner-user
- Method 4: Specific Bundle Inspection History

For this project, Method 1 is preferable to be used to perform the calculation of probability of failure. Method 1 involves the step of filtering the reliability library for the heat exchanger to obtain the TTF of identical or similar exchanger to be evaluated. The matching criteria or the cut-set has been described in API 581 under section 8.3.3 and the matching criteria are listed in Table 8.1 from the publication. Among the criteria include the exchanger start date, exchanger type, exchanger orientation, tube finished thickness,   Hence, only Method 1 will be discussed further throughout the literature analysis and in Chapter 3 (Methodology).

The aim of matching criteria is to filter the database sufficiently enough to isolate the failure mechanism within the cut-set to one specific damage mechanism and to obtain an acceptable Weibull plot. Once the Weibull line is constructed, a goodness of fit test should be applied and added confidence (API recommends a 90% lower bound confidence interval) is applicable. Then, the Weibull parameters, β and η can be measured from the plot accordingly. Chapter 3 will discuss further on the steps and process flow in obtaining the probability of failure, P_f from Weibull plot.

2.4 PVE% as The Method for Goodness of Fit Test

Apart from using the r^2 method, the other option is to use the p-value estimates (pve%) for the goodness of fit test. This method is recommended by API RBI as one of the method to determine whether a not the subset of data obtained from the failure database is correct. According to the publication, pve% of greater than 20 is considered adequate for small size of failure sample, typically less than 20. Equation 2.5 is used to determine the pve% of the subset of data.

$$\frac{\left(\sum(x-\bar{x})(y-\bar{y})\right)^2}{\sum(x-\bar{x})^2 . \sum(y-\bar{y})^2} \quad X \ 100\% \quad \dots\dots\dots\dots\dots (2.5)$$

where, x = ln TTF

$\bar{x}$ = mean of ln TTF

y = ln(ln(1/(1-MR)))

$\bar{y}$ = mean of ln (ln(1/(1-MR)))

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2.5 Estimating Weibull Parameters through Rank Regression Method

Weibull parameter estimates can be obtained through several ways and one of methods that can be used is by performing a simple linear regression. It is expected that the graph of the ln (TTF) vs. the transformed median ranks will result in straight line. It can be proven by transforming the Weibull cumulative distribution function, the cdf so that it appears in the familiar form of a straight line, the Y=mX+c. Below shows the cdf of Weibull being transformed into the equation of straight line.

$$F(x) = 1 - e^{-\left(\frac{x}{\eta}\right)^{\beta}}$$

$$1 - F(x) = e^{-\left(\frac{x}{\eta}\right)^{\beta}}$$

$$ln\big(1 - F(x)\big) = -\left(\frac{x}{\eta}\right)^{\beta}$$

$$ln\left(\frac{1}{1 - F(x)}\right) = -\left(\frac{x}{\eta}\right)^{\beta}$$

$$ln\left[ln\left(\frac{1}{1 - F(x)}\right)\right] = \beta ln\left(\frac{x}{\eta}\right)$$

$$ln\left[ln\left(\frac{1}{1 - F(x)}\right)\right] = \beta ln\left(\frac{x}{\eta}\right)$$

$$ln\left[ln\left(\frac{1}{1-F(x)}\right)\right] = \beta lnx - \beta ln\eta \quad \text{.........................} \quad (2.6)$$

By comparing the Equation 2.6 with the equation of a straight line Y=mX+C, it is noticed that the left side of the equation $ln\left[ln\left(\frac{1}{1-F(x)}\right)\right]$ corresponds to the Y, lnx corresponds to X, β corresponds to m or the gradient and the C or y-intercept having the value of $-\beta ln\eta$. From Equation 2.6, the two parameters of Weibull distribution can be estimated through the X or Y rank regression method. The methodology in obtaining the β and η values through rank regression method will be further discussed in Chapter 3.

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2.6 Consequence of Failure

Equation 2.7 is used to determine the consequence, $C_f{}^{tube}$ of an unplanned shutdown due to a bundle tube leak.

$$C_f{}^{tube} = Cost_{prod} + Cost_{env} + Cost_{bundle} + Cost_{maint} \ldots\ldots\ldots\ldots (2.7)$$

The lost opportunity cost or the unit production cost, $Cost_{prod}$ is determined by using Equation 2.8.

$$Cost_{prod} = Unit_{prod} \left(\frac{Rate_{red}}{100}\right) D_{sd} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.8)$$

where, $Rate_{red}$ = rate reduction of production impact

D_{sd} = unplanned shutdown days to repair

Equation 2.9 may be used to estimate the bundle replacement cost (API RP 581,2008).

$$Cost_{bundle} = \frac{Cost_{rep}\left(\frac{\pi D_{shell}{}^2}{4}\right) L_{tube} M_f}{C_1} \ldots\ldots\ldots\ldots\ldots\ldots (2.9)$$

where, $Cost_{rep}$ = bundle replacement cost in $

D_{shell} = heat exchanger shell inside diameter in in

L_{tube} = tube length of the bundle in ft

M_f = material cost factor

The replacement $Cost_{rep}$ referred to Equation 2.9 depends on the type of material and dimensions of the bundle used. For example, API RBI assumes $Cost_{rep}$ equals to $22,000 for typical sized carbon steel bundle with 800mm diameter x 6m long bundle with a volume of 3.016m^3.

2.7 Risk Analysis

According to a classical definition (Henley and Kumamoto, 1981; Vose, 2000), the risk of failure, $Risk_f^{tube}$ is defined as:

$$Risk_f^{tube} = P_f^{tube} C_f^{tube} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(2.10)}$$

where, $\quad\quad\quad\quad\quad\quad P_f^{tube}$ = probability of failure

$\quad\quad\quad\quad\quad\quad\quad\quad C_f^{tube}$ = cost given failure

To an operator of production equipment C_f^{tube} may include several components (Todinov, 2007):

- Cost of production
- Medical costs
- Insurance costs
- Legal costs
- Cost of cleaning up polluted environment
- Costs of mobilisation of emergency resources
- Costs of loss of business due to low customer confidence and loss of reputation

While for manufacturer of the equipment, cost of failure may include:

- Loss of sales
- Penalty payments
- Compensation and legal costs
- Warranty payment if the equipment fails before the agreed warranty time

Equation 2.10 is used in performing the risk evaluation and will be discussed further in Section 2.8 (Inspection Planning).

There are three main types of risk assessment method which are qualitative, semi-quantitative and quantitative methods. Qualitative risk assessment uses a relative or descriptive scale to measure the probability of occurrence. For example, a scale of {Unlikely, Possible, Frequent} is used to indicate the likelihood of a risk event occurring while a scale of {Minor, Moderate, Severe} is used to indicate the

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consequences severity of the failure. This is usually applicable to risk rating matrix (Bateman, 2006). The other examples of qualitative analysis include Fault Tree Analysis (FTA), Event Tree Analysis (ETA) and Failure Mode and Effect Analysis (FMEA).

2.7.1 Quantitative Risk Assessment

Quantitative risk assessment provides the numerical evaluation of risk by evaluating risks with a score (Andreone, 1998). It avoids some of the greater ambiguities that a qualitative risk assessment may produce. Furthermore, it offers a more consistent and rigorous approach to assessing and comparing risks and risk management strategies than does qualitative risk assessment. It does not require the same amount of data and hence risk assessment strategies can be performed where precise data are missing (Todinov, 2007).

2.7.2 Risk Rating Diagrams

Evaluating the risk associated with a single failure situation begins with assessing its probability and consequences. Each combination of values (usually multiplication) for the probability of failure and the consequence given failure defines a point in the risk rating matrix as shown in Figure 2.3.

Risk assessment matrix			Likelihood of adverse effect		
			Unlikely	Possible	Frequent
			1	2	3
Severity of consequences	Minor	1	1	2	3
	Moderate	2	2	4	6
	Severe	3	3	6	9

Figure 2.3: Risk assessment matrix. (Adapted from *Tolley's Practical Risk Assessment Handbook*, by Bateman)

The numbers can be replaced by descriptions of the level of risk as shown in the Figure 2.4.

Risk assessment matrix		Likelihood of adverse effect		
		Unlikely	Possible	Frequent
Severity of consequences	Minor	Low	Low	Medium
	Moderate	Low	Medium	High
	Severe	Medium	High	Very high

Figure 2.4: Risk assessment matrix. (Adapted from *Tolley's Practical Risk Assessment Handbook*, by Bateman)

If the box representing the risk is in the low-risk region, no response is required since the risk is so low that it is considered insignificant. If the risk score defines in the high risk region, the risk is considered unacceptable. Risk reduction actions are necessary to exit this region (Todinov, 2007).

2.8 Inspection Planning

By rearrange Equation 2.10, the maximum acceptable probability of failure for bundles, $P_{f,max}^{tube}$ as a function of the risk target specified by the user, $Risk_{tgt}$ and the consequence of tube failure, C_f^{tube} can be determined by using Equation 2.11.

$$P_{f,max}^{tube} = \frac{Risk_{tgt}}{C_f^{tube}} \quad \text{................................…....…} \quad (2.11)$$

By utilising Equation 2.11 together with Equation 2.4, the time to a target inspection date, t_{tgt} can be determined by using Equation 2.12. The resulting target date is the date at which the risk of the bundle encounters the risk target stated by the user.

$$t_{tgt} = \eta \left(-\ln\left[1 - P_{f,max}^{tube}\right] \right)^{\frac{1}{\beta}} \quad \text{.........................} \quad (2.12)$$

According to API RP 581, the inspection planning can be classified into two which are planning with inspection history and planning without inspection history. Inspection planning without the inspection history means the planning is for the first inspection date.

2.8.1 Inspection Planning Without Inspection History (First Inspection Date)

The probability of failure can be determined by using the matching heat exchanger bundles from reliability database and obtain the Weibull plot of that similar heat exchanger bundles. Table 2.1 shows the example of some data of similar bundles from database and Figure 2.5 shows the Weibull plot of the similar bundle data.

Table 2.1: Matching bundles from reliability database
(Source: API RP 581)

Bundle Tag #	In-Service Duration (years)	Failure Reported
191-X-25A-T1	18	Yes
191-X-25A-T2	22	Yes
191-X-25A-T3	16	No
E101-A-T1	10	Yes
E322-A-T1	12	No
E322-A-T2	13	No
HE-115-T1	14	Yes
HE-115-T2	25	No
PR6419-T1	8	Yes
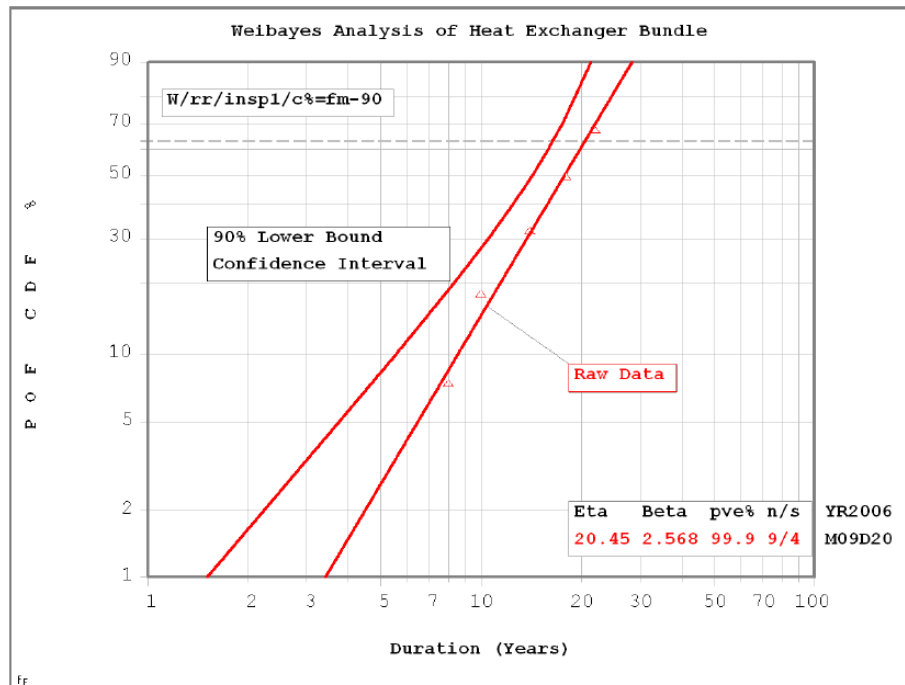
Figure 2.5: Weibull plot of similar bundle data. (Source: API RP 581)

To account for bias and uncertainties that are inherent from the database, API RBI recommends a default value of 50% for additional uncertainties (AU) to be introduced into the statistics and Weibull plot. Figure 2.6 represents the Weibull plot with AU 50%. The plot is shifted to the left as the result of the added uncertainty. Table 2.2 shows the time in-service as a function of Probability of Failure (POF) and the uncertainty. Besides that, the recommended length of service for the bundle being evaluated may be determined by using the curve on Figure 2.6 or can be obtained from the Table 2.2.
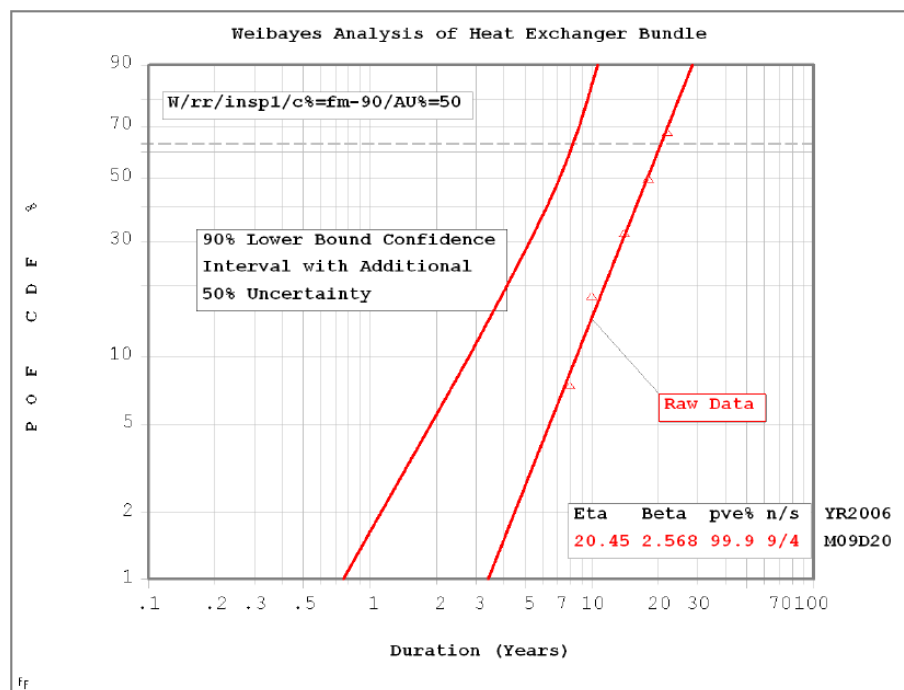
Figure 2.6: Weibull plot with 50% additional uncertainty
(Source: API RP 581)

Table 2.2: Time in-service as s function of POF and uncertainty
(Source: API RP 581).

Method	Time in Service (years)						
	POF=1%	2%	5%	10%	20%	50%	90%
Weibull, Raw Data	3.48	4.47	6.43	8.51	11.4	17.7	28.3
90% LBC	1.51	2.24	3.76	5.57	8.31	14.3	21.3
90%LBC with 5% AU	1.44	2.13	3.57	5.29	7.89	13.54	20.2
90%LBC with 10% AU	1.36	2.01	3.38	5.01	7.48	12.8	19.2
90%LBC with 20% AU	1.21	1.79	3.00	4.46	6.65	11.4	17.0
90%LBC with 30% AU	1.06	1.57	2.63	3.9	5.82	9.98	14.9
90%LBC with 50% AU	0.76	1.12	1.88	2.79	4.15	7.13	10.6

Note: The values in this table are for example only and are specifically for a Weibull distribution with $\beta = 2.568$ and $\eta = 20.45$.

Based on Table 2.2 (or Figure 2.6), the recommended first inspection for POF of 0.5 would be 7.13 years after installation based on the API RBI default value of 50% AU plus 90%LBC. Weibull raw data with only 90%LBC without the AU shows time in service of 14.3 years. This shows the impact of uncertainty in calculating the risk and the planning the next inspection.

2.8.2 Inspection Planning With Inspection History

There are several points to be taken into account while performing the inspection planning for bundle with inspection history. These points which are listed in API 581 include the effect of inspection on Probability of Failure (POF), the reduction in uncertainty due to inspection effectiveness, shift of POF curve due to knowledge of true bundle condition, predicted future failure date based on the Estimated Remaining Life (ERL) and the adjustment to the failure rate curve based on actual condition of bundle.

Referring to API RP 581, one of the significant effects of inspection history is the reduction of uncertainty due to the effectiveness of the past inspections. This will results in the use of more accurate failure rate curve, e.g. moving from 50% AU (without any inspection history) to a curve with 20% AU (recommends AU value by API for Moderately Effective Inspection). As more effective technique of inspection is used, the uncertainty will reduce and the failure rate curve will be shifted to the right. Table 2.3 shows the inspection effectiveness and the corresponding value of uncertainty recommended by API RBI.

Table 2.3: Inspection effectiveness and uncertainty
(Source: API RP 581)

Inspection Effectiveness	Inspection Cost ($)	Uncertainty (%)
E – Ineffective	0	50
D – Usually Not Effective	1,000	30
C –Moderately Effective	2,000	20
B – Usually Effective	3,000	10
A – Highly Effective	5,000	5

Apart from that, the inspection history also provides the knowledge of the current condition of the bundle. For instance, the average measured tube thickness data may be useful to predict the failure date when the general corrosion is the controlling damage mechanism of the bundle. The thinning rate of the tube bundle t_{rate} can be determined by using Equation 2.13.

$$t_{rate} = \frac{\bar{t}_{orig} - \bar{t}_{insp}}{t_{duration}} \quad \text{................................} \quad (2.13)$$

where, $\bar{t}_{orig}$ = average furnished wall thickness
$\bar{t}_{insp}$ = average of wall thickness as measured on the last inspection

For bundle with thickness inspection history, the predicted bundle life adjusted, PBL_{adj} for inspection can be calculated by using Equation 2.14.

$$PBL_{adj} = \frac{(RWT_f)(\bar{t}_{orig})}{t_{rate}} \quad \text{............................} \quad (2.14)$$

where, RWT_f = fraction of remaining wall thickness (failure point)

t_{rate} = thinning rate

2.8.3 Effects of Bundle Life Extension Efforts.

In most cases, only minor repairs and cleaning operations are performed on exchanger bundles during an inspection. The POF of the bundle will be calculated at service duration or time in service, t_{dur} going back to the bundle's original installation date. However, several life extensions methods have been done in plant during shutdowns to serve the bundle back into service in an improved condition (but not as new). Thus, an adjustment is made whereby there will be a new installation date for the purpose of calculation. Table 2.4 shows the credit allocated according to the type of life extension method used and it is named as the Life Extension Factor, LEF.

Table 2.4: Effects of Life Extension Methods (Source: API RP 581)

Life Extension Method	Life Extension Factor (LEF)
Plug Tubes	0.10
180° Bundle Rotation	0.50
Partial Re-tube	0.50
Total Re-tube	0.75
Install Spare Bundle	0.50

The adjusted service duration, $t_{dur_{adj}}$ will then be calculated using the LEF value in accordance with Equation 2.15.

$$t_{dur_{adj}} = (1 - LEF)t_{dur} \quad \text{..................................} (2.15)$$

The actual service duration, t_{dur} of the bundle is calculated as a time period from the installation date of the bundle to the inspection date where the life extension method was performed. Equation 2.16 is used to calculate the actual service duration, $t_{dur.}$

$$t_{dur} = Inspect\ date - Install\ date \quad \text{.....................} (2.16)$$

All the subsequent POF calculation will then be based on the new installation date which can be calculated by using the Equation 2.17.

$$New\ install\ date = Inspect\ date - t_{dur_{adj}} \text{.....................} (2.17)$$

2.9 Program Validation Tools & Process.

Validation of the developed program is necessary to ensure the mathematical algorithm used in the application will give an accurate outcome. It is also important to determine if the system complies with the requirements and performs the function for which it is intended and meets the organization's goals and user needs. Usually, validation is done at the end of development process and takes place after program verifications are completed. According to the Capability Maturity Model (CMMI-SW V1.1) published by Software Engineering Institute in 2002, validation can be defined as the process of evaluating the software during or at the end of the development process to determine whether or not it satisfies the specific requirements.

2.9.1 Weibull ++ by ReliaSoft Corp.

Weibull++ is the industry standard in life data analysis commonly used by thousands of companies worldwide. The software provides a complete array of data analysis, plotting and reporting tools for standard life data analysis (LDA) with integrated support for a variety of related analyses such as warranty data analysis, degradation data analysis, recurrent event data analysis, non-parametric life data analysis and reliability test design.

ReliaSoft has developed an integrated platform called Synthesis in which it unites any or all the Reliasoft's main reliability engineering applications such as Weibull++, BlockSim and RBI into one easy-to-deploy integrated reliability solution. Figure 2.7 shows the main menu of the Synthesis Platform.
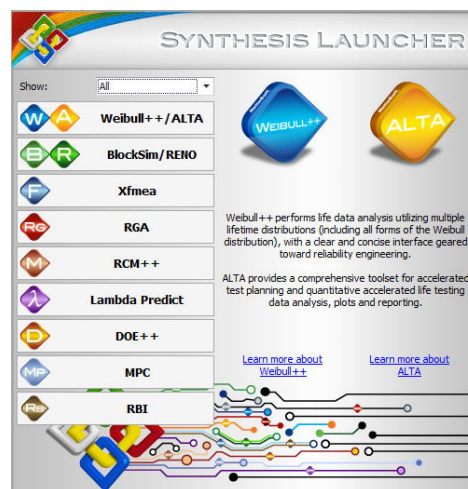
Figure 2.7: The main menu of the Synthesis Launcher.

2.9.2 The Analysis ToolPak by Microsoft Excel

The Analysis ToolPak is a Microsoft Office Excel add-in program that is available for the Excel's users. It is an Excel add-in program that provides data analysis tools for financial, statistical and engineering data analysis.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.9777
R Square	0.9558
djusted R Squa	0.9411
Standard Error	0.2809
Observations	5

ANOVA

	df	SS	MS	F	Significance F
Regression	1	5.1254	5.1254	64.9470	0.0040
Residual	3	0.2368	0.0789		
Total	4	5.3622			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-7.2791	0.8065	-9.0262	0.0029	-9.8456	-4.7127	-9.8456	-4.7127
ln(data value)	2.4700	0.3065	8.0590	0.0040	1.4946	3.4454	1.4946	3.4454
Beta	2.4700							
Alpha	19.04953206							

Weibull Plot — $y = 2.47x - 7.2791$, $R^2 = 1$

Figure 2.8: The Analysis ToolPak by the Microsoft Excel.

The Excel Analysis ToolPak can be used to validate the program as it provides the beta and alpha values for the Weibull distribution through regression function. It also has the ability to perform other statistical tasks e.g., Fourier analysis, F-test, t-test, Z-test etc. Apart from that, it is also useful to calculate the pve% and the MTTF of the failure distribution. Weibull probability plot can be drawn based on the values provided in the Summary Output. This feature can be used to inspect the relationship of the data drawn on the Weibull plot and the value of pve% as a method for the goodness of fit test. Chapter 4 will elaborate further on the validation process of the developed application and its result by using these two statistical tools.

2.10 Heat Exchanger

A heat exchanger is equipment designed to efficiently transfer or "exchange" heat from one matter to another. The fluid used to transfer heat could be a liquid, such as water or oil, or could be moving air. The most familiar example of heat exchanger is a car radiator. In a radiator, the antifreeze or ethylene glycol and water mixture used to transfers heat from the engine to the radiator and then from the radiator to the ambient air

Figure 2.9: Segments of a tubular exchanger. (Source: Cripps, 2014)

flowing through it. This process helps to keep a car's engine from overheating (Lytron, 2014).

Heat exchangers work on the heat transfer principle that states heat naturally flows from higher temperature to lower temperatures. Hence, if a cold fluid and a hot fluid are separated by a heat conducting surface, heat can be transmitted from the hot fluid to the cold fluid (Cripps, 2006).

In a heat exchanger, normally two fluids of different temperatures are brought into close contact there will be physical barrier to prevent them from mixing. According to (Andreone &Yokell, 1998), the temperature of both fluids will tend to equalize. It is possible for the temperature at the outlet of each fluid to get close to the temperature at the inlet of the other by arranging counter-current flow. The heat content from one fluid is simply exchanged with the other and no energy is added or removed.

2.10.1 Tabular Exchangers Manufacturers Association (TEMA)

The Tubular Exchanger Manufacturers Association (TEMA) is an association of manufacturers of shell and heat exchangers tube bundles. TEMA has established a set of construction *standards* for Shell and Tube Heat Exchangers. The construction standards by TEMA are regularly updated and published. Most of the shell and tube exchangers operated by the process industries and ordered for other high-severity applications throughout the world are built according to TEMA standards. The Standards recognize three classes of heat exchanger construction:

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- Class R for the severe requirements of petroleum processing (and usually including most large scale processing applications).
- Class C for general commercial application.
- Class B for chemical process service.

TEMA has its own nomenclature and designation. The name is usually divided into three section which are first section defines the internal diameter of vessel, second section defines the tube length and third section defines the type and configuration of the exchanger. For example, 23-192-BEM indicates that the internal diameter of the vessel is equal to 23 units, the tube length is equal to 192 units and the type of the exchanger is BEM. The B defines the type of front head, E defines the shell type and M indicates the type of rear head.

2.11 Inspection Codes

Throughout this project, there will be three API codes that will be used as reference which are API 510, API 580 and API 581 (main guidance). The descriptions are as follows:

- <u>API 510</u>: This code covers the maintenance, inspection, repair, alteration and re-rating procedures for pressure vessels used by the petroleum and chemical process industries.
- <u>API RP 580</u>: Provides users with the basic elements for developing, implementing and maintaining a risk-based inspection (RBI) program. It is a generic document on RBI that can be used as a measuring stick by which the quality of any and all RBI methods and work processes could be evaluated to determine if they meet the level of quality prescribes in the Recommended Practice (RP)
- <u>API581</u>: The purpose of this publication is to provide quantitative RBI methods that support the minimum general guidelines presented by API RP 580.

CHAPTER 3

METHODOLOGY

3.1 Chapter Introduction

This chapter will discuss the methodology used in completing the project. First section will discuss the process flow of the project through the project flowchart. Several processes involved in this project will be discussed in detail on how the tasks are being conducted. Then, the next section will explain the planning of the tasks to be carried out with respect to the timeline by using the Gantt chart. Last section will discuss the methodology used in developing the application through the flow of several algorithms diagrams related to this project. The developed application has been named as RIHEX which stands for Risk-based Inspection for Heat Exchanger Tube Bundles and the term RIHEX sometimes will be used in Chapter 3 until Chapter 5 to refer to the application.

3.2 Project Process Flow

Figure 3.1 shows the flowchart used to illustrates the process flow of the tasks required for this project. The first task involved in this project is to define the project details which include the objectives, the project scope and any assumptions that need to be made to proceed with the project. The huge scope of the main guidelines used in this project needs to be narrowed down to certain scope in order to accomplish the objectives of the project. This is important to ensure the time available is consumed wisely and no unnecessary tasks are being carried out. The scope of study also will state any limitations to this project thus some assumptions can be made beforehand to ensure the project is carried out accordingly and will not be out of topic. Once all the project background has been stated clearly, the research and literature review is performed. Research is done through several sources. These include research papers and journals accessible through the E-Resources subscribed by Universiti Teknologi Petronas (UTP), books available in UTP IRC etc. All the required mathematical formulae and functions are collected through several sources, mainly from the API 581. Research is also done qualitatively through consultation with the project supervisor and personnel from industry who come to UTP during career talk and adjunct lectures. The next process is to develop the Excel mathematical functions based on the formula and equations collected earlier. The algorithms diagrams are constructed beforehand to ease the task of writing the Excel functions to solve for any

required values in this project. This project involves a lot of Excel mathematical functions since most of the calculations in the application are executed by using the Excel worksheet. Proper and accurate Excel functions are required to avoid any dispute in the values calculated in the result section.
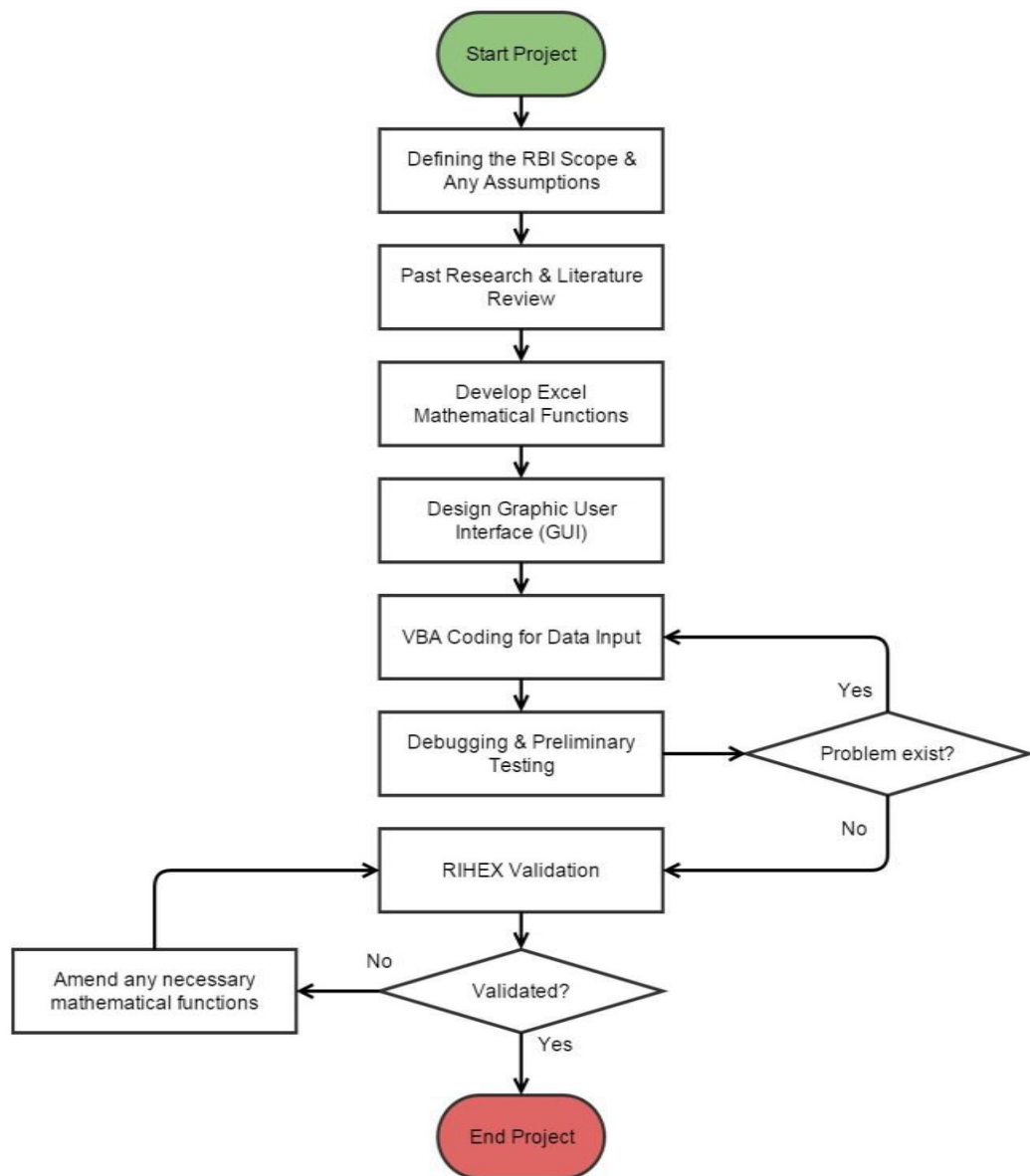

Figure 3.1: The project flow chart.

After setting the Excel mathematical functions to the each of the specific cell in the worksheet, the succeeding process is to design the Graphic User Interface, GUI by using the Microsoft Visual Basics for Applications, VBA. In this project, VBA is used as the 'form' for the user to enter all necessary input for the system to process. It also sends the input data to the Excel worksheet to be analysed with the Excel functions that has been set before. Most of the programming tasks involved in VBA are to deliver the input data to the worksheet and to direct the user to several sections of the applications. Attractive and user-friendly GUI has to be considered in conducting this task. Once the GUI has been designed, the coding is required to run the application. Simple and precise codes used while doing the coding for the program are among the criteria in programming this application. This is to avoid any issues related to complexity of the coding which can end up with unstable application.

The next process is to perform the preliminary testing of the developed application. This can be done by analyse any available data by using the application. All the sections and command buttons of the application has to be tested with no error in coding. If the error exists, immediate debugging will be done to fix the error in the coding.

Once all the required coding has been programmed and tested with no error, the application, RIHEX will be validated by using several applications and statistical software. These include Weibull++ by ReliaSoft Corp. and Analysis ToolPak which is statistical analysis tool pre-installed with the Microsft Excel. Several dataset can be used to validate the application and the percentage difference will be observed. Decision will be made whether or not the resulting data obtained through the calculations performed by RIHEX is acceptable. If the result is unacceptable, then the Excel functions will be checked for any mistakes and changes will be done to the mathematical functions. Once all the necessary alterations have been done, RIHEX will go through the validation process once again until the values in the result are acceptable.

3.3 The Gantt Chart

Figure 3.4 shows the Gantt chart from the beginning of Sept 2014 Semester until the end of Jan 2015 semester.
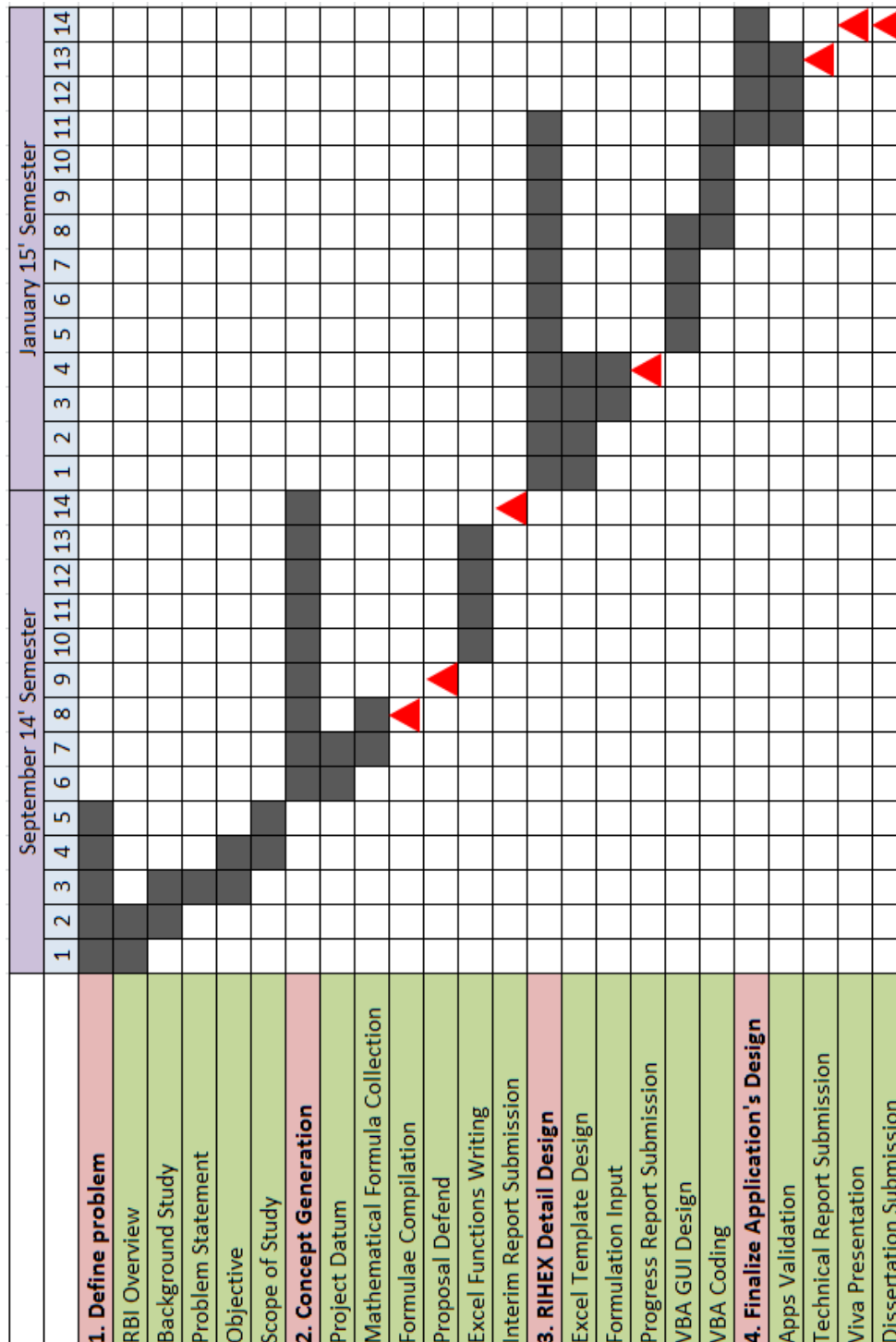

Figure 3.2: Project Gantt Chart.

From Figure 3.2, at the beginning of Sept 2014 semester (FYP1), all activities involved are in the introduction part. The objectives and problem statement are being stated clearly for the project by the end of Week 4. Some inputs about the project are expected during the 5 weeks. Then, the scope of study is being specified during Week 4 and Week 5. In the concept generation part which takes place during Week 6 to the end of Sept 2014 Semester, there will be past research papers and literature review to collect useful information and inputs for this project. All the mathematical formulae required in the project are collected from several literatures by the end of Week 9. After having the Proposal Defend assessment, the project continues with the Excel functions development and writing for several parts of the calculation, mostly the POF part. There is also minor testing of the functions and these takes place until Week 13. Then, the Interim Report is submitted in Week 14 of the Sept 2014 Semester. For the Phase 2 (Jan 2015 semester), detail concept of RIHEX will be done which involves Excel template design and formulation input based on the developed functions earlier. These take place until the end of Week 4. Then, the Progress Report is submitted. The project continues from Week 5 until Week 11 whereby the Graphic User Interface (GUI) was designed and the VBA coding for user inputs were developed. Finalizing process of the design application takes place from Week 11 until the end of Jan 2015 Semester. This involves the validation process which includes any minor changes to the application to improve its functionality and practicality and also to make it more user-friendly. The Technical Report, Viva presentation and Dissertation were submitted at the end of Jan 2015 Semester.

3.3.1 Project Key Milestones

There are several key milestones are being considered in this project. For instance, all the presentations and report submissions are considered as the key milestones in this project since there is fixed time for the task to be completed. Lateness of the submission will subsequently affect the tasks thereafter. This indicates the all the required input for the reports must be done to be included in the report. Apart from that, from Figure 3.2, notice that one key milestone in week 8 (Sept 2014 semester) which is the formulae collection. This task must be completed within the due date to avoid lateness of report submission and subsequently affect the writing of the Excel functions.

3.4 The Mathematical Algorithms

In order to explain the methodology used in calculating the POF, COF and methodology in analyzing the risk and inspection planning, algorithm diagrams will be used as a tool in the following sections. Most of the calculation process of the application is carried out with the use of Excel Functions through several templates and worksheets in a single Excel Workbook. The raw data is processed through several stages: The Rank Regression Analysis, the Probability of Failure (POF) section, Consequence of Failure (COF) section, the Risk Analysis part ended with the Inspection Planning part. The following sections will further discuss the methodology implemented in each of these sections.

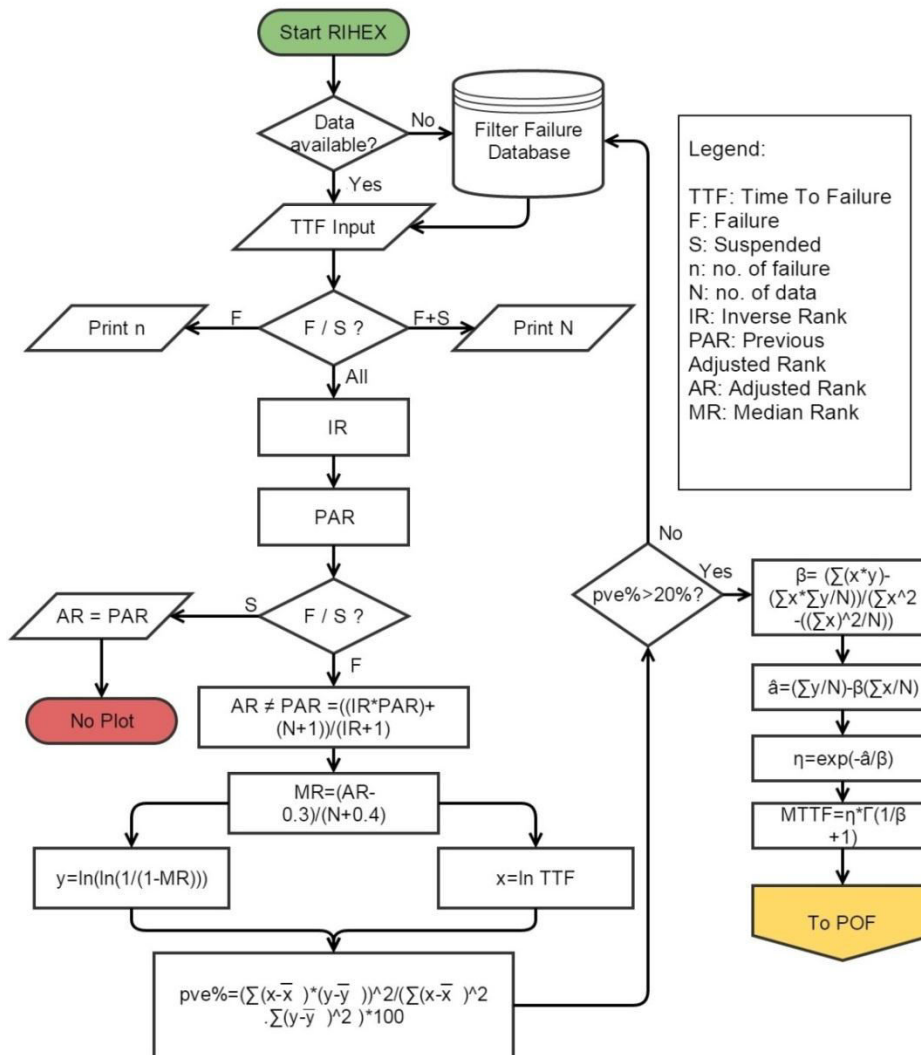## 3.5 The Algorithms for Rank Regression Analysis.

Figure 3.3: Algorithm Diagram for the Rank Regression Calculation.

Figure 3.3 shows the algorithm diagram which describes the process in obtaining the 2 Weibull parameters, η and β through the rank regression method. The process starts with the input of failure data of tube bundle by the user. The user will have two options: to obtain the failure data or the TTF by filtering the failure database through several matching criteria to obtain TTF of several identical exchanger or to enter the TTF directly without going through the filtering process. The latter option is usually possible if the exchanger has gone through several inspection sessions thus providing the inspection result including the TTF data. While for the case of inadequate TTF data and for the first inspection of a new exchanger, the earlier option will be preferable.

Once the TTF data has been entered to the system, the application will read the TTF value one by one whether it is a failure of suspension data. The total number of data entered, N and the total number of failure data, n will be calculated for further use. The Excel will then inverse the rank (IR) of the TTF dataset (from largest to smallest) and assigned the data with the corresponding Previous Adjusted Value (PAV). Next, decision will be made whether the individual data will be plotted or not based on the status of the data. For the plotted or failure data, the process will continue with the calculation of Adjusted Rank (AR), Median Rank (MR), x values and y values by using the formulae stated in Figure 3.3.

The pve% will be calculated as the requirement stated in the API 581 as a method of goodness of fit test. This is necessary to ensure that the TTF data will be properly plotted in Weibull plot especially when the TTF is obtained from the failure database. If a Weibull plot is created from a too broad of a cut-set on the failure reliability database, the data will not be properly plotted on the Weibull plot. Reason being is that multiple failure mechanisms are being considered for the single exchanger to be evaluated. Thus, pve% value which is less than 20% as recommended by API 518 require a more specific list of matching criteria to isolate the failures to one mechanism. This is illustrated in Figure 3.3.

Once the pve% satisfies the minimum of 20% for the goodness of fit, the two important Weibull parameters, η and β will then be calculated followed by the MTTF by using the formulae stated in the algorithm diagram.

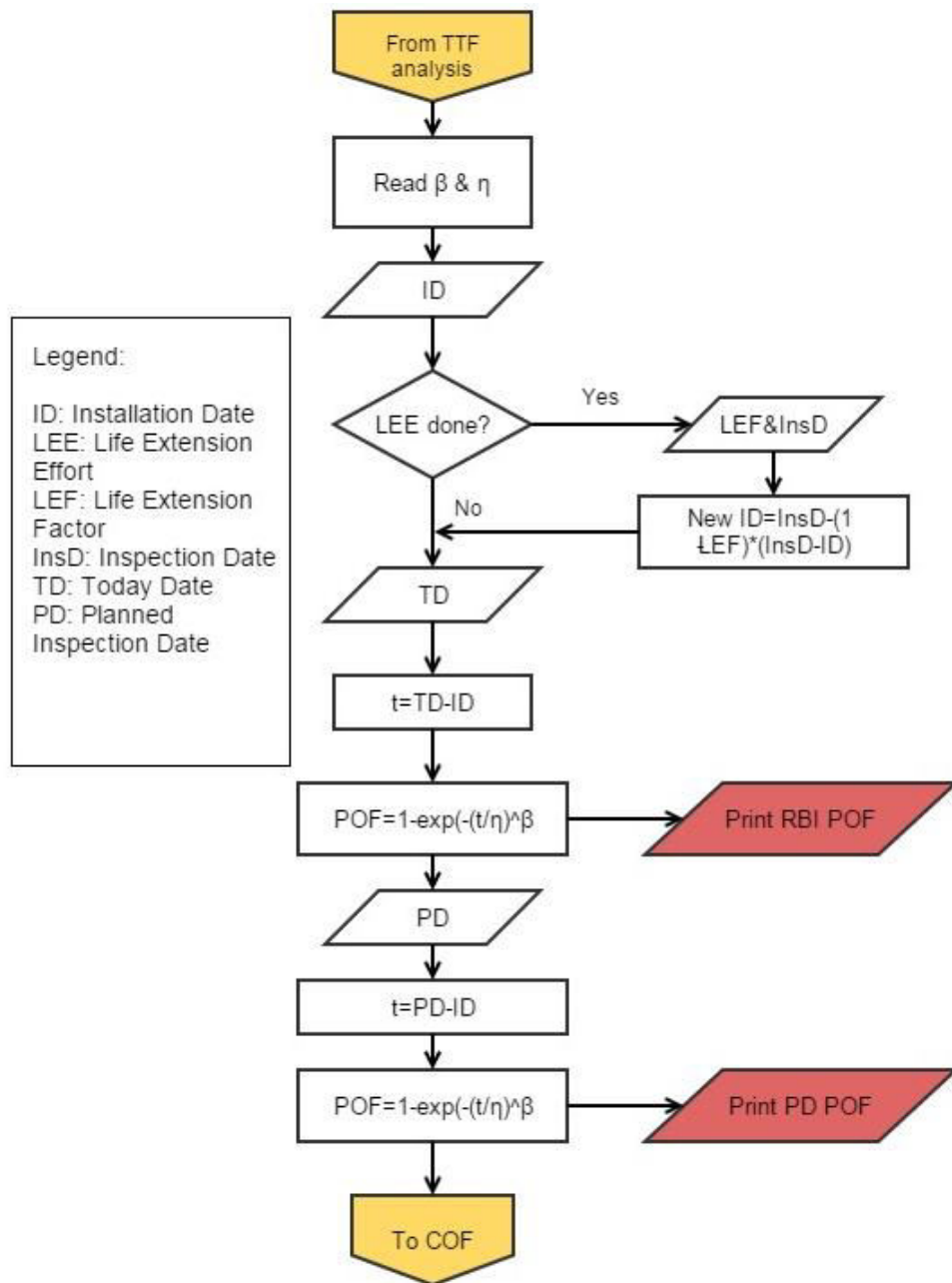## 3.6 The Algorithm for Probability of Failure, POF

Figure 3.4: Algorithm Diagram for the Probability of Failure
Calculation.

Figure 3.4 shows the algorithm diagram for the second section which is the POF calculation part. From the Weibull parameters estimation section, η and β were calculated and these parameters will be used to obtain the value of POF for several of time duration in this section.

The process starts when the system reads the values of η and β. Then, it will be an input of Installation Date by the user. Next, decision will be made whether the system has any Life Extension Effort (LEE) done before. This will be confirmed by the user. If the exchanger has the history of LEE before, there will be an input of Life Extension Method (LEM) and the Inspection Date when the LEE was performed. Life Extension Factor, LEF value which has been initialized or pre-saved in the application will then be read by the system. LEF is depending on the type of life extension method that has been performed whether it is plug tubes, 180deg bundle rotation, partial re-tube, total re-tube or install spare bundle. (Refer to Table 2.4 for LEF value). Next, the new installation date will be calculated based on the formula shown in Figure 3.4.

The process continues with the calculation of RBI POF after the system received the input of today's date. RBI POF is defined by API 851 as the Probability of Failure of the bundles at the date of RBI analysis was performed. The duration time, t is calculated from the date of installation until the date of RBI was performed. Then, the Cumulative Distribution Function, CDF of Weibull distribution will be used to calculate the POF as shown in the algorithm diagram. System then will print the RBI POF and send it to the result page.

Next, calculation of POF for Plan Inspection Date will be done whereby it starts with the input of the next planned inspection date by the user. Time duration will be calculated from the installation date until the next plan inspection date. The POF for the time duration will then be calculated by using the CDF of Weibull distribution and it will send it to the result page.

3.7 The Algorithm for Consequence of Failure (COF).
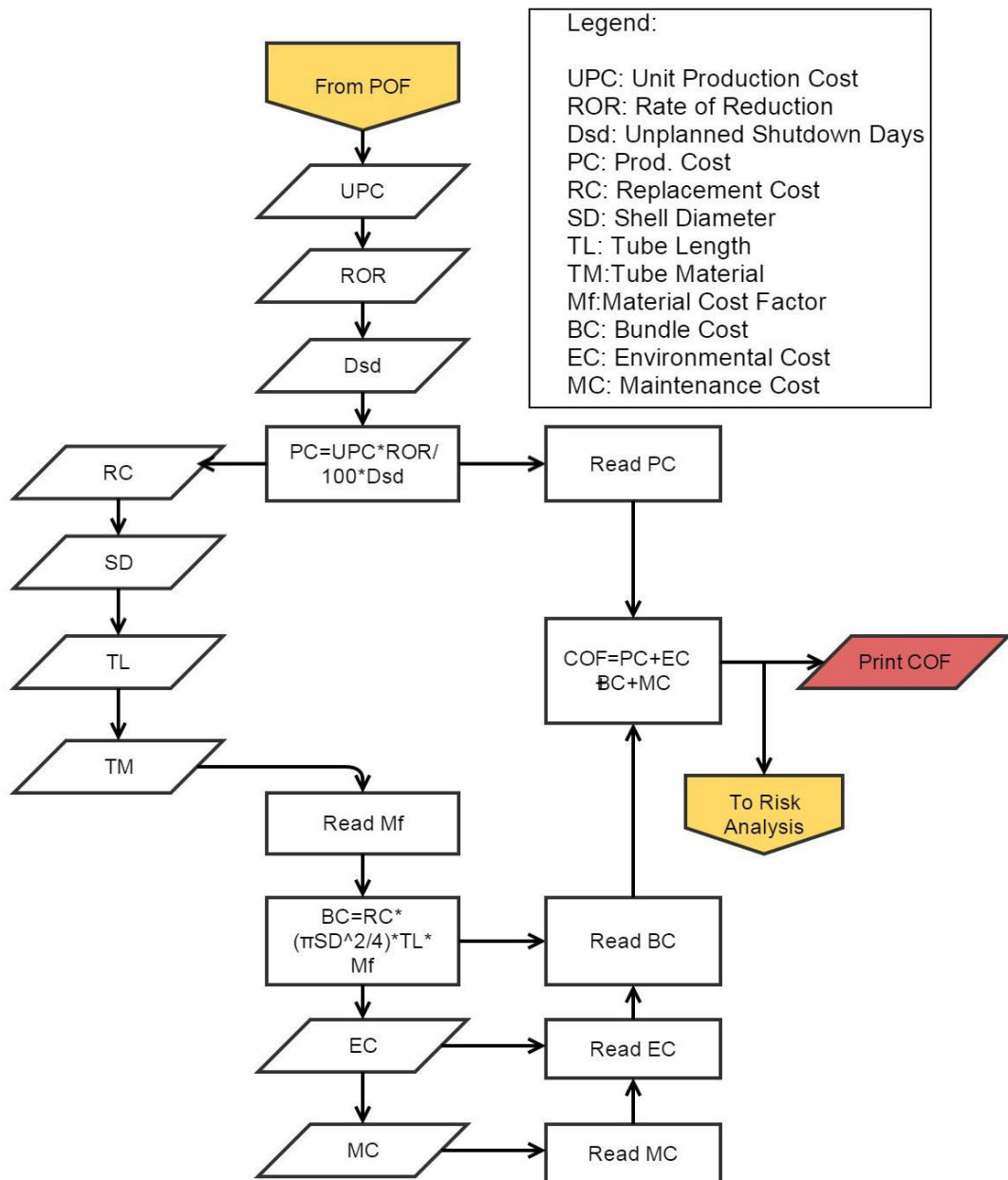
Figure 3.5: Algorithm Diagram for the Consequence of Failure
Calculation.

Figure 3.5 displays the algorithm diagram for the calculation of Consequence of Failure (COF). Generally, there will be four main values required for the calculation of COF as illustrated in the last process box just before the "To Risk Analysis" connector and the "Print COF" output. These four values are the Production Cost, Environmental Cost, Bundle Cost and the Maintenance Cost. These values are determined by several numbers of inputs by the user.

The process of COF calculation starts with the input of Unit Production Cost, Rate of Reduction, ROR of production bypassed due to the bundle failure and the Unplanned Shutdown Days to repair the exchanger in the case of bundle failure. Then, the Production Cost due to the failure will be calculated by using the formula shown in the algorithm diagram based on the inputs stated earlier.

The next step is to calculate the second type of cost which is the Bundle Cost due to the failure. Four specifications of the bundle are taken into account while calculating the Bundle Cost value. These are the Replacement Cost, Shell Diameter, the Tube Length and the Tube Material. All these values will be entered by the user. The system will read the Tube Material Cost Factor, M_f based on the tube material entered by the user. Based on these values, the application will calculate the Bundle Cost associated with the bundle failure.

The third and the fourth costs which are the Environmental Cost and the Maintenance Cost will be directly entered by the user. API RBI assumes the environmental cost for the cooling water service is $100,000. Finally, the COF will be calculated based on the four costs associated with the bundle failure.

3.8 The Algorithm for the Risk Analysis.

Figure 3.6 shows the algorithm diagram to analyze the risk based on both the POF and the COF calculated in the earlier sections. No formula is required to obtain and analyze the risk. The algorithm can be divided into two parts: the POF part and the COF part. Both parts have their own sets of range to locate the category for POF and COF. These sets of range are defined based on the API 581. Nested IF function as shown in Table 3.1 can be used to gives the output for the category.

Table 3.1: Nested IF Functions.

No.	Section / Part	Written Nested IF Excel Functions
1	POF	=IF(G26="","",IF(G26<0.1,1,IF(G26<0.2,2,IF(G26<0.3,3,IF(G26<0.5,4,IF(G26<1,5,IF(G26=1,5,"")))))))
2	COF	=IF(N17="","",IF(N17<10000,"A",IF(N17<50000,"B",IF(N17<150000,"C",IF(N17<1000000,"D",IF(N17>1000000,"E","")))))))

*Note: Cell G26 contains the POF while Cell N17 contains the COF in this case.
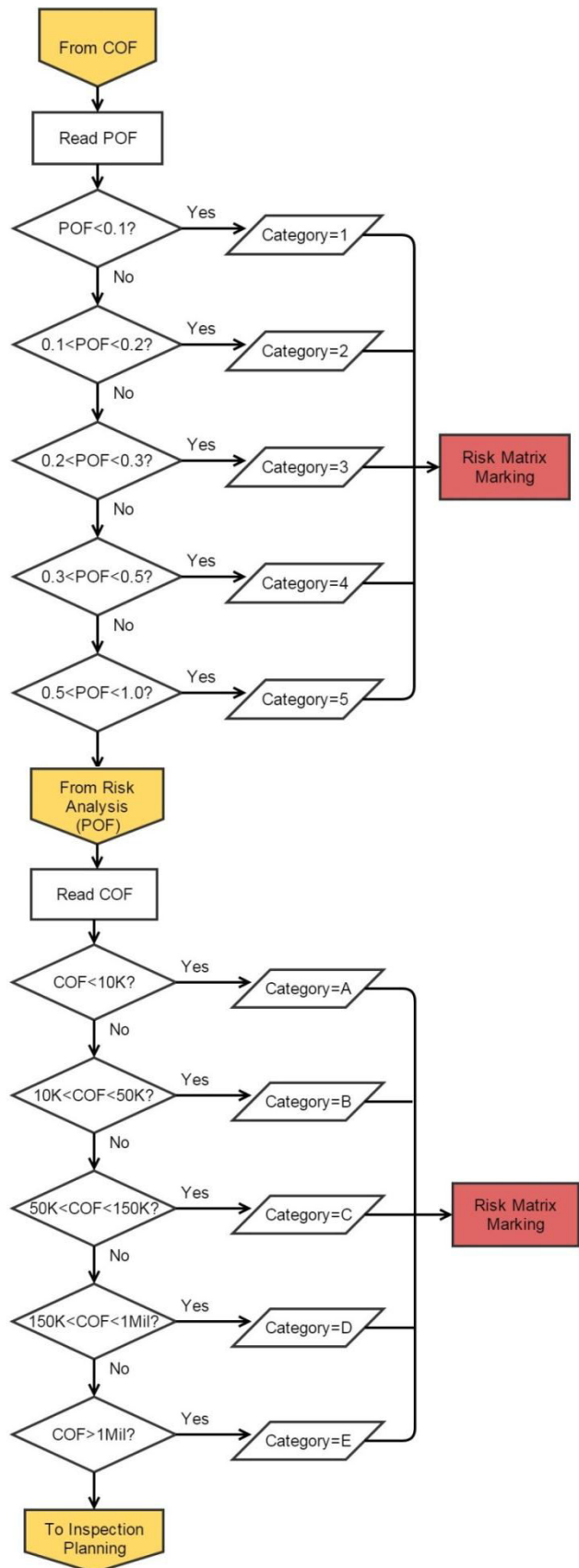
Figure 3.6: Algorithm Diagram for the Risk Assessment.

3.9 The Algorithm for the Inspection Planning.
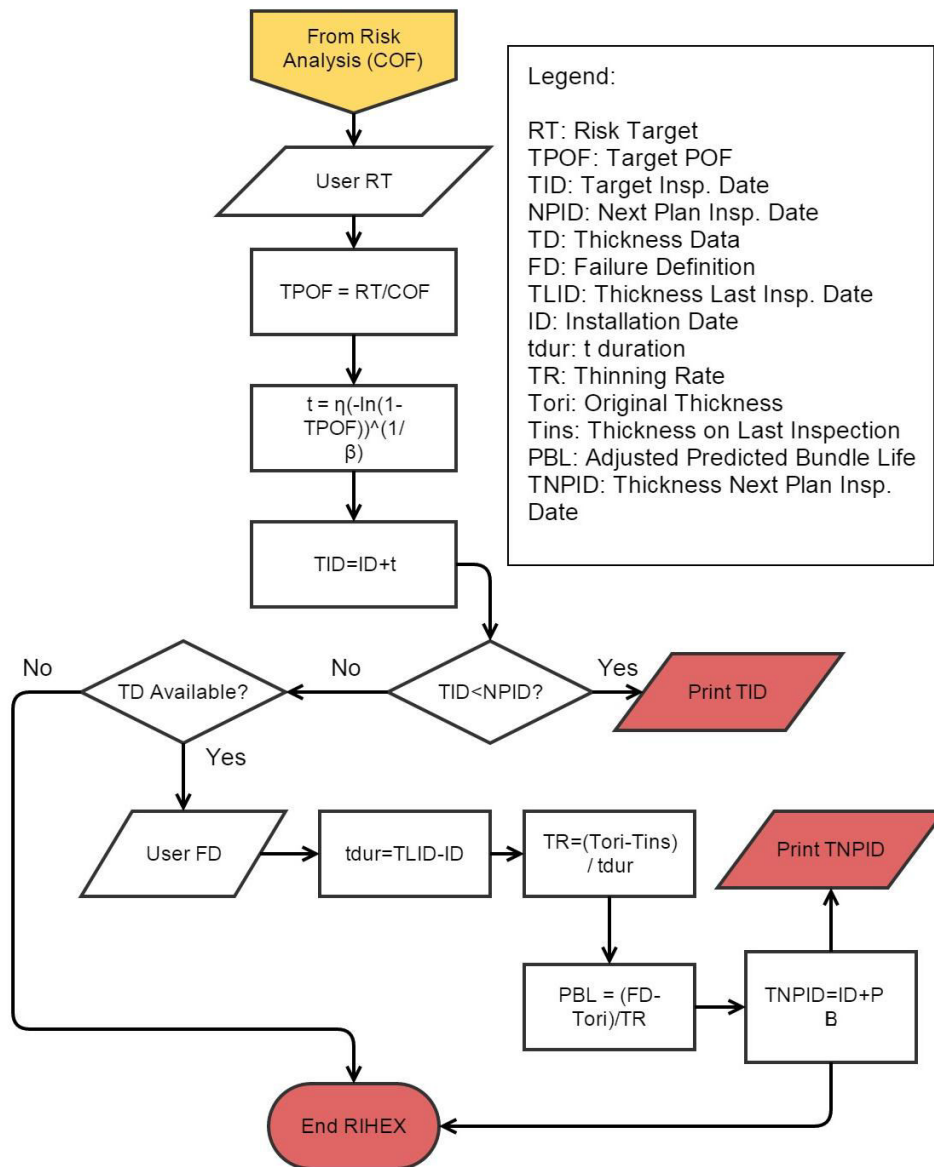
Figure 3.7: Algorithm Diagram for the Inspection Planning.

The last part of calculation for the RIHEX application is the Inspection Planning. This is the result part of the RIHEX application where it displays when the next inspection should takes place. Two main outputs will be displayed here: The Target Inspection Date which is based on the Risk Target by the User and the Next Inspection Date based on the thinning rate of the bundles.

     The algorithm starts with user input of Risk Target. Risk Target should be in the unit of $. Once the system reads the user's Rist Target, it will then calculate the

TPOF which stands for Target Probability of Failure or the maximum acceptable POF for any bundle. TPOF is calculated by using the Equation 2.11. Once the TPOF is obtained, the time to reach the desired Target Risk will be calculated based on the formula shown in the algorithm diagram (4th process box).

The Target Inspection Date based on the Risk Target by the user can be calculated by adding the time to reach the TPOF to the exchanger installation date. The Target Inspection Date will then be compared to the Next Planned Inspection Date. If the Target Inspection Date falls before the Next Planned Inspection Date, RIHEX will return an output "To Perform Inspection on Calculated Target Inspection Date". Otherwise, the next inspection can be done on the planned inspection date.

Next, the user has to confirm the availability of thickness data of the tube bundles. This data is recorded during corrosion inspection of the bundle. If the thickness data is available, the user is required to enter the FD or the user Failure Definition. It is denoted with RWT_f in API 581 which stands for the Remaining Wall Thickness for failure to occur. Then the duration time between the installation date and the thickness inspection date will be calculated. The next step is to calculate the thinning rate of the bundles by using the formula mentioned in the algorithm diagram. Then the PBL or the Predicted Bundle Life adjusted for inspection can be calculated before the next inspection date based on the thinning rate is calculated. This marks the end of RIHEX application.

CHAPTER 4

RESULT & DISCUSSION

4.1 Chapter Introduction

This chapter will discuss the result of the modeled application of RIHEX. First section will discuss the resulting Excel worksheet for the Rank Regression process to estimates the parameters, worksheet for the Probability of Failure (POF) and Consequence of Failure (COF) and lastly the Risk Analysis together with the Inspection Planning. The next section will explain the developed RIHEX application including the coding developed in the VBA and the process flow of the input data to the Excel template. Then, the result of validation process of RIHEX will be discussed in the following section. Lastly, there will be discussion on the limitation of this project.

4.2 The Excel Worksheets Developed

There are several Excel worksheets used in this project to perform most of the calculations based on the algorithms as described in Chapter 3. Most of the calculations are required in estimating the Weibull parameters through the Rank Regression method. As described earlier in Chapter 2, the rank regression and median rank methods requires several steps to be followed. These include media ranking, inverse ranking, adjusting the previous rank etc. These all tasks have to be performed by the Excel worksheets.

Figure 4.1 shows the worksheet named "Probability Analysis" where the process of calculation involved in carrying out the rank regression takes place for the Rank Regression section. There are several columns used for the calculation in estimating the parameters such as Prev. Adjusted Rank, Adjusted Rank, Media Rank, calculation for the ln (ln(1/1-MR)) which is the Y-value for probability plotting and ln TTF as the X-value. Note that the data shown in the worksheet is used for the explanation purpose only. Table 4.1 shows the Excel functions written for each of the columns displayed in Figure 4.1. Please refer to number of row and column alphabet contained in the functions to locate the cell in Figure 4.1.

Probability of Failure Using Weibull Analysis

Data No.	Inverse Data No	Enter In-Service Duration (TTF)	Status	Sorting data	Status	Rank	Inverse Rank	Plot/No plot	Previous Adjusted Rank	Adjusted Rank	Median Rank (MR)	ln(ln(1/(1-MR))) (Y Value)	ln (TTF) (X Value)	XiYi	Xi^2
1	9	18	Failure	8	Failure	1	9	Plot	0	1	0.074468085	-2.558940818	2.079441542	-5.32117	4.324077
2	8	22	Failure	10	Failure	2	8	Plot	1	2	0.180851064	-1.611994375	2.302585093	-3.71175	5.301898
3	7	16	Censored	12	Censored	3	7	No Plot	2	2					
4	6	10	Failure	13	Censored	4	6	No Plot	2	2					
5	5	12	Censored	14	Failure	5	5	Plot	2	3.333333	0.322695035	-0.942548359	2.63905733	-2.48744	6.964624
6	4	13	Censored	16	Censored	6	4	No Plot	3.333333	3.333333					
7	3	14	Failure	18	Failure	7	3	Plot	3.333333	5	0.5	-0.366512921	2.890371758	-1.05936	8.354249
8	2	25	Censored	22	Failure	8	2	Plot	5	6.666667	0.677304965	0.123144251	3.091042453	0.380644	9.554543
9	1	8	Failure	25	Censored	9	1	No Plot	6.666667	6.666667					
									6.666667						
									0						
									0						

Sheet tabs: Probability Analysis | Input & Output | TTF From VBA | Database Entry | History Tab | Result

Figure 4.1: The Excel Template Used for Calculation in Rank Regression.

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Table 4.1: Excel Functions Used in Rank Regression.

No.	Column Name	Written Excel Function
1	Data No	=IF(D9="","",1), D10 onwards: =IF(D10="","",B9+1)
2	Invers Data No	=IF(B9="","",RANK(B9,B9:B43,0))
3	In Service Duration	(Input from VBA Userform)
4	Status	(Input from VBA Userform)
5	Sorting Data	=IF(B9="","",LARGE($D$9:$D$43,C9))
6	Rank	=IF(D9="","",RANK(F9,$F$9:$F$100,1))
7	Inverse Rank	=IF(D9="","",RANK(F9,$F$9:$F$100,0))
8	Plot/No Plot	=IF(D9="","",IF(G9="failure","Plot","No Plot"))
9	Prev. Adjud Rank	For K9, =0, K10 onwards: =L9
10	Adjusted Rank	=IF(D9="","",IF(J9="plot",((I9*K9)+($V$7+1))/(I9+1),K9))
11	Median Rank	=IF(OR(D9="",J9="no plot"),"",((L9-0.3)/($V$7+0.4)))
12	ln(ln(1/(1-MR))), Y	=IF(OR(D9="",J9="no plot"),"",LN(LN(1/(1-M9))))
13	ln (TTF) (X Value)	=IF(OR(D9="",J9="no plot"),"",LN(F9))
14	XiYi	=IF(OR(D9="",J9="no plot"),"",(N9*O9))
15	Xi^2	=IF(OR(D9="",J9="no plot"),"",((O9)^2))

From Table 4.1, it is noticed that all of the functions will start with (="","") for a given IF function. This is added to ensure the cell is empty for easy viewing and to avoid "#ref" error if the dependent cell is missing in value or set to be empty.

Figure 4.2 shows the continuation part of Figure 4.1 which is the right side of Figure 4.1. It illustrates the calculation for the pve%, Mean Time to Failure (MTTF), Weibull shape parameter, β and the Weibull characteristic life, η. Table 4.2 shows the Excel functions written to calculate the required values as shown in Figure 4.2.

From Figure 4.2, the table on right side is used to calculate the pve%. It is not involved in the process of estimating the Weibull parameters. Pve% is required per API 581 as a goodness of fit test as an indicator whether or not the TTF data well fitted with the Weibull distribution.

Figure 4.2: Excel Template for Weibull Parameters Calculation.

Table 4.2: Excel Functions Used in Rank Regression.

No.	Row Name	Written Excel Function
1	Total Number of Available Data	=COUNT(D9:D643)
2	Sum of Y-Value	=SUM(N9:N135)
3	Sum of X-Value	=SUM(O9:O127)
4	Sum of XiYi	=SUM(P9:P125)
5	a cap	=IF(D10="","",(V8/U26)-(V14*(V9/U26)))
6	Xb (as mean of X)	=V9/U26
7	Yb (as mean of Y)	=V8/U26
8	pve%	=IF(D10="","",((X6^2)/Y6/Z6)*100)
9	MTTF	=IF(D10="","",V15*(EXP(GAMMALN(1+(1/V14)))))
10	No. of Plot Data	=COUNTIF(J9:J43,"plot")
11	(X-Xb)(Y-Yb)	=IF(OR(D9="",J9="no plot"),"",(O9-$T$19)*(N9-$T$20))
12	(X-Xb)^2	=IF(OR(D9="",J9="no plot"),"",(O9-$T$19)^2)
13	(Y-Yb)^2	=IF(OR(D9="",J9="no plot"),"",(N9-$T$20)^2)
14	Sum (X-Xb)(Y-Yb)	=SUM(X9:X51)
15	Sum (X-Xb)^2	=SUM(Y9:Y51)
16	Sum (Y-Yb)^2	=SUM(Z9:Z51)
17	Shape factor, β	=IF(D10="","",(V10-((V9*V8)/U26))/(V11-((V9^2)/U26)))
18	Characteristic Life, η	=IF(D10="","",EXP(-T17/V14))

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The calculation of the POF and the COF are performed in the same worksheet namely Input and Output worksheet. The worksheet is divided into two segments: POF segment and COF segment. The estimated values of Weibull parameters from previous worksheet will be send to this worksheet for the POF calculation while for the COF calculation will be based on the input by the user. Figure 4.3 shows the worksheet for the POF and the COF calculation and Table 4.3 shows the list of functions used in performing the calculations.
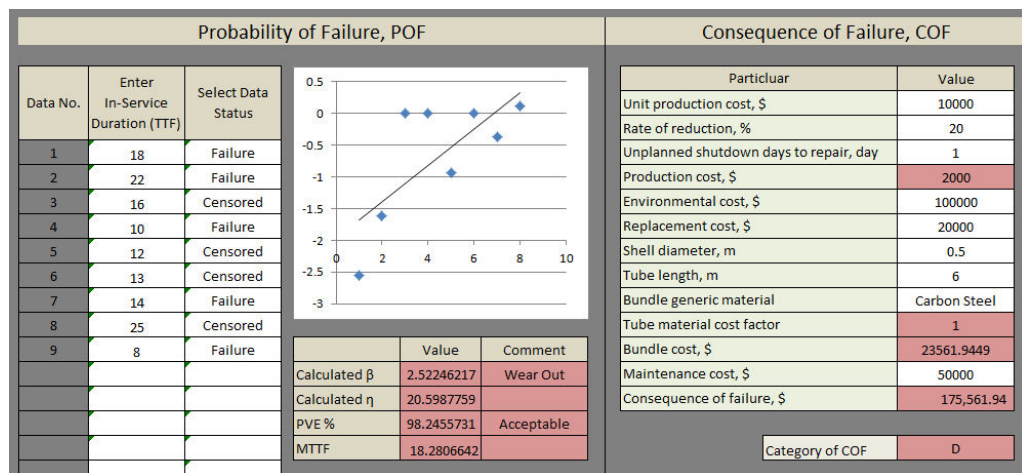
Figure 4.3: The worksheets used to calculate POF and COF.

Table 4.3: The Excel functions used to perform the calculations.

No.	Cell	Cell	Excel Function
1	G26	POF calculation on Plan Ins. Date (PID)	=IF(C8="","",WEIBULL.DIST(F200,G16, G17,TRUE))
2	F200	Duration time from Install Date to PID	=(YEAR(C200)- YEAR(C202))+((MONTH(C200)- MONTH(C202))/12)
3	C200	PID	(Input from User)
4	C202	Installation Date	(Input from User

From Table 4.3, Weibull function is used to calculate the POF of the next Planned Inspection Date (PID). G16 and G17 are the β and η respectively. The duration time from the installation date to the next plan inspection date can be calculated by using the function as shown in the second row of Table 4.3.

Figure 4.4 shows the COF calculation section of the worksheet attached with the column alphabets and the row numbers for easy viewing and Table 4.4 shows the corresponding Excel functions used for the calculation. The cells with the input from User are not shown in the table.

Figure 4.4: The COF calculations.

Table 4.4: The Excel functions used for the calculations.

No.	Cell	Cell	Excel Function
1	N8	Production Cost	=N5*(N6/100)*N7
2	N14	Material Cost Factor	=IF(N13="Carbon Steel",1,IF(N13="1-1/4 Cr",2,IF(N13="5 Cr",4,IF(N13="9 Cr",6,IF(N13="304/309/310 SS",8,IF(N13="304L/321/347 SS",10,IF(N13="316 SS",14,IF(N13="316L SS",14,IF(N13="317 SS",18,""))))))))))
3	N15	Bundle Cost	=N10*(PI()/4*(N11^2))*N12*N14
4	N17	Consequence of Failure	=N8+N9+N15+N16
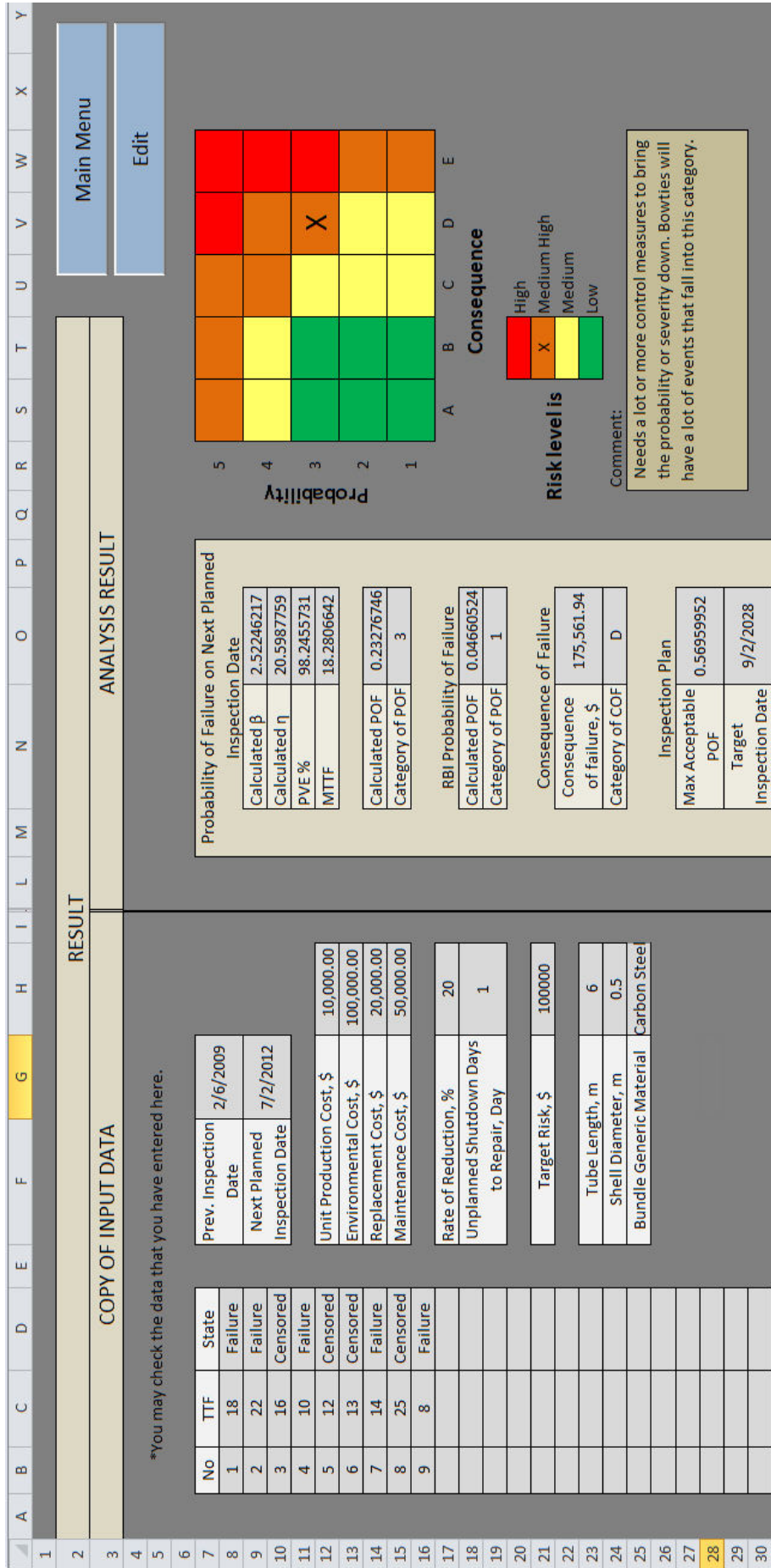
Figure 4.5: The result page.

Figure 4.5 shows the result worksheet consists of the risk analysis and the inspection plan calculation. For the risk analysis, an X mark will be automatically located in the risk matrix by using the Excel function based on the category of POF and COF calculated earlier. Then, there will be comment located below the risk matrix based on the location of the X in the risk matrix. For the inspection plan, there will be display for the target date based on the risk target entered by the User and the next planned inspection date based on the thinning rate. These values are obtained through calculations as described in Chapter 3 by using Excel functions.

4.3 The RIHEX Application

RIHEX consists of two parts which are the VBA part and the Excel template part. This section will discuss the use VBA as the Graphic User Interface (GUI) and the input platform for the User to enter the input data.
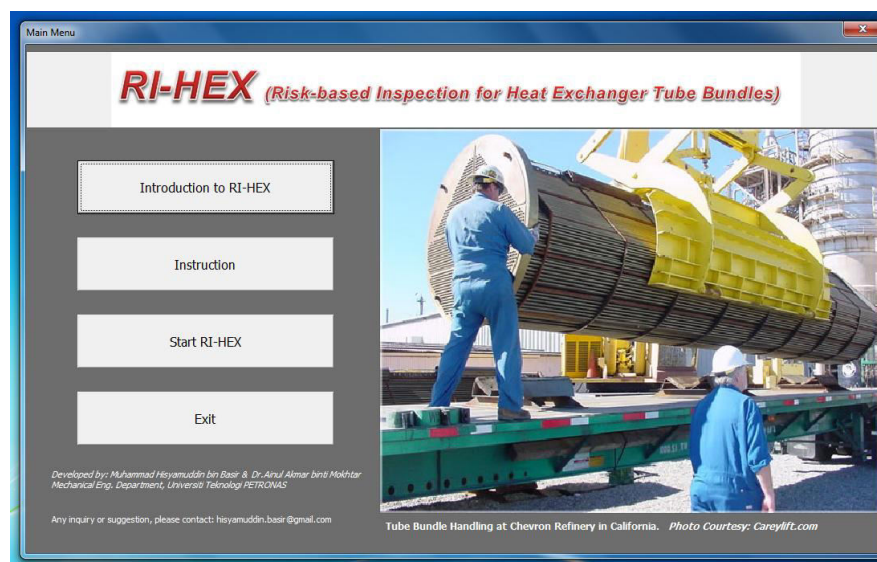
Figure 4.6: The Main Menu of RIHEX.

Figure 4.6 shows the Main Menu of RIHEX application. It consists of four command buttons which are Introduction of RIHEX, Instruction, Start RIHEX and Exit button. These all buttons has been assigned with programming code to direct the User to the specific page based on the button clicked by the User. For example, Introduction to RIHEX will direct the User to the introduction part of the application as shown in Figure 4.7.
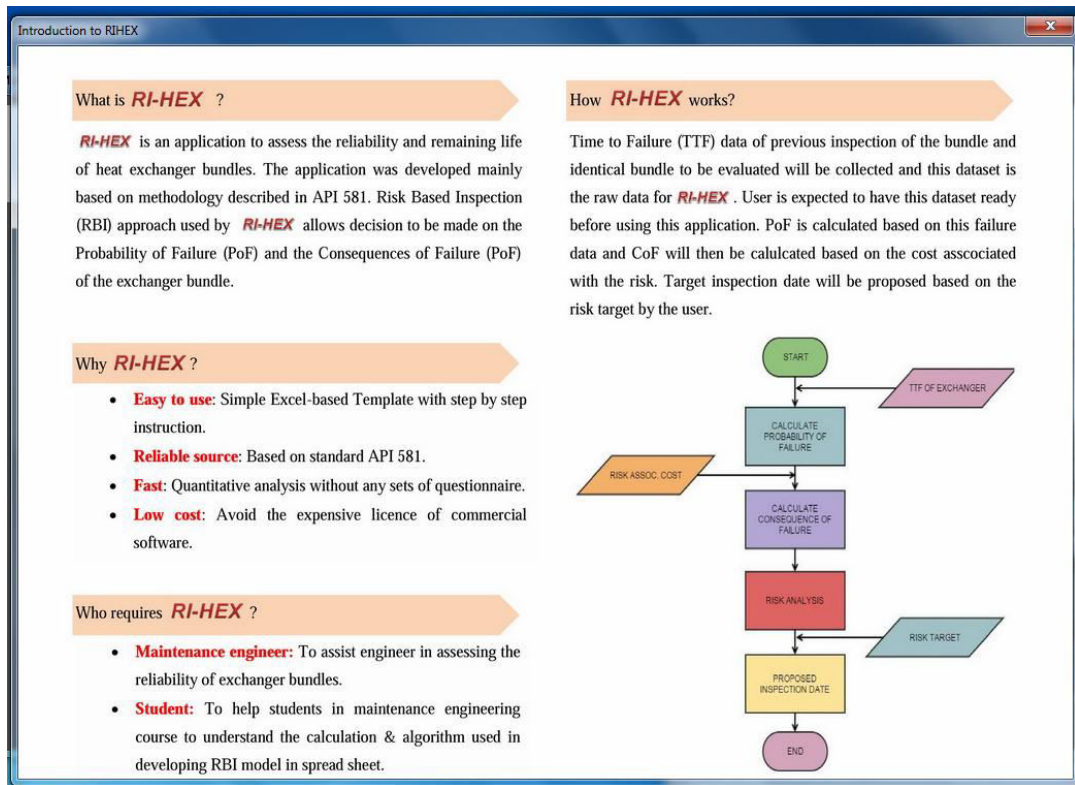
Figure 4.7: The introduction page of RIHEX.

To proceed with the analysis, User has to click on the Start RIHEX button and the analysis page will be displayed as shown in Figure 4.8. For the instruction on how to perform the analysis, User may click on the Instruction button on the Main Menu.

Figure 4.8: The input data for analysis.

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From Figure 4.8, there are several tabs in the analysis sections which include the Bundle Failure Library Data tab, Add Failure Data tab, Inspection Date tab, Inspection history tab etc. All these entries must be completed by the User to perform the analysis.

Throughout the project, there are two versions of RIHEX has been developed which are Version 1.0 and Version 2.0. Version 1.0 has been developed for the risk and inspection analysis only whereby Version 2.0 has been included with the Reliability Database functions. This additional feature enables the User to enter the reliability data from any inspections done on the bundles. Apart from that, filtering the TTF form the identical exchanger can be performed by using this feature.

To ensure the data is safely kept in the database, the worksheet has been protected by the password. Thus, the worksheet can be only entered by using RIHEX application and observed by the User. Figure 4.9 shows the code used in VBA to transfer the data to the worksheet named "Database".

Figure 4.9: The coding for entering the reliability data.

From Figure 4.9, there is a line of code written "ws.Unprotect XXXXX" on the top part of the VBA coding. This code is required to unprotect the protected worksheet in order to enter the reliability data. On the bottom part of the code, there will be a line of code to protect the worksheet back after the data has been entered.

For further information on the use of RIHEX application, one copy of the application has been attached on the back cover of this report.

4.4 RIHEX Validation

The developed application, RIHEX requires validation process to ensure that the methodology and the algorithms in the calculating the Weibull parameters used are correct. The validation process has been done with the use of Weibull++ software and the Analysis ToolPak by Microsoft Excel. The In-Service Duration or the TTF data used for the validation process is shown in Table 4.5.

Table 4.5: The TTF data used for the validation.

In-Service Duration (years)	Failure Reported
18	Yes
22	Yes
16	No
10	Yes
12	No
13	No
14	Yes
25	No
8	Yes

These data will be analyzed with all three applications, RIHEX, Weibull++ and the Analysis ToolPak. The values of η and β calculated by the three applications will be recorded and the percentage different among them will be analyzed. Figure 4.10, Figure 4.11 and Figure 4.12 shows the values of η and β obtained from RIHEX, Weibull++ and Analysis ToolPak respectively.

Probability of Failure on Next Planned Inspection Date	
Calculated β	2.52246217
Calculated η	20.5987759
PVE %	98.2455731
MTTF	18.2806642
Calculated POF	0.23276746
Category of POF	3

Figure 4.10: Parameters value from RIHEX.

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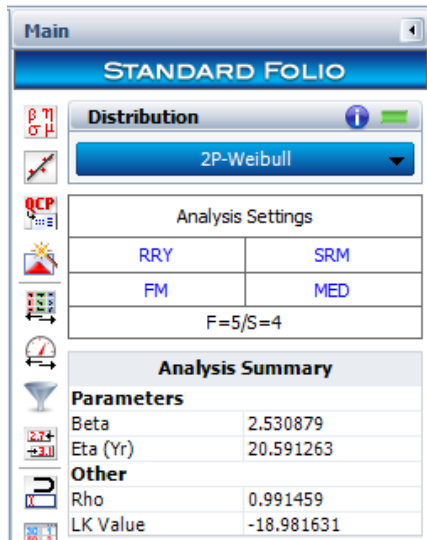
Figure 4.11: Parameters value from Weibull++.

Figure 4.12: Parameters value from Analysis ToolPak.

Figure 4.13 summarizes the values of parameters obtained from these three applications and the percentage difference between the values obtained from the analysis.

	RIHEX	Weibull++	ToolPak
β	2.522	2.531	2.522
η (years)	20.599	20.591	20.598

Percentage Difference %		
	RIHEX vs Weibull++	RIHEX vs ToolPak
β	0.356	0
η (years)	0.039	0.005

Figure 4.13: Percentage difference between the parameters.

From Figure 4.13, most of the percentage difference for the β and η for RIHEX vs. Weibull++ and RIHEX vs. ToolPak are noticeably low. Note that there is small percentage difference between RIHEX and Weibull++ for both β and η. This is due to the difference method used to estimates the parameters by both applications. Since the percentage difference recorded are insignificant, thus RIHEX is validated to be used to perform Life Data Analysis (LDA) and the inspection planning.

4.5 The Limitation of the Project

API RBI recommends the 90% Lower Bounds Confidence to be included in calculating the Time in Service or the time to the next failure for a given POF. This is to account for the statistical distribution in the data especially when the TTF is obtained from the reliability database (not the historical data of the exchanger to be evaluated). Figure 4.14 shows the example of the Weibull probability plot with 90% confidence bounds on time whereby the blue error indicates the Time in Service which falls on the 90% lower bound confidence of the raw data for a given fixed value of the unreliability or the POF.
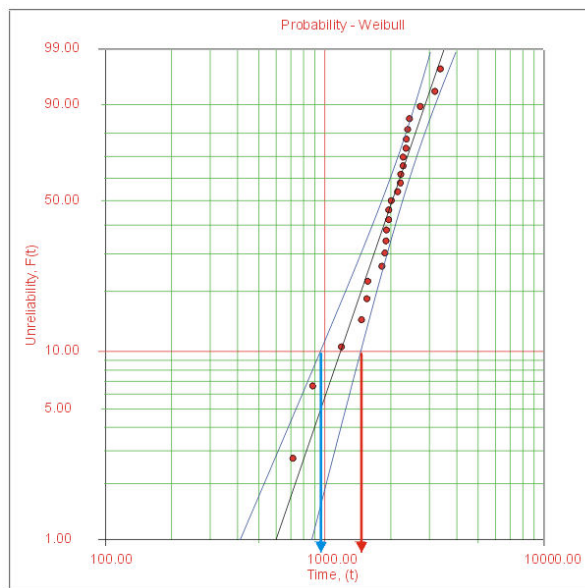
Figure 4.14: The Weibull probability plot.

In order to fulfill this recommendation, Fisher Matrix Bounds has been proposed by most of the literature including API 581 to solve for the 90% LBC on the Time in Service. The confidence bounds on time (Type 1) can be estimated by the following methods.

$$\ln R = -\left(\frac{T}{\eta}\right)^{\beta}$$

$$\ln(-\ln R) = \beta \ln\left(\frac{T}{\eta}\right)$$

$$\ln(-\ln R) = \beta(\ln T - \ln \eta)$$

$$u = \frac{1}{\beta}\ln(-\ln R) + \ln \eta$$

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Where   u = ln (T)

R = the reliability (1-POF)

T = Time in Service (90% LBC required)

The lower confidence bounds on u is estimated from Equation 4.1.

$$u_U = \hat{u} + K_\alpha \sqrt{Var(\hat{u})}$$ .... (4.1)

Where

$$Var(\hat{u}) = \frac{1}{\hat{\beta}^4}[\ln(-\ln R)]^2 Var(\hat{\beta}) + \frac{1}{\hat{\eta}^2} Var(\hat{\eta})$$
$$+ 2\left(-\frac{1}{\hat{\beta}^2}\right)\left(\frac{\ln(-\ln R)}{\hat{\eta}}\right) Cov\left(\hat{\beta},\hat{\eta}\right)$$ .... (4.2)

Thus, the lower confidence bounds on time can be found by Equation 4.3.

$$T_U = e^{u_U}$$ .... (4.3)

From Equation 4.2, the variance and covariance of the two parameters can be found from the Fisher Matrix Equation as shown by Equation 4.4.

$$F_0 = \begin{bmatrix} E_0\left[-\frac{\partial^2 \Lambda}{\partial \theta_1^2}\right]_0 & E_0\left[-\frac{\partial^2 \Lambda}{\partial \theta_1 \partial \theta_2}\right]_0 \\ E_0\left[-\frac{\partial^2 \Lambda}{\partial \theta_2 \partial \theta_1}\right]_0 & E_0\left[-\frac{\partial^2 \Lambda}{\partial \theta_2^2}\right]_0 \end{bmatrix}$$ .... (4.4)

The subscript 0 indicates that the quantity is evaluated at $\theta_1 = \theta_{1_0}$ and

$\theta_2 = \theta_{2_0}$, which is the true values of the parameters but for this case, it is η and β.

Thus, for a sample of N units where R units have failed, M have been suspended, and P have failed within a time interval then, N=R + M + P and with this equation a sample local information matrix can be obtained as shown by Equation 4.5.

$$F = \begin{bmatrix} -\frac{\partial^2 \Lambda}{\partial \theta_1^2} & -\frac{\partial^2 \Lambda}{\partial \theta_1 \partial \theta_2} \\ \\ -\frac{\partial^2 \Lambda}{\partial \theta_2 \partial \theta_1} & -\frac{\partial^2 \Lambda}{\partial \theta_2^2} \end{bmatrix}$$ …………..…..……… (4.5)

Equation 4.6 shows the log-likelihood function for censored data. It is obtained by using the Maximum Likelihood Estimates (MLE) for a two parameter distribution.

$$\ln[L] = \Lambda = \sum_{i=1}^{R} \ln[f(T_i; \theta_1, \theta_2)]$$
$$+ \sum_{j=1}^{M} \ln[1 - F(S_j; \theta_1, \theta_2)]$$
$$+ \sum_{l=1}^{P} \ln\left\{F(I_{l_U}; \theta_1, \theta_2) - F(I_{l_L}; \theta_1, \theta_2)\right\}$$ ………… (4.6)

In the Equation 4.6, the first summation is for the complete data, the second summation is for right censored data and the third summation is for interval or left censored data. Then, by inverting the matrix and substituting the values of estimated parameters of η and β into θ_1 and θ_2, the local estimate of the covariance matrix can be found as shown in Equation 4.7.

$$\begin{bmatrix} \widehat{Var}\left(\hat{\theta}_1\right) & \widehat{Cov}\left(\hat{\theta}_1, \hat{\theta}_2\right) \\ \\ \widehat{Cov}\left(\hat{\theta}_1, \hat{\theta}_2\right) & \widehat{Var}\left(\hat{\theta}_2\right) \end{bmatrix} = \begin{bmatrix} -\frac{\partial^2 \Lambda}{\partial \theta_1^2} & -\frac{\partial^2 \Lambda}{\partial \theta_1 \partial \theta_2} \\ \\ -\frac{\partial^2 \Lambda}{\partial \theta_2 \partial \theta_1} & -\frac{\partial^2 \Lambda}{\partial \theta_2^2} \end{bmatrix}^{-1}$$ …..... (4.7)

Since this project involved 2-parameters of Weibull distribution, the Fisher Information Matrix become more complex to be executed with the non-statistical software like Microsoft Excel.

Other simpler alternatives can be considered to perform confidence bound on time. Several alternatives have been described in several literature and reference books including Practical Reliability Engineering written by Patrick O' Conner under Section 3.6.3 Alternative Methods for Calculating Confidence Bounds. The text explains in detail on the alternatives for Fisher Matrix in obtaining the confidence bounds on time. One of the method is to include the confidence bounds on the

parameters instead of apply it on time. Most of the alternatives which based on this approach are based on formulation that depends on which analytical method is used to obtain the parameters bounds. These include Fisher Matrix, Monte Carlo or Bayesian Confidence Bounds. However these methods of parameters bound still requires statistical software package to be done.

There is simplified formula developed based on the Maximum Likelihood method in performing confidence bound on parameters. It is a two-tailed confidence bound of the β and η as shown by Equation 4.8 and Equation 4.9 respectively. The 90% LCB of parameters can be found by using these two equations. Then, The Time in Service can be calculated by using Equation 2.4 by putting in the values of the bounded η and β as well as the desired POF into the equation.

$$\hat{\beta}\exp\left(\frac{-0.78z_{\alpha/2}}{\sqrt{n}}\right) \le \beta \le \hat{\beta}\exp\left(\frac{0.78z_{\alpha/2}}{\sqrt{n}}\right)$$ ………........……. (4.8)

$$\hat{\eta}\exp\left(\frac{-1.05z_{\alpha/2}}{\hat{\beta}\sqrt{n}}\right) \le \eta \le \hat{\eta}\exp\left(\frac{1.05z_{\alpha/2}}{\hat{\beta}\sqrt{n}}\right)$$ .... (4.9)

Before deciding to implement this approach, justification is required whether or not this method can be implemented into the project thus providing the unambiguous result of Time in Service to the user. Justification can be done by comparing the resulting 90% LBC time with the nominal value of 90% value provided in the API 581.

The values of 90% LBC given in the API 581 as show in Table 4.6 has been verified first with the Weibull++ software to ensure there is no misprint or mistakes in the calculation. Once all the values are certified true, then the calculated value of 90% LBC by using Equation 2.4 is compared with the values shown in Table 4.6.

Table 4.6: 90%LBC on time. (Source: API 581)

Method	Time in Service (years)						
	POF=1%	2%	5%	10%	20%	50%	90%
Weibull, Raw Data	3.48	4.47	6.43	8.51	11.4	17.7	28.3
90% LBC	1.51	2.24	3.76	5.57	8.31	14.3	21.3

90% Confidence Bound for Parameters			
nom beta		lower	upper
2.568		1.449258	4.027371

nom eta		lower	upper
20.45		15.15149	25.89027

Given POF	Time in Service (By Equation)			API Value		Percentage Error %	
	90% LBC	Raw Data	90% UBC	90% LBC	Raw Data	90% LBC	Raw Data
0.01	0.633787	3.409779	8.261826	1.51	3.48	58.02733	2.017841
0.02	1.026063	4.475134	9.825804	2.24	4.47	54.19361	0.114862
0.05	1.951581	6.43251	12.3835	3.76	6.43	48.09625	0.039033
0.1	3.206971	8.513657	14.80698	5.57	8.51	42.42421	0.042977
0.2	5.382366	11.4032	17.83978	8.31	11.4	35.23025	0.028079
0.5	11.76586	17.73003	23.63814	14.3	17.7	17.72126	0.169658
0.9	26.93936	28.29717	31.84748	21.3	28.3	26.47585	0.009993

Figure 4.15: Percentage error of the 90% LBC.

Figure 4.15 shows the screenshot of the Excel worksheets where the calculation has been done. As shown in Figure 4.15 (the red box), there is considerably high percentage error between the value of 90% LBC from API RBI and the value calculated by using the parameters obtained by the Equation 4.8 and Equation 4.9. However, the raw data (nominal on Weibull probability plot) shows acceptable range of percentage error with the highest value of 2.018% for the given POF value of 0.01.

Due to this reason, this project disregard the recommendation by the API 581 to include the 90% LBC on the Time in Service leaving with only Raw Data is being used in the calculation. Further research might be done to formulate simple equations to estimate the confidence bounds on time like the ones that have been done for the parameters as shown in Equation 4.8 and Equation 4.9.

CHAPTER 5
CONCLUSION & RECOMMENDATIONS

As the conclusion, the project has been conducted successfully in order to accomplish the objectives stated in the Chapter 1. The first objective of the project is to develop a Risk-Based Inspection (RBI) model for heat exchanger tube bundles. This objective has been fulfilled through several tasks starting with the collection of data and theoretical formulae required to model an RBI for the heat exchanger. Then, the calculation starts with the constructing the algorithm diagrams to perform the calculation for the POF, COF, risk analysis and the inspection planning. The second objective to apply Microsoft Excel and VBA in developing RBI application in order to perform calculation, analyze information and visualize data for RBI model. This has been accomplished by starting with the developing the Excel functions to perform the calculations. All necessary values and standards required by the main reference which is the API 581 have been calculated in the worksheet to perform the analysis. These include the estimating the Weibull parameters through rank regression method in order to calculate the POF of the bundles. Then, Excel functions also have been utilized to calculate the COF of the tube bundle which gives the output of the category of POF and the COF. Then based on this, risk analysis is performed by using the risk matrix. The next inspection plans are performed based on the POF of the planned inspection date, risk target and the thickness data provided by the User.

For the recommendation, further research might be done to solve the complexity of the method required to produce the 90% LBC on the Time in Service. Currently, most of the literature recommends Fisher Matrix as the common method to be used in obtaining the 90%LBC. Other simplified formulae may be proposed in the future to gives a good estimation to the 90%LBC on the Time in Service.

REFERENCES

API RP 581. (2008). Risk-Based Inspection Technology. *API Recommended Practice 58.* 2nd Edition, September 2008.

Andreone, C. F., & Yokell, S. (1998). *Tubular Heat Exchanger Inspection, Maintenance, and Repair*: McGraw-Hill.

Bateman, M. (2006). *Tolley's Practical Risk Assessment Handbook*: Newnes.

Board, U. C. S. (2011). Goodyear Heat Exchanger Rupture.   Retrieved November 1, 2014, 2014, from http://www.csb.gov/goodyear-heat-exchanger-rupture/

Board, U. C. S. (2014). Tesoro Refinery Fatal Explosion and Fire.   Retrieved November 1, 2014, 2014, from http://www.csb.gov/tesoro-refinery-fatal-explosion-and-fire/

Bragatto, P. A., Ansaldi, S., Delle Site, C., & Agnello, P. (2015). *Collection and analysis of failure data for pressure equipment.* Paper presented at the Safety and Reliability: Methodology and Applications - Proceedings of the European Safety and Reliability Conference, ESREL 2014.

Cripps, H. R. (2006). Principles of heat exchangers.   Retrieved November 1, 2014, from http://www.vesma.com/tutorial/hr_principles.htm

Das, N. G., & S, S. *Process Dynamics and Control*: PHI Learning.

Krystek, M. (2015) Decision rules and risk analysis. *Vol. 625. Key Engineering Materials* (pp. 26-33).

Lytron. (2012). What is a heat exchanger?   Retrieved November 1, 2014, from http://www.lytron.com/Tools-and-Technical-Reference/Application-Notes/What-is-a-Heat-Exchanger

Reynolds, J. T. *Risk Based Inspection - Where Are We Today?*

Todinov, M. T. (2007). *Risk-Based Reliability Analysis and Generic Principles for Risk Reduction*: Elsevier Science.

Appendix A: Basic Data for Bundles Risk Analysis (Source: API RP 581)

Bundle Attribute	Comments/Example Input		Required Bundle Failure Library Data
General Data			
Corporation	Corporation		No
Plant	Plant Location		Yes
Unit	Process Unit		Yes
Tag Number	Bundle Tag Number, e.g. E101-T3, where E101 represents the exchanger ID or Tag number and T1, T2, T3, etc. represents the bundles that have been installed in the exchanger, T1 being the original bundle.		Yes
Description	Exchanger Description, eg. Debutanizer Reboiler, Crude O/H exchanger, may be found on the TEMA datasheet.		No
Status	Active or Inactive. Inactive bundles are past bundles that have been removed from service		No
Start Date	Exchanger Start Date (YYYY-MM-DD)		No
TEMA Type	AES AET AEU AHS AJS AKU	BEU BFU BJU BKU Brown Fintube Plate & Frame	Yes
Exchanger Type	Steam Generator HSRG/Waste Heat Boiler Steam Reboiler Liquid Steam Heater Process Liquid Water Cooler Liquid/Liquid Heat Exchanger	Vaporizer Vapor Condenser Vapor Cooler HT Feed/Effluent Exchanger Product Cooler Compressor Vapor Coolers	Yes
Exchanger Orientation	Horizontal or Vertical		Yes
Shell Diameter	Shell Diameter, mm [in]		No
Bundle Details			
Install Date	Bundle Installation Date (YYYY-MM-DD)		Yes
Tube Type	Plain, finned tube or twisted tube; default is Plain		No
Tube Quantity	Number of tubes, required for statistical analysis and for bundle cost estimate		Yes
Tube OD	Tube Outside Diameter, mm [in]		Yes
Tube Length	Tube Length, ft [m]		No
Number of Tubeside Passes			No
Tube Furnished Thickness	The average wall thickness, mm [in]		Yes
Tube Specification	SA-106-B SA-179 SA-213-TP304 SA-213-TP316 SA-213-TP316L	SA-213-T5 SA-213-T9 SA-213-T11 SA-214 Unknown	No

Appendix A: Basic Data for Bundles Risk Analysis (Source: API RP 581) (cont.)

Bundle Attribute	Comments/Example Input			Required Bundle Failure Library Data
Tube Material	Carbon Steel C-1/2 Mo 1Cr 1.25Cr 2.25Cr 5Cr 9Cr 12Cr 304L/321/347 304/309/310 316L 317L 2205 Duplex SS 2304 Duplex SS 2507 Duplex SS	Ferralium 255 Zeron 100 Alloy 20Cb3 904L AL6XN/254 SMO 430 SS 439 SS 444 SS Sea-Cure/E-Brite Admiralty Brass Aluminum Brass Red Brass 90/10 CuNi 70/30 CuNi Monel 400	Alloy 800 Alloy 825 Alloy 600 Alloy 625 Alloy C276 Nickel 200 Titanium Gr. 2 Titanium Gr. 12 Titanium Gr. 16 Aluminum Alloy Zirconium Alloy Bimetallic Ceramic Plastic Other	Yes
Tube Coating	None, ID, OD, or both ID and OD			No
U-Tube PWHT	Yes or No			No
Impingement Plate	Yes or No; may be found on the TEMA datasheet.			No
Tube Layout	Triangular Square	Rotated Square Unknown		No
Tube Pitch	Tube pitch, mm [in]			No
Baffle Type	Single Segmental Double Segmental Triple Segmental	Rod Baffle Unknown		No
Baffle Cut	Baffle Cut (%), may be found on the TEMA datasheet.			No
Baffle Spacing	Spacing between baffles, mm [in] , may be found on the TEMA datasheet.			No
Tube Joint Design	Rolled Only Seal Welded	Strength Welded Unknown		Yes
Tubesheet Material Specification	SA-105-II SA-182-F5 SA-182-F9 SA-182-F11	SA-182-F316 SA-212-B-FBX SA-240-TP304 SA-240-316L SA-240-TP321	SA-266-II SA-515-70 SA-516-70 Other Unknown	No
Tubesheet Material	Carbon Steel C-1/2 Mo 1Cr 1.25Cr 2.25Cr 5Cr 9Cr 12Cr 304L/321/347 304/309/310 316L 317L 2205 Duplex SS	Alloy 20Cb3 904L AL6XN 430 SS 439 SS Admiralty Brass Aluminum Brass Red Brass 90/10 CuNi 70/30 CuNi Copper-other Monel 400 Alloy 800	Alloy 825 Alloy 600 Alloy 625 Alloy C276 Nickel 200 Titanium Gr. 2 Aluminum Alloy Zirconium Alloy Ceramic Plastic Other Unknown	No

Appendix A: Basic Data for Bundles Risk Analysis (Source: API RP 581) (cont.)

Bundle Attribute	Comments/Example Input			Required Bundle Failure Library Data
Tubesheet Cladding Material	Carbon Steel C-1/2 Mo 1Cr 1.25Cr 2.25Cr 5Cr 9Cr 12Cr 304L/321/347 304/309/310 316L 317L 2205 Duplex SS 2304 Duplex SS	2507 Duplex SS Alloy 20Cb3 904L AL6XN 430 SS 439 SS Sea-Cure/E-Brite Admiralty Brass Aluminum Brass Red Brass 90/10 CuNi 70/30 CuNi Copper-other Monel 400	Alloy 800 Alloy 825 Alloy 600 Alloy 625 Alloy C276 Nickel 200 Titanium Gr. 2 Titanium Gr. 12 Titanium Gr. 16 Aluminum Alloy Zirconium Alloy Non-metallic Coating Plastic Other Unknown	No
Process/Operating Conditions (Tubeside and Shellside)				
Process Unit	Amine Regeneration Amine Treating Aromatics Recovery Catalytic Reforming (CCR) Catalytic Reforming (Fixed) Caustic Treating (Merox) Crude Distillation Unit Cumene Delayed Coker Distillate Fractionator Fluid Coker Dimersol Ether Plant (MTBE/TAME) Fluid Catalytic Cracking Sat Gas Plant Unsat Gas Plant Gas Separation HF Alkylation Hydrotreater/Hydrocracker	Hydrocracker (2nd Stage) Hydrogen Reforming Isomerization LPG Refrigeration Lube Plant Polymerization Partial Oxidation Selective Hydrogenation Sour Water Stripper Sulfolane Sulfur Recovery Unit Sulfuric Acid Alkylation Sulfuric Acid Plant Tail Gas Treater Thermal Cracking Vacuum Unit Cooling Tower Water Cooling Water – other		Yes
Fluid Name	Generic Name, e.g. Crude, Effluent, HGO, etc.			No

Appendix A: Basic Data for Bundles Risk Analysis (Source: API RP 581) (cont.)

Bundle Attribute	Comments/Example Input		Required Bundle Failure Library Data
Fluid Category	Light Crude Feed Heavy Crude Feed Crude Tower O/H Hydrogen Fuel gas Ethylene Syngas LPG (C3/C4) Olefins Gasoline Ethers (MTBE/TAME) Alcohol Light Distillate Medium Distillate Heavy Distillate Atmospheric Resid. Lube oil (seal oil) Vacuum Residue Visbreaker Residue Sludge Rich Amine Lean Amine	Benfield or other acid gas treating Sour Water Tempered water/non-corrosive Steam/Condensate Caustic Solution Spent Caustic Acid Gas (Tail Gas) Sulfur Liquid H2S Hydrofluoric Acid Sulfuric Acid Phosphoric Acid Other Acid; Cooling Tower Water- corrosive Cooling Tower Water- non-corrosive River water Well water Brackish water Sea water Waste Water Inert Gas Air CO2	Yes
Operating Pressure	Operating Pressure, kPa [psig]		Yes
Inlet Temperature	Inlet Temperature, °C [°F]		Yes
Outlet Temperature	Outlet Temperature, °C [°F]		Yes
Fluid Phase	Gas, Liquid or Two-phase		Yes
Fouling Severity	Unknown None Mild	Moderate Severe Unknown	No
Flowrate	Fluid Flowrate, kg/hr [lb/s]		No
Design Velocity	Enter the fluid design velocity from the TEMA datasheet, optional entry, consider entering for CW, amine, slurries or any other fluids where velocity is an important parameter for corrosion or erosion.		No
Process Fluid Damage Modifiers (Tubeside and Shellside)			
Free Water	Does the tubeside or shellside fluid have any free water, Yes/No		Yes
Sulfidation	Is sulfidation a concern for the tubeside or shellside fluid, Yes/No		Yes
Dealloying	Is dealloying is a concern for the tubeside or shellside fluid, Yes/No		Yes
Naphthenic Acid	Is naphthenic acid corrosion a concern for the tubeside or shellside fluid, Yes/No		Yes
Ammonium Chloride	Is ammonium chloride a concern for the tubeside or shellside fluid, Yes/No		Yes
CO_2	Is CO_2 corrosion a concern for the tubeside or shellside fluid, Yes/No		Yes
Salt Deposits	Are salt deposits likely on the tubeside or shellside, Yes/No		Yes
Weight % H_2S	If H_2S is present in tubeside or shellside fluid, provide amount, (wt.%).		Yes
Mole % Sulfur	If Sulfur is present in tubeside or shellside fluid, provide amount, (mole %).		Yes
Weight % Acid	If Acid is present in tubeside or shellside fluid, provide amount, (wt.%).		Yes
Weight % Caustic	If Caustic is present in tubeside or shellside fluid, provide amount, (wt.%).		Yes
Weight % Ammonium Bisulfide	If Ammonium Bisulfide is present in tubeside or shellside fluid, provide amount, (mole %)		Yes
Cyanides	Are cyanides present in tubeside or shellside fluid, Yes/No		Yes

Appendix A: Basic Data for Bundles Risk Analysis (Source: API RP 581) (cont.)

Bundle Attribute	Comments/Example Input		Required Bundle Failure Library Data
Erosive Particles	Are erosive particles present in tubeside or shellside fluid, Yes/No		Yes
Brine	Does the tubeside or shellside fluid have any Brine, Yes/No		Yes
Asphaltenes or Polymer Deposits	Does the tubeside or shellside fluid have any Asphaltenes or Polymer Deposits, Yes/No		Yes
Oxidation	Is oxidation a concern for the tubeside or shellside fluid, Yes/No		Yes
Estimated Corrosion Severity	None Inert (<1 mpy) Mildly Corrosive (11 to 5 mpy) Moderately Corrosive (5 mpy to 10 mpy) Severely Corrosive (10 mpy to 20 mpy) Unpredictable or Localized (>20 mpy)		Yes
Bundle Inspection History (Multiple Records for Each Bundle)			
Inspection Date	Date inspection was performed (YYYY-MM-DD).		No
Event Type	Planned S/D Unplanned S/D Bypass - No Rate Cut	Rate Cut Online Unknown	No
Bundle Leak	Was there a bundle leak discovered during the inspection? Enter Yes, No or Unknown. (Default is Unknown)		No
Failure Mode	None Unknown Tube Leak Floating Head Leak General Thinning Underdeposit Corrosion Tube End Thinning	Localized Pitting Tube Joint Leak Environmental Cracking Flow-Induced Damage Handling Damage	No
Action Taken	None Clean Only Minor Repairs Rerolled Plugged Tubes Rotated Bundle 180° Partial Retube	Retube – Same Alloy Retube – New Alloy Replacement-in-Kind Redesign – New Alloy Redesign – Mechanical Rerate	No
Number of Tubes Plugged during this SD	Number of tubes plugged during inspection. Do not include any tubes plugged as a result of handling damage, these should be documented in the Comments area		No
Inspection Method	Visual Only IRIS Remote Field Eddy Current	Elliot Gage/Caliper MFL Other	No
Percent Inspected	None Unknown <10% 10-20% 20-40%	40-60% 60-80% 80-100%	No
Inspection Effectiveness	A, B, C, D or E per Table 8.5		No
% Wall Loss	Average measured wall thickness divided by the original furnished wall thickness		No
Remaining Wall Thickness	Average measured wall thickness from inspection, mm [in]		No
Hydrotest	Yes/No		No

Appendix A: Basic Data for Bundles Risk Analysis (Source: API RP 581) (cont.)

Bundle Attribute	Comments/Example Input		Required Bundle Failure Library Data
Primary Damage	None Unknown General Thinning Underdeposit Corrosion Tube End Thinning Localized Pitting	Environmental Cracking Flow-Induced Vibration Erosion Mechanical Damage Handling Damage	No
Secondary Damage	None Unknown General Thinning Underdeposit Corrosion Tube End Thinning Localized Pitting	Environmental Cracking Flow-Induced Vibration Erosion Mechanical Damage Handling Damage	No
Tube Joint Leak on Hydrotest	Yes/No		No
Estimated Remaining Life	Based on the inspection data, provide the estimated remaining life (years). Required, if Remaining Wall Thickness or the % Wall Loss is not provided.		No
Baffles, Tie-rods and Spacers	Good Serviceable Mechanical Damage Heavy Corrosion	Poor Unknown	No
ID/OD Fouling	Unknown None Mild	General Heavy	No
ID/OD Corrosion	Unknown None Mild	General Heavy	No
Bundle Remaining Life Assessment			
Specified MTTF	User specified Mean Time to Failure for bundle (years). If supplied, will govern the calculations.		No
Specified Weibull η	User specified Weibull characteristic life (years). If supplied along with the β value, will govern the calculations.		No
Specified Weibull β	User specified Weibull slope parameter. If supplied along with the η value, will govern the calculations.		No
Bundle Life	Provide the bundle life for the bundle being evaluated (years). Required if the bundle is inactive. Optional for active bundles.		Yes
Controlling Damage Mechanism	Corrosion Pitting Environmental Cracking Erosion Tube to Tubesheet Failures	Mechanical Vibration Underdeposit Corrosion Severe Plugging/Fouling Unknown	Yes
Consequences of Bundle Failure			
Financial Risk Target	User risk target ($/year).		No
Tube Wall Failure Fraction	Define the fraction of wall thickness that constitutes bundle failure (number between 0.0 and 1.0).		No
Production Cost	Unit production costs ($/day). This is equal to the production rate (bbls/day) times the margin ($/bbl).		No
Production Impact	None Bypass	Bypass with Rate Reduction Shutdown	No
Rate Reduction	Rate Reduction (%). Required if Production Impact set to "Bypass with Rate Reduction".		No
Planned Shutdown Days	Number of days required to repair or replace failed exchanger bundle when the shutdown is planned (days).		No

Appendix A: Basic Data for Bundles Risk Analysis (Source: API RP 581) (cont.)

Bundle Attribute	Comments/Example Input	Required Bundle Failure Library Data
Unplanned Shutdown Days	Number of days required to repair or replace failed exchanger bundle when the shutdown is unplanned (days). This should typically be a longer duration than a planned shutdown to allow for lead time to mobilize or to purchase a replacement bundle	No
Environmental Impact	Environmental costs associated with bundle failure. Includes damage to cooling water system and towers	No
Lost Opportunity Cost	Additional cost beyond production losses or environmental costs as a result of bundle failure ($)	No
Bundle Cost	Cost of replacement bundle ($)	No
Bundle Installation Cost	Cost of maintenance required to remove, clean, and re-install exchanger bundle ($)	No
Hurdle Cost	This is the dollar amount above the economic break even point at which a decision to inspect or replace a bundle is made ($).	No
Turnaround Date 1	The date for the next scheduled turnaround from the RBI date (YYYY-MM-DD). Used in the risk analysis as the plan date for calculating risk.	No
Turnaround Date 2	The date for the second scheduled turnaround from the RBI date (YYYY-MM-DD). Used in the cost benefit analysis to make inspection or replacement decisions.	No