UNIVERSITI TEKNOLOGI PETRONAS

Prioritizing the Maintenance of Pipeline Based on Risk Analysis

By

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A THESIS

SUBMITTED TO THE POSTGRADUATE STUDIES PROGRAMME

AS A REQUIREMENT FOR THE

DEGREE OF MASTER OF SCIENCE IN CIVIL ENGINEERING

CIVIL ENGINEERING PROGRAMME

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ACKNOWLEDGEMENTS

This thesis would not have been possible without the blessing from God and a large number of people who give help, advice and support. First I would like to express my gratitude to my supervisor AP Dr Nasir Shafiq and my co supervisor Dr Muhammad Asif Shadiq for the guidance and support during my study. I express my gratitude also to Dr Mohd Faris bin Khamidi for the guidance, support and technical advice during my studies.

I would also like to thank to AP Dr Che Mokhtar Bin Che Ismail for the support and advice regarding my research. Special thanks to Mr Imam Djauhari for reading and correcting the manuscript. I would also like to thank the pipeline engineers of West Malaysia and East Kalimantan who became the respondents for this research, without their participation and contributions this research would not have been possible.

Furthermore I would like to thank my husband for the love, support that always strengthens my spirit. To Rafa my son who brings happiness and encourages me be a better person. My parents and my brothers and sisters who always give help, pray and spirit to through this life. My parents in law whose give spirit and support during my study.

I also would like to thanks to all the civil engineering lecturers, all postgraduate officers and all my friends especially Mr. Chris, Mrs. Ervina, Mrs. Friska, Mr. Oj, Mrs. Tiul, Mr. Lava and all my housemate who became my adviser, great friends and also thank you to my colleagues at Institute Technology Sepuluh Nopember Surabaya for the motivation and all those who supporting me during my study at Universiti Teknologi Petronas.

Finally, I would like to acknowledge the scholarship granted by Universiti Teknologi PETRONAS.

ABSTRACT

There have been a number of incidences reported for pipeline failures at both onshore and offshore facilities. In order to minimize the failure causes, it is required to clearly understand the failure mechanism, probability and consequences of failure and also the methodology for data to be analyzed. This thesis was based on an Analytical Hierarchy Process (AHP) to determine the risk factors of pipeline failure. AHP provide a multiple criteria scoring results based on expert judgment for prioritizing the maintenance of the pipeline. To perform the AHP approach, two pipeline systems have been chosen for case studies was located in Kertih, Malaysia and Kutai Basin, Indonesia.

Analysis of the AHP process showed that the gas pipeline in Kertih involves greatest risk failure covers probabiliy and consequences. The highest probability is internal corrosion of 41.7% and the rest is caused by internal erosion of 19.1%, external impacts of 13.8 %, external corrosion of 10.7%, free span of 8.1%, and on bottom stability of 6.7%. The greatest consequences of pipeline failure would impact on the environment of 59.4%, and the others will be the impact on economic of 24.9% and safety of 15%. On the other hand the highest probability for oil pipeline at Kutai Basin is caused by system operation of 34.7% and the other factors are design index of 23.7%, maintenance of 23.7%, and third party index of 18%. The greatest consequences will be on business of 60%, the second impact is environment of 20% and the last impact is on population of 20%.

Based on these two pipelines systems then the moderation for probability and consequence of failure have been determined. The result of analysis shows in general the factor of probability and consequence of failure are similar in various pipeline areas. By clearly knowing and understanding the probability and consequences of pipeline failure, then the risk level and category can be determined. From this analysis the pipelines can be ranked according to risk will assists the prioritization of pipelines maintenance. The inspection and maintenance budgets would be more effectively plan by setting priorities based on these pipelines risk. Those pipelines with higher risk should be given more urgent attention for maintenance action while those with lower risk rank may be put on a waiting list.

The AHP method has been compared to the existing method in formulating the pipeline maintenance, from the analysis the detail and complete result for AHP has been showed. AHP can exactly show the factors that may cause the pipeline failure based on the structure of hierarchy of risk pipeline failure and categorize the risk into risk category so that proper maintenance can be determined. Where as in the existing method the maintenance plans only based on inspection and comparison of each factor has not been made. This practice will result in improper maintenance which may incur unnecessary cost.

ABSTRAK

Ada beberapa insiden kegagalan pipeline yang tercatat di fasiliti pantai dan lepas pantai. Dalam langkah perancangan untuk meminimumkan punca kegagalan ini adalah penting dalam memahami mekanisme kegagalan, kemungkinan dan kesan-kesan kegagalan tersebut dan juga metodologi data untuk dianalisiskan. Tesis ini berdasarkan kaedah Analitic Hirarki Proses (AHP) untuk memastikan risiko faktor-faktor kegagalan pipeline. AHP menyediakan beberapa kriteria yang terbesar berdasarkan penilaian pakar dalam mengutamakan penyelenggaran pipeline. Untuk mengendalikan kaedah AHP, dua sistem pipeline telah dipilih sebagai kajian kes yang terletak di Kertih, Malaysia dan Kutai Basin, Indonesia.

Analisis daripada proses AHP menunjukkan pipeline gas di Kertih mempunyai risiko kegagalan terbesar yang berpunca daripada pengaratan dalaman pipeline tersebut dengan 41.7% kebarangkalian dan selebihnya disebabkan oleh hakisan dalaman 19.7%, kesan luaran 13.8%, pengaratan luaran 10.7%, bebas span 8.1% dan kestabilan bawah pipeline 6.7%. Kegagalan pipeline memberi kesan yang mendalam terhadap persekitaran dengan 59.4% dan kesan lain adalah terhadap ekonomi 24.9% dan keselamatan 15%. Sebaliknya risiko yang terbesar antara pipeline minyak di Kutai Basin disebabkan oleh sistem operasi dengan 34.7% kebarangkalian dan disokong oleh faktor-faktor lain iaitu design index dengan 23.7%, penyelenggaraan 23.7% dan third party index 18%. Kesan terbesar adalah perniagaan iaitu 60%, dan kesan kedua ialah pada persekitaran dengan 20% dan kesan terakhir ialah pada populasi sebanyak 20%.

Berdasarkan dua sistem pipeline maka pengubahsuaian bagi kebarangkalian dan kesan kegagalan telah dapat ditentukan. Hasil analysis menunjukan secara umum faktor kebarangkalian dan kesan kegagalan adalah sama di dalam pelbagai kawasan pipeline. Melalui pengetahuan dan pemahaman yang jelas mengenai kebarangkalian dan kesan kegagalan pipeline maka tahap dan kategori risiko dapat ditentukan. Daripada analisis ini pipeline boleh dikategorikan berdasarkan risiko dan ini membantu dalam pengutamaan penyelenggaraan pipeline. Pemeriksaan dan penyelenggaraan akan menjadi lebih mudah dirancang secara efektif dengan cara pemberian keutamaan berdasarkan risiko-risiko ini. Pipeline yang berisiko tinggi patut diberi perhatian dan yang berisiko rendah diletakkan di dalam senarai yang akan diperiksa kemudian.

Kaedah AHP telah dibandingkan dengan kaedah yang ada di dalam merumuskan pemeriksaan pipeline, AHP menunjukkan keputusan yang lengkap dan terperinci. AHP juga boleh menunjukkan faktor yang sebenar yang menyebabkan kegagalan pipeline tersebut berdasarkan struktur risiko kegagalan pipeline dan dikategorikan dalam kategori risiko supaya penyelenggaraan yang lebih baik dapat ditentukan. Walaubagaimana pun, kaedah penyelenggaraan yang telah dirancang hanya berdasarkan pemeriksaan dan tidak ada perbandingan pada setiap faktor. Kaedah ini akan menyebabkan penyelenggaraan yang tidak sempurna yang tidak boleh menyebabkan pembiayaan yang tidak perlu.

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INTRODUCTION OF STUDY

1.1. Introduction

Pipelines are the most economical means for conveying the fluid substances on mass scale to larger distances. For example, in oil and gas industry transportation of hydrocarbon and similar products through pipelines to overland and across the seas is the most economical means as compared to conveyance by truck, rail and/or tankers. There exists a very huge network of pipeline systems worldwide that extends more than a million kilometer in length, such pipelines are being used for conveying different types of substances that ranges from domestic water supply to some kind of hazardous fluids.

The term pipe is defined as a closed conduit, usually of circular cross section as illustrated in figure 1.1. It can be made of any appropriate material such as steel or plastic. The term pipeline refers to a long line of connected segments of pipe, with pumps, valves, control devices, and other equipment/facilities needed for operating the system. It is intended for transporting a fluid (liquid or gas), mixture of fluids, solids, fluids-solid mixture (DNV, 2003).

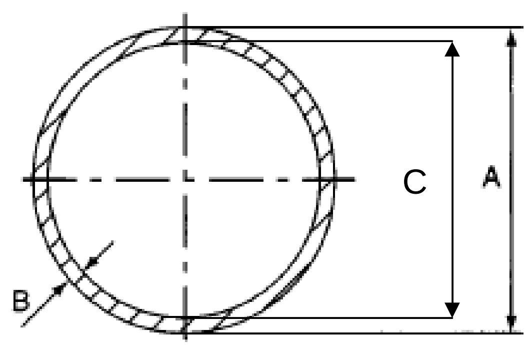

Figure 1.1. Pipeline Cross Section

Where:

A is the Outside Diameter (OD)

B is the Wall Thickness (WT)

C is the Inside Diameter (ID)

Pipeline system is an interconnected system of submarine pipelines, their risers, supports, isolation valves, all integrated piping components, associated safety systems and the corrosion protection system (DNV, 2003). Pipeline network is an integrated transmission and distribution grid that can transport natural gas to and from fields offshore to end users in the power, industrial and commercial sectors.

For the transport of large quantities of fluid (liquid or gas), a pipeline is undisputedly the most favored mode of transportation. Even for solids, at many instances the pipeline is a favorable option over the other modes of transportation. The advantages of pipelines are (Liu, 2003):

- Economical in many circumstances
- Low energy consumptions
- Friendly to environment
- Safe for humans
- Unaffected by weather
- High degree of automation
- High reliability
- Less sensitive to inflation
- Convenience
- Less susceptible to theft
- Efficient land use
- High degree of security

A riser system is essentially conductor pipes connecting floaters on the surface and the wellheads at the seabed. There are essentially two kinds of risers, namely rigid risers and flexible risers. A hybrid riser is the combination of these two. As explained by Bay (2005) the riser system must be arranged so that the external loading is kept within acceptable limits with regard to:

- Stress and sectional forces
- VIV and suppression
- Wave fatigue
- Interference

The riser should be as short as possible in order to reduce material and installation costs, but it must have sufficient flexibility to allow for large excursions of the floater (Bay, 2005).

Offshore pipelines can be classified as follows (Guo et all, 2005):

- Flow lines transporting oil and/or gas from satellite sub sea wells to sub sea manifolds;
- Flow lines transporting oil and/or gas from sub sea manifolds to production facility platforms;
- Infield flow lines transporting oil and/or gas between production facility platforms;
- Export pipelines transporting oil and/or gas from production facility platforms to shore;
- Flow lines transporting water or chemicals from production facility platforms, through sub sea injection manifolds, to injection wellheads.

Oil and gas transport systems normally consist of medium to large diameter pipelines, with an estimated lifetime in the order of 30 to 50 years. The pipeline systems are built from a limited number of components or elements, each designed with a lifetime in the same order of magnitude as the system lifetime. Thus, the extent of maintenance and repair is generally low (Hroar, 2001).

The design engineers need to understand the environments in which the pipeline will be installed and operated, before designing an offshore pipeline. Guo et all, (2005) said the parameters that will affect the mechanical design of the pipeline system are :

- The water depth
- The waves occur
- The water currents
- The fluids inside the pipelines
- The operating pressure
- The temperature
- Sand concentration
- Meteorological and oceanographic data

The pipe coating is used to protect the pipe against corrosion. There are some layer coatings, which are (Guo et all, 2005):

1. A single layer coating is used when the installed pipeline is always in a static,
2. Additional layer of coating are used for additional protection, for weight to help the pipeline remain laterally stable on the seabed,
3. A multi layer coating is generally used in cased where the external environment tends to easily wear out the external coating.

Palmer (2004) explained the properties that are considered desirable for deepwater pipeline coatings are:

1. Resistance to seawater absorption
2. Resistance to chemical in seawater
3. Resistance to cathodic disbandment
4. Adhesion to the pipe surface
5. Flexibility
6. Impact and abrasion resistance
7. Resistance to weathering
8. Compatibility with cathodic protection

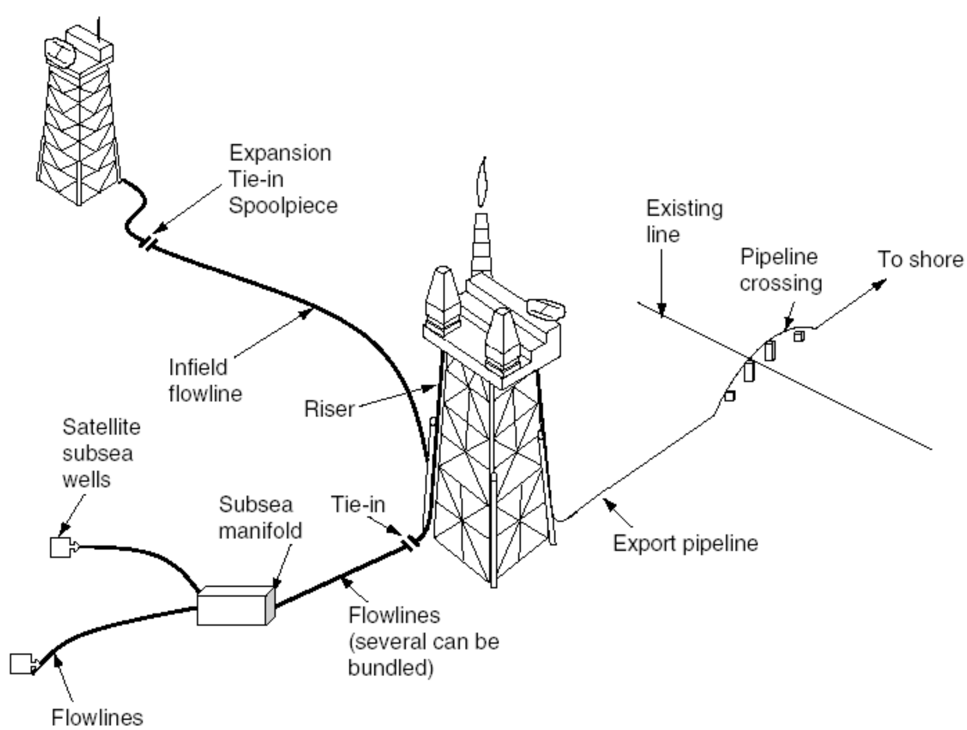

Figure 1.2. Uses of Offshore Pipelines (Guo et all, 2005)

The cost of pipeline construction and management is not uncommon higher than that of drilling and production components (Guo, et all, 2005). Optimizing pipeline development process has become a vitality important topic for achieving cost effective management in offshore and deepwater pipeline operations. Above figure 1.2 is the example use of offshore pipelines.

Usually pipelines are operated at various ranges of temperature and pressure. Apart from the types of fluid to be transported and operational conditions, pipelines are also exposed to various environmental conditions such as underwater conditions, remote terrain, hilly and mountainous topography etc. by combining all these situations, always there existing a number of threats to the pipeline networks that may cause a major and/or minor failure to the system. If a pipeline system carrying hazardous substances, the failure may not only cause damages to the system but it can pollute the environment, which may become harmful for living beings. There have been a number of tragic incidences happened those have brought some unwanted consequences.

In 1993, in Venezuela, 51 peoples were burst to death due to gas fire happened as a result of failure of gas pipeline (Hopkins 1994). The pipeline explosion at a Texas refinery killed 15 people and injured 170 in 2005 and spends $6 billion to repair and replace Alaskan pipelines (Isidore, 2006). The burst, leaks and damage of pipeline may be caused by corrosion. The damage may not appear significant but it can show a leak by corrosion inside stress fractures (Loth, 2004).

In order to operate the pipeline network safely and to prevent any major and/or minor failure to happen, it is very essential to perform pipeline inspection, monitoring and assessment routinely to determine whether any maintenance is needed or not. For assessing the need and extent of pipeline maintenance a risk based analysis is being used to determine the pipeline condition. Usually three approaches qualitative, semi quantitative and quantitative are applied to estimate the likely level of accident using risk based analysis (Dziubinski, 2006).

The terms quantitative and qualitative are often used to distinguish the amount of historical failure related data analyzed in the model and the amount of mathematical calculations employed in arriving at a risk answer. “A model that exclusively uses historical frequency data is sometimes referred to as quantitative whereas a model employing relative scales, even if later assigned numbers, is referred to as qualitative or semi quantitative" (Muhlbauer, 2004).

This research choose the pipeline for the case study because transportation of products by pipeline is a risk because there is some probability of the pipeline failing, releasing its contents, and causing damage in addition to the potential loss of the product itself (Mulhbauer, 2004) and the other reason is support by Dey (2004d) said that petroleum pipelines are the nervous system of oil industry, as this transports crude oil from sources to refineries and petroleum products from refineries to demand points. Therefore, the efficient operations of these pipelines determine the effectiveness of the entire business.

1.2. Problem Statement

Maintenance activities are to ensure that the physical assets continue to fulfill the intended purpose of the system. The maintenance function is to increase the operational and design life, reliability and availability of the pipeline system. The main purposes of maintaining the pipeline are to maintain an acceptable margin of safety for personnel and the environment and to maximize the availability of the pipeline system during its operational life and to maximize the pipeline life.

Maintenance can be minimized during the detailed design phase by the selection of appropriate engineering concept, equipment and materials. During pipeline operations, review of routine inspections may result in decisions to undertake either preventative or corrective maintenance activities on the pipeline. Correct method for pipeline maintenance is one of the major issues in this discipline because on the basis of current practices some operators performed improper maintenance, which may incur cost as well as unnecessary pause in the operation. On the other hand, in some instances much overlooked maintenance operations might result into failure or sometimes disaster of the pipeline system.

1.3. Objectives of Study

The principal objective of this research study is to develop an appropriate method based on risk analysis to prioritize the maintenance planning of a pipeline network. The main objective is supported by three sub objectives, which are;

i. To determine the probability and consequence of pipeline failure system with Analytical Hierarchy Process as one of the multicriteria decision system.
ii. To perform the sensitivity analysis on the probability of failure and its corresponding consequence in order to test the priority.
iii. To formulate the appropriate inspection and maintenance strategies for pipeline systems.

1.4. Significance of this Research

For this study, two pipeline networks are chosen as a case study, the first one is located in Kertih, West Malaysia and the other one is located in Kutai Basin, East Kalimantan. The outcome of this research may be referred by the pipeline operators for maintenance planning program. The existing method of pipeline maintenance in many operators still using traditional techniques, means that the method based on the simple observation, straight forward decision and with out comparing the factors. This method may cost a lot of million dollars wasted, therefore pipeline maintenance based on risk analysis become very important to achieve effective management in offshore pipeline operators.

The method of this research used Analytic Hierarchy Process (AHP) which is one of the tools in multi criteria decision making system. In AHP the problem is constructed to hierarchy with several levels. Each level consists of factors that can be compared which one is the important. By comparing the factors then the priority factor involved in pipeline system can be known. When the factor comes into major then the maintenance should be concentrated well, and if the factor is minor then the maintenance could be reduced or the frequency could be minimized.

Analytic Hierarchy Process (AHP) is completed with sensitivity analysis to reanalyze the result of decision, whereas the existing method in the pipeline operators the decision is final result. Sensitivity analysis is used to investigate how sensitive the results of study are to changes in how it was done. Sensitivity analysis can be useful in eliminating alternatives and providing information as to the robustness of a decision.

1.5. Scope and Limitations of the Research

The scope of this research is to determine the greatest risk factors that describe the probability of failure of pipeline network system by applying multi criteria decision making approach based on Analytic Hierarchy Process. Therefore the research is limited to the following scope:

a. It involved 2 operators from oil and gas industry based in Malaysia and Indonesia.
b. The information is assessed to develop the theoretical model based on Analytic Hierarchy Process (AHP).
c. This research is focused on the application of Analytic Hierarchy Process as one of the tools in multi criteria decision making system.

CHAPTER 2

LITERATURE REVIEW

2.1. Risk Factors

Pipelines are commonly known as a safe way of transporting a certain substance, but their failure can be very catastrophic. A series of recent major industrial accidents have once again highlighted the need for better management of routine and accidental risks. Probability of an event that causes a loss and the potential magnitude of such loss are usually defined as Risk. Under this definition, risk is increased when the probability of the event increases or when the magnitude of the potential loss (the consequences of the event) increases. The most commonly accepted definition of risk is often expressed as a mathematical relationship :

$$Risk = \text{event probability (PoF)} \times \text{event consequence (CoF)}$$

The risk of failure is calculated as the Probability of Failure (PoF) and Consequence of Failure (CoF) (Mulbauer, 2006b), where:

- Probability is defined as "degree of belief" regarding the probability of an event occurring in a specified future period. Probability is most often expressed as a decimal ≤ 1.0 or a percentage $\leq$ 100%. Historical data, usually in the form of summary statistics, often partially establishes our degree of belief about future events. However such data is not, the only source of our probability estimates.
- Consequence of Failure is defined for understanding and quantifying potential consequences from a pipeline failure and evaluated as the outcome of a failure based on the assumption that such a failure will occur. So, all consequence estimations will include some simplifications and assumptions in order to make the solution process manageable.

Risk is often expressed in measurable quantities such as the expected frequency of fatalities, injuries, or economic loss (Muhlbauer, 2004). The factors that may affect probability and consequence should be identified in order to make decisions on whether risks need to be treated or maintenance plan strategies need to be carried out (SAI, 2005).

2.1.1. Risk Analysis : Methods and Techniques

Developing an understanding of the risk is called “risk analysis”. It provides an input to decisions on whether risks need to be treated in the most appropriate and cost-effective risk treatment strategies. Risk analysis involves consideration of the sources of risk, their positive and negative consequences and the probability of the occurrence of such consequences. Factors that affect consequences and probability can be identified. Risk is analyzed by combining consequences and their probability (Lawson, K. 2005). In most circumstances existing controls are taken into account. A preliminary analysis can be carried out so that similar risks are combined or low-impact risks are excluded from detailed study. Excluded risks should, where possible, be listed to demonstrate the completeness of the risk analysis (SAI, 2005).

The magnitude of the consequences of an event, should it occur, and the probability of the event and its associated consequences, are assessed in the context of the effectiveness of the existing strategies and controls (Rishi, 2007). An event may have multiple consequences and affect different objectives. Consequences and probability are combined to produce a level of risk. Consequences and probability may be estimated by using statistical analysis and calculations. Where no reliable or relevant past data is available, subjective estimates may be made reflecting an individuals or groups degree of belief that a particular event or outcome will occur. The most pertinent information sources and techniques should be used when analyzing probability and consequences.

Sources of information may include the following (SAI, 2005):

- Past records.
- Practice and relevant experience.
- Relevant published literature.
- Market research.
- Results of public consultation.
- Experiments and prototypes.
- Economic, engineering or other models.
- Specialist and expert judgments.

Techniques include (SAI, 2005):

- Structured interviews with experts in the area of interest;
- Use of multi-disciplinary groups of experts;
- Individual evaluations using questionnaires; and
- Use of models and simulations.

Risk analysis is a tool decision makers can use to prioritize as plan maintenance actions (Backlund and Hannu, 2002). Risk analysis may be undertaken to varying degrees of detail depending upon the risk, purpose of analysis, and information, data and resources available. Analysis may be qualitative, semi-quantitative or quantitative or a combination of these, depending on the circumstances. The order of complexity and costs of these analyses, in ascending order, is qualitative, semi quantitative and quantitative. In practice, qualitative analysis is often used first to obtain a general indication of the level of risk and to reveal the major risk issues. Later, it may be necessary to undertake more specific or quantitative analysis on the major risk issues (SAI, 2005). The similar opinion to identify risks in terms of where they are located in a system and how serious they are, risk analysis is often used. The approach used is simple qualitative, qualitative and quantitave (Hannu and Backlund, 2002; Murthy et all, 2002).

Model is a set of rules which predict the future performance of pipeline from a risk perspective. The goal of any risk assessment model is to quantify risks, in either a relative or absolute sense. But no one can definitively state where or when an accidental pipeline failure will occur. However more likely failure mechanisms, locations, and frequencies can be estimated in order to focus risk efforts. There are three general types of models (Muhlbauer, 2004):

- Matrix models: it ranks pipeline risk according to probability and potential consequences of an event by a simple scale, such as high, medium, or low, or a numerical scale for example from 1 to 5. This approach may simply use expert opinion or a more complicated application might use quantitative information to rank risks. While this approach cannot consider all pertinent factors and their relationships, it does help to crystallize thinking by at least breaking the problem into two parts (probability and consequences) for separate examination.

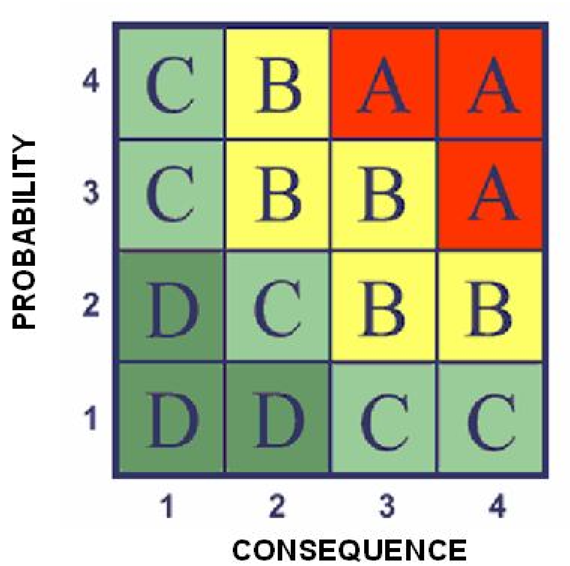

Figure 2.1. Example of Risk Matrix (Mosaic, 2002).

- Probabilistic model: it commonly refers to as Probabilistic Risk Assessment (PRA) and sometimes also called Quantitative Risk Assessment (QRA) or Numerical Risk Assessment (NRA). This technique is used in the nuclear, chemical, and aerospace industries and to some extent, in the petrochemical industry. The output of PRA is usually in a form whereby its output can be directly compared to other risks such as motor vehicle fatalities or tornado damages. However, in rare event occurrences, historical data present an arguable blurred view.

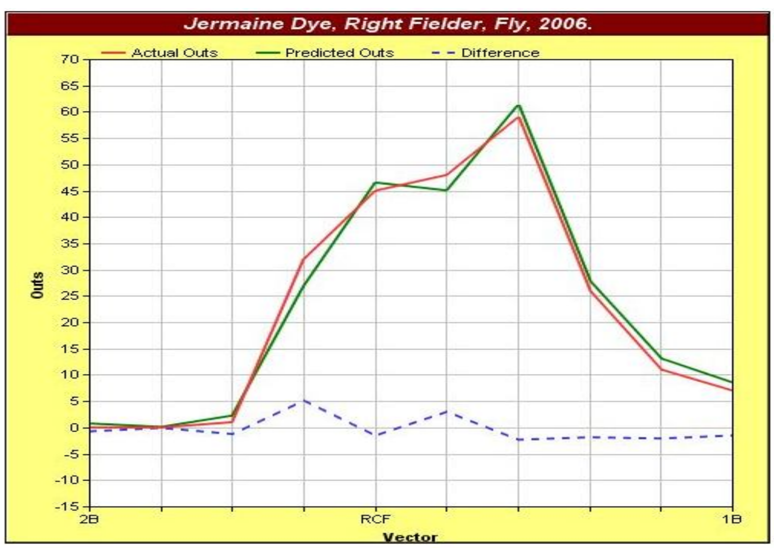

Figure 2.2. Example of Probabilistic (Dye, 2006)

- Indexing model: this approach numerical value (score) is assigned to important conditions and activities on the pipeline system that contributes to the risk picture. Weightings are assigned to each risk variable. The relative weight reflects the importance of item in risk assessment and is based on statistic if any, and on engineering judgment where data are not available. Each pipeline section is scored based on all of its attributes. The various pipe segments may then be ranked according to their relative risk scores in order to prioritize repairs, inspections, and other risk mitigating efforts.

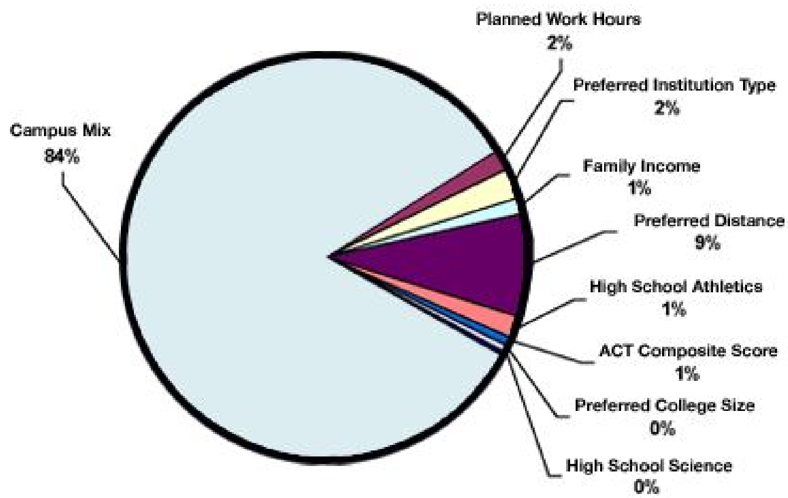

Figure 2.3. Example of Indexing Model (ACT, 2008)

Scoring or ranking of risk assessments for pipeline types has served the pipeline industry well for many years in many ways. The new roles of risk assessments have prompted some changes to the way risk algorithms are being designed. The changes lead to more robust risk results that better reflect reality and fortunately are readily obtained from data used in previous assessments. Scoring systems as a means of analysis have been around for a long time. When knowledge is incomplete and a decision structure is needed to simultaneously consider many factors, scoring system often appears. Many risk assessments are based on such scoring systems.

Scoring systems often use a simple summation of numbers assigned to conditions and activities that are expected to influence risks. Whenever conditions with more increasing risk are present with fewer risk reducing activities, risk is relatively higher. As risky conditions decrease or are offset by more risk reduction measures, risk is relatively lower

(Cabeza et all, 2007). In the pipeline industry, relative risk scoring or ranking systems have been around for decades (Mulhbauer, 2006a).

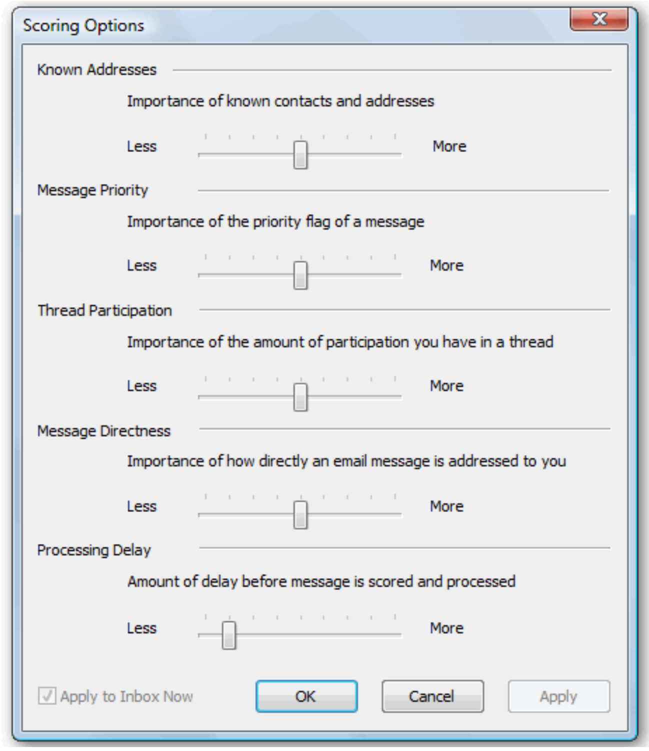

Figure 2.4. Example of Scoring (Clear, 2008)

Analytic Hierarchy Process (AHP) by Saaty provides an adequate tool for multi criteria decision making which quantitatively supports the evaluation of best alternative with regard to quantitative and qualitative criteria (Saaty, 1988). It considers human judgment, experience, perception and feelings in the decision making process (Manoharan, 2005).

Risks are by nature subjective, so to analyze their potential contribution to a failure, the AHP developed by Saaty is used here. This technique allows subjective and objective factors to be considered in risk analysis and also provides a flexible and easily understandable able way to analyze subjective risk factors. It is a multiple criteria decision-making technique that permits active participation of those involved, and provides managers a rational basis to make decisions. (Dey, 2001)

AHP has been applied by researchers in various industrial applications. In operation management, Partovi et al. (1990) has applied AHP in making decision. Korpela and Tuominen (1996) applied AHP for benchmarking performance of logistics; their study shows how AHP helps compare process performance of various organizations under study to improve the performance. Reynolds (1997) has shown that risk based inspection and maintenance is a systematic way to integrate both probability and consequence of risk in inspection and maintenance decision making. Mian and Christine (1999) used AHP for evaluation and selection of a private sector project.

Bhattacharya and Dey (2003) applied AHP in power sector for selecting power market structure. They argue that selection of power market structure depends on various factors like technical, socio-economic, and financial and moreover utility of various interest groups (stakeholders) affect the decision. Dey (2004a) used AHP framework for managing various technology management issues in oil pipelines industry. (Dey et al., 2004b) demonstrated applications of AHP in managing operational risk of oil and gas pipelines in India.

Khalil, et al., in 2005 presented a rational and systematic method for maintenance management of the pipelines. It was a risk based approach using an analytical hierarchy process model to determine the probability of pipeline failure and the expected value approach to determine the expected costs of failure. The author demonstrated applications of AHP in prioritizing the maintenance of pipelines based on risk analysis in Malaysia and Indonesia. To author's knowledge this study is the first application of AHP for pipeline maintenance in Malaysia and Indonesia.

2.1.2. Risk Matrix

Risk matrix is a two-dimensional array; an array made of rows and columns. In risk management the risk matrix is a mean to visualize these two dimensions in order to display the ranking of a risk. It is made of the consequence of a risk when occurring and the likelihood of a risk to occur (SAI, 2005).

The number of columns and rows in a risk matrix can be different depending on how much refined the risk assessment shall be. Very common are 5x5 or 9x9 risk matrices (Cabeza et all, 2007). Construction of a risk matrix starts by first establishing how the matrix is intended to be used. Some typical uses for risk ranking are process hazard analyses and safety audits.

A key initial decision that has to be made is to define the risk acceptability or tolerability criteria for the organization using the matrix. Without adequate consideration of risk tolerability, a risk matrix can be developed that implies a level of risk tolerability much higher than the organization actually desires. Another key aspect of risk matrix design is having the capability to evaluate the effectiveness of risk mitigation measures. The risk matrix should always allow the risk ranking for a scenario to move to a risk tolerable level after implementation of mitigating measures. Otherwise it may be difficult to determine the effectiveness of mitigation measures.

2.2. Analytic Hierarchy Process (AHP)

Analytical Hierarchy Process (AHP) is an approach to decision making that involves structuring multiple choice criteria into a hierarchy, assessing the relative importance of these criteria, comparing alternatives for each criterion, and determining an overall ranking of the alternatives (Knott, 2006). By organizing and assessing alternatives against a hierarchy of multifaceted objectives, AHP provides a proven, effective means to deal with complex decision making. Indeed, AHP allows a better, easier, and more efficient identification of selection criteria, their weighting and analysis. AHP is very useful when the decision-making process is complex, for instance, by being unstructured. Indeed, when the decision cycle involves a variety of multiple criteria in which rating is based on a multiple-value choice, AHP splits the overall problem to solve into so many evaluations of lesser importance, while keeping at the same time their part in the global decision (Tanino et al., 2003).

The similar opinions indicate that AHP is appropriate for the task of selecting components when several criteria must be considered (Cangussu, et al., 2006). AHP provides a framework to view the problems in an organized but complex framework that allows for interaction and interdependence among factors and still enables the decision maker to think about them in a simple way (Pandejpong, 2002). The general concept of AHP is about decomposing a problem into sub problems and then aggregating the solutions of all the sub problems into a conclusion (Chantrasa, 2005).

There are four principles in AHP method as problem solving, (Saaty, 2003);

- Decomposing

  The goal is to structure the problem into humanly manageable sub problems. To do so, iterating from top (the more general) to bottom (the more specific), split the problem, which is unstructured at this step, into sub-modules that will become sub-hierarchies. Navigating through the hierarchy from top to bottom, the AHP structure comprises goals (systematic branches and nodes), criteria (evaluation parameters) and alternative ratings (measuring the adequacy of the solution for the criterion).

  Each branch is then further divided into an appropriate level of detail. At the end, the iteration process transforms the unstructured problem into a manageable problem organized both vertically and horizontally under the form of a hierarchy of weighted criteria. By increasing the number of criteria, the importance of each criterion is thus diluted, which is compensated by assigning a weight to each criterion.

- Weighing

  Assign a relative weight to each criterion, based on its importance within the node to which it belongs. The sum of all the criteria belonging to a common direct parent criterion in the same hierarchy level must be equal to 100% or 1. A global priority is computed that quantifies the relative importance of a criterion within the overall decision model.

- Evaluating

  Score alternatives and compare each one to others. Using AHP, a relative score for each alternative is assigned to each leaf within the hierarchy, then to the branch the leaf belongs to, and so on, up to the top of the hierarchy, where an overall score is computed.

- Selecting

  Compare alternatives and select the one that best fits the requirements.

The Analytic Hierarchy Process (AHP) is a basic approach to decision making. It is designed to cope with both the rational and the intuitive to select the best from a number of alternatives evaluated with respect to several criteria. In this process, the decision maker carries out simple pair wise comparison judgments which are then used to develop overall priorities for ranking the alternatives. The AHP both allows for inconsistency in the judgments and provides a means to improve consistency. (Dey, 2004a).

In the pair wise comparison method, criteria and alternatives are presented in pairs of one or more referees (e.g., experts or decision-makers). It is necessary to evaluate individual alternatives, determining weights for the criteria, constructing the overall rating of the alternatives and identifying the best one (Dey, 2004b). Similar opinion to Dey, by using pair wise comparison method, the attributes of the various alternatives and computation of the unified index value of a system can be determined (Lee et all, 2006).

Table 2.1 shows the scale of judgments and their definitions. After scales of judgment have been identified for all levels of hierarchy, matrices are constructed for each level starting from the top of the hierarchy.

Table 2.1. Analytical Hierarchal Process Scale of Judgments (Saaty, 1988)

Intensity of importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the property.
3	Moderate importance of one over another	Experience and judgment slightly favor one element over another.
5	Essential or strong importance	Experience and judgment slightly strongly favor one element over the another
7	Very strong importance	An element is strongly favorable and its dominance is demonstrated in practice
9	Extreme importance	The evidence of favoring one element over another is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate values between two adjacent judgments	Compromise is needed between two judgments

2.2.1. Mathematical Model in Analytic Hierarchy Process

The basic tool in Analytic Hierarchy Process is a matrix number, representing the judgments of pair wise comparisons. Consider the elements C1, C2, ...,Cn of some level in a hierarchy. Weights of influence w1, w2, ...wn on some element in the next level. Denote aij as the number indicating the strength of Ci, when compared to Cj. The matrix of these number aij is denoted A, or A = (aij). aji = 1/aij, that is the matrix A is reciprocal. If judgments is perfect in all comparison, then aik = aij . ajk for all i, j, k and the matrix A is called consistent, Saaty (1988).

Then the mathematic formulation is : aij = wi/wj ; i,j = 1,2,…n (1)

And thus $a_{ij}.a_{jk} = {}^{w_i}\!/_{w_j} . {}^{w_j}\!/_{w_k} = {}^{w_i}\!/_{w_k} = a_{ik}$

The matrix equation A . x = y , where $x = (x_1,...,x_n)$ and $y = (y_1,..., y_n)$ is a shorthand notation for the set of equations.

$\sum_{j=1}^{n} a_{ij} x_i$, where i = 1,… n

From equation (1) $a_{ij} . {}^{w_j}\!/_{w_i} = 1$, i, j = 1, …, n

And consequently $\sum_{j=1}^{n} a_{ij} . w_j . {}^{1}\!/_{w_i} = n$, i = 1, … n

Or $\sum_{j=1}^{n} a_{ij} . w_j = n w_i$, i = 1, …, n

Which is equivalent to Aw = n w (2)

$$\begin{bmatrix} {}^{w_1}\!/_{w_1} & {}^{w_1}\!/_{w_2} & \cdots & {}^{w_1}\!/_{w_n} \\ {}^{w_2}\!/_{w_1} & {}^{w_2}\!/_{w_2} & \cdots & {}^{w_2}\!/_{w_n} \\ \cdots & \cdots & \cdots & \cdots \\ {}^{w_n}\!/_{w_1} & {}^{w_n}\!/_{w_2} & \cdots & {}^{w_n}\!/_{w_n} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \\ w_n \end{bmatrix} = n \begin{bmatrix} w_1 \\ w_2 \\ \\ w_n \end{bmatrix}$$

In matrix theory, the above formula expresses the fact that w is an eigenvector of A with eigenvalue n. The aij are not based on exact measurements, but on subjective judgments. Thus, the aij will deviate from the “ideal” ratio wi/wj, and therefore Eq. 2 will no longer hold. But, there are two matrix theory, the first of is, if $\lambda_1,...,\lambda_n$ are the numbers satisfying the equation $Ax = \lambda x$, i.e., are the eigenvalues of A, and if aii = 1 for all I, then

$$\sum_{i=1}^{n} \lambda_i = n$$

Therefore, if Eq.2 holds, then all eigenvalues are zero, except one, which is n. Clearly then in the consistent case, n is the largest eigenvalue of A. Second is if one changes the entries aij of a positive reciprocal matrix A by small amounts, then the eigenvalues change by small amounts. It will result the diagonal of a matrix A consisting of ones (aii = 1), and if A is consistent, then small variations of the aij keep the largest eigenvalue, $\lambda_{\max}$ close to n, and the remaining eigenvalues get close to zero.

Then, if A is the matrix of pairwie comparison values, in order to find the priority vector, so the vector w is: $Aw = \lambda_{\max} w$. Since it is desirable to have a normalized solution, alter w slightly by setting and replacing w by $\left(1/\alpha\right)w$. This ensures uniqueness, and also that $\sum_{i=1}^{n} w_i = 1$. Since small changes in aij imply a small change in $\lambda_{\max}$, the deviation of the latter from n is a measure of consistency. Then, the consistency index, as indicator of “closeness to consistency less then 0.1 (Saaty, 1988) is given by :

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{3}$$

Saaty suggests that a consistency index less or equal to 0.10 indicates that the decision maker has adequately structured the problem in question, but (Apostolou and Hassell, 1993) if the consistency index is greater than 0.10 then the response by subject can be considered as random. Saaty proposes the following index for measuring consistency :

$$CR = \frac{CI}{RI} \tag{4}$$

where ‘*RI’* is the average value of ‘*CI*’ for a random matrices using the Saaty’s scale (Saaty, 1988). CR is a normalized value, because it is divided by an arithmetic means of a random matrices consistency indexes (*RI*).

Table 2.2. Random Index for A Several Matrix Dimensions (Saaty, 1988).

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.45	1.49

Perfect consistency is hard to achieve especially when considering multiple conflicting criteria, but AHP provides a mechanism of measuring the consistency of the decision made, and allows for revisions of the decision in order to reach an acceptable level of consistency. AHP measures the consistency of judgment by means of consistency ratio (CR). A good decision is when the value of consistency ratio is 10% or less. If the value exceeds 10%, it means that the judgment may somehow be random and should be revised.

The reasons this research uses AHP because it allows one to organize data, thoughts, and the intuition on a decision in a logical, hierarchical structure as outlined below :

- The ability of AHP to incorporate both objective and subjective (Dey, 2004c).
- It helps decision-making by quantifying many subjective factors.
- Qualitative judgment and quantitative data can be included in the priority setting process.
- The goal is broken down into sub factors of failure causes
- AHP is an effective tool for conducting group planning sessions in an analytical and systematic manner.
- AHP provides sensitivity analysis to show its effects when judgement are changed.

2.2.2. Sensitivity Analysis

Once the analysis has been completed, the factors of risk should be analyzed for unexpected case. This is usually done through a set of “what if” calculations that tests the risk factors sensitivity. Because risk is uncertain and the analysis results may vary from the actual condition, it is often useful to perform a sensitivity analysis.

Sensitivity analysis is a procedure used to describe analytically the effects of uncertainty on one parameter or more involved in the analysis of a risk failure of the pipeline (McAllister, 2005).

Sensitivity analysis may investigate how sensitive the rankings of the alternatives are to changes in the importance of the criteria. Sensitivity analysis from the Goal node will show the sensitivity of the alternatives with respect to the criteria below the goal. Expert choice software can perform sensitivity analysis to see how the different weight assigned to each criterion could affect the outcomes of the model (Abdullah, 2003). There are five modes for graphical sensitivity analysis:

- Performance :
  The criteria are represented by vertical bars, and the alternatives are displayed as horizontal line graphs. The intersection of the alternative line graphs with the vertical criterion lines shows priority of alternative for a given criterion.
- Dynamic :
  The dynamic sensitivity analysis is a horizontal bar graph able to increase or decrease priority of any criterion and sees the change in priorities of the alternatives.
- Gradient :
  The gradient sensitivity analysis assigns each criterion a separate gradient graph. The vertical line represents current priority of the selected criterion. The slanted lines represent the alternatives. The current priority of an alternative is where the alternative line intersects the vertical criterion line.
- Two-dimensional
  The two-dimensional plot sensitivity shows how well the alternatives perform in respect to any two criteria.
- Difference graph: The difference graph shows the differences between priorities of the two alternatives taken at a time for all of the criteria.

2.2.3. Expert Choice Professional Software

Expert Choice represents a significant contribution to the decision making process. It assists a decision maker in solving complex problems involving many criteria and several courses of action. An Expert Choice solution to a problem reflects the expertise of the decision maker, not the computer. Behavioral scientists have spent many years studying human mind and how it makes decisions. They have found that humans are influenced by their previous experiences and this causes them to have biases. Basic instincts, preferences and environmental factors also play key roles in how we analyze data and make decisions. There is no way to remove these factors from human decision making, nor would we necessarily want to, but as the problems of our world become more and more complex, it is necessary for us to employ a framework to help make more logical and less biased decisions while still taking our feelings and intuition into consideration.

Expert Choice is based on the Analytic Hierarchy Process (AHP), a methodology for decision making. It provides users with the tools to construct decision frameworks from both routine and non-routine problems and ways to include value judgments in these decision frameworks. This framework is a hierarchy, used to organize all the relevant factors to solve a problem in a logical and systematic way, from the goal to the criteria to the sub criteria and so on down to the alternatives of a decision. The user must define the problem and enter all the relevant issues into the hierarchy.

The decision maker then provides judgments on the elements in the hierarchy in pairs as to their relative importance. After the decision maker sorts the elements into hierarchy levels clustered into similar or homogeneous entities, Expert Choice asks the user how much more important, or preferred, X is compared to Y with respect to some property. A judgment is made using the AHP verbal or graphical scale or the equivalent 1 to 9 numerical scale. The process is also extended to dissimilar or non-homogeneous entities. Expert Choice determines if the comparisons are logical and consistent and if not assists the user to improve consistency through its "inconsistency measure". Finally, all the separate pair wise comparisons are synthesized to rank the alternatives overall. Expert Choice does not make a choice in some mysterious way, or assume that the answer is hidden in the elegance of the underlying mathematics, but helps make an informed choice based on knowledge, experience, and preferences.

2.3. Pipeline Maintenance : Strategy and Planning

Applying AHP to pipeline maintenance offers a highly effective and proactive method of isolating areas (Nataraj, 2005). Maintenance has an important role directly related to the competitiveness of a given company. It concerns the industry’s most important capital assets and deals with manufacturing systems that are subject to deterioration and failure due to usage and age. Preventive maintenance is a necessary activity to restore or keep the function of a repairable system in a good state (Bardey, et all 2005). There is also an emerging view that maintenance not only reduces business risks, but also should be seen as a value adding process in today's dynamic and competitive business environment (Liyange and Kumar, 2003 ; Markeset, 2003).

Pipelines require regular patrol, inspection and maintenance, including internal cleaning and checking for signs of gas leaks. The integrity of the pipeline network and its related equipment is one of the industry's top concerns. The threat of a catastrophic pipeline rupture, though extremely unlikely given the industry's safety precautions, hangs over the head of every pipeline executive and employee. One of the most important causes of pipeline failures is mechanical damage. This occurs when heavy construction equipment dents the pipe, scrapes off its coating, gouges the metal, or otherwise deforms the pipe in some way.

Mechanical damage is difficult to prevent and pipeline companies cannot continuously monitor every foot of the line over thousands of miles to keep people from digging anywhere near it. Many of the pipeline industry's safety programs involve mapping and marking the location of pipe underground to warn people off (Busby, 1999). Knowledge of the maintenance engineers who are expert in judgments can be useful in the design maintenance concept (Garg, 2006).

2.3.1. Inspection Techniques

The inspection plan needs to take into account previous inspection reports in order to assess the present condition of the pipeline. A majority of the inspection is usually performed through General Visual Inspection by using Remotely Operated Vehicles (Macdonald, 2007). Specific damages to the pipeline such as dent, buckle, etc, require Close Visual Inspection (CVI). Internal corrosion inspections are performed by utilizing Intelligent Pig or external Automated UT. For internal corrosion assessment the chemical analysis of fluid samples and examination of corrosion probes are also part of inspection. The routine external inspection of pipeline includes general visual inspection at a frequency depending upon the risk level of the pipeline. This inspection usually covers:

a. Mechanical damage of the pipeline
b. Coating damages
c. Anode consumption and condition
d. Scouring or built up of seabed substances

e. Signs of lateral and axial movement
f. Leaks
g. Extent of exposed sections of buried pipelines

The aim of performing inspections is to maintain a level of safe operations, both related to accidents and costs. A normal inspection program for pipeline may include:

- General Visual Inspection (GVI) underwater using diver or Remotely Operated Vehicles (ROV)
- Close Visual Inspection (CVI) underwater using diver or Remotely Operated Vehicles (ROV)
- General Visual Inspection (GVI) or Close Visual Inspection (CVI) above water
- Cathodic Potential (CP) measurements using diver or Remotely Operated Vehicles (ROV)
- Intelligent Pigging Inspection using Magnetic Flux Leakage or Ultrasonic Pig.

As a general practice, the inspection of pipeline is usually limited to General Visual Inspection and Close Visual Inspection.

2.3.2. Maintenance Plans

Maintenance activities are to ensure the physical assets continue to fulfill the purpose of pipeline process for increasing the operational and design life. Pipelines maintenance is very expensive activities if it has to shut down the offshore pipelines (Guo, et all, 2005). With advanced technology, it is possible to carry out some maintenance activities without shutting down the pipeline. Maintenance can be minimized during the detailed design phase by selection of appropriate engineering concept, equipment and materials.

The purposes of pipeline maintenance are:

- To minimize inspection, maintenance and repair activities which could be hazardous to personnel.
- To maximize the availability of the pipeline system during its operational life and to maximize the pipeline life.
- To maintain an acceptable margin of safety for personnel and the environment.

The following maintenance plans are commonly used in maintaining the offshore pipelines:

Table 2.3. Maintenance Plans

No	Maintenance Plans	Guo, et all. 2005	McAllister, 2005	Dey, et all. 2004
1.	Pigging	√	√	√
2.	General Visual Inspection	√	√	√
3.	Cathodic Protection	√	√	√
4.	Corrosion Inhibitor	√	√	-
5.	Acoustic Leak Detector	-	√	√

Table 2.4. Maintenance Plans Function

No.	Maintenance Plans	Function
1.	Pigging	To clean the pipeline and identify pipeline defects
2.	General Visual Inspection	To evaluate the condition in order to assess the pipeline integrity
3.	Cathodic Protection	To protect a sub sea pipeline from corrosives
4.	Corrosion Inhibitor	To protect and to control the a sub sea pipeline from corrosives
5.	Acoustic Leak Detector	To identify the condition and leak of pipeline

Based on the literature review regarding pipeline maintenance, the main maintenance for both pipeline under study Kertih and Kutai Basin that should be applied are pigging, general visual inspection and cathodic protection. The three types of pipeline maintenance of pigging, visual inspection and cathodic protection have been practiced in many pipeline industries. Beside those three methods as explained above, there are also other maintenance plans that may be applied to ensure the good operation of pipeline such as corrosion inhibitor and acoustic leak detection. The procedure in formulating the pipeline maintenance can be seen in Chapter Five.

2.3.2.1. Pigging

The pigging operation is carried out by using pigs inserted into the pipeline via a pig launcher (Braestrup et al., 2005). In this method, pipeline inspection gauge or pig is used to perform various operations on a pipeline without stopping the flow of the product in it.

In oil pipelines, pigging is utilized for removing debris, whereas in gas pipelines it is used for removing liquids and for meter proving (Guo, 2005). PIGs can also specify the position in pipeline that may be in damaged condition and requires maintenance.

Pigging has function as follows (Tiratsoo, 1992) :

- Cleaning out deposits and debris
- Internal inspection
- Pipe geometry measurements
- Separation of products
- Gauging the internal bore
- Location of obstructions
- Improving flow efficiency
- Liquids removal
- Gas removal
- Coating of internal bore
- Corrosion inhibition

There are many configurations of pig to be chosen, but some configurations may not work in some of the pipelines. It is very important to compare the pipeline information to the pig specifications. The purposes of operational pigging are to obtain and maintain the efficiency of the pipeline. To clean the pipelines from internal corrosion, special pigs are available, such as those equipped with independent scraping wires that will go into a pit to break up and remove deposits preventing corrosion inhibitors from getting to the corroding area.

2.3.2.2. General Visual Inspection

General Visual Inspection is one of the types of underwater inspection (Ricci, 1991). General Visual Inspection may use Remotely Operated Vehicles (ROV). The aim of this inspection is to evaluate the condition in order to assess the pipeline integrity. The ROV is performed by using high quality colour TV camera, cathodic potential measurement system, marine growth measurement device, and accurate depth sensor and performed under the instruction of inspection engineer. Findings are reported and documented on video tape and still photos.

2.3.2.3. Cathodic Protection

Cathodic protection is a method by which corrosion of the parent metal is prevented. "The principle for cathodic protection is to provide enough current from an external source to overpower the natural current flow as described" by Guo, et al (2005). To signs the CP system that may be ineffective at areas of coating damage visual inspection should be done, for example to the rusting of exposed steel, disbanded corrosion coating, increase in coating loss compared with previous surveys. If steel of pipe is found to be damaged, engineering assessment should be performed to determine whether remedial measures are necessary. Extensive areas of coating loss should be assessed to determine whether these represent significant loss of stability or corrosion protection and if any remedial measures are required.

2.3.2.4. Corrosion Inhibitor

Corrosion inhibitor is similar with cathodic protection. The function of corrosion inhibitor is to controll the pipeline corrosion. Corrosion inhibitor is used as protective layer on the walls of the pipe by sticking to the metal or corrosion product layer such as iron carbonate or iron sulfide.

2.3.2.5. Acoustic Leak Detector (ALD)

The acoustic principle is based on sound wave. "Acoustic is "wavealert" monitoring though more correctly called a negative pressure wave detector. When a line rupture or leak occurs, there is a sudden drop in line pressure at the source of the problem, followed by the line repressurization a few milliseconds later." (Mc Allister, 2005).

Acoustic Leak Detector (ALD) has the following advantages, (Mc Allister, 2005):

- Not affected by current, turbidity or visibility
- No need to stop production
- High sensitivity for small leak detection
- 100% reliability - never left behind a leaking pipeline
- Rapidity
- Works on buried pipelines

2.4. Summary of Literature Review

Transportation of products by pipeline is a risk because there are some probabilities of pipeline failing, releasing its contents, and causing damage (in addition to potential loss of the product itself). The most meaningful of risk are the key issue of probability and consequence. The probability expresses a degree of belief. The degree of belief is determined by consistent method, so that the judgments would arrive at the same conclusion given the same evidence. The consequence defines the outcome of a failure. The purpose of this study is to define the greatest risk of the pipeline network system and to prioritize the maintenance of pipeline with the highest risk and also to formulate appropriate inspection and maintenance plans.

The key objectives of this study are as follows:

1. To define the probability of failure and consequence on failure on pipeline system by using Analytical Hierarchy Process.
2. To perform the sensitivity analysis on probability of failure and its corresponding consequence in order to test the priority with the change in scenario.
3. Formulating the appropriate inspection and maintenance strategies for pipeline systems.

Risk is characterized by uncertainty. Risk can be assumed as a range of outcomes and their probabilities, how ever there is specific value unknown within the range. Risk analysis is obtained by establishing probability and consequences of hazards. The probability of failure can be obtained under the basis of statistical information and the consequences can be determined as loss of property, fatalities and pollution of the environment. The evaluation of structural consequences may be performed based on engineering judgment or detailed computer modeling. By using engineering judgment the Analytical Hierarchy Process (AHP) is applied in this research to investigate the risk failure of pipeline network system.

The Analytical Hierarchy Process (AHP) should assess all relevant damage modes, which are predictable and directly observeable. The AHP approaches are systematic and well known techniques tested in many problems. Efficiency of AHP can be seen through the preferences of decision maker towards individual criteria showed by pair wise comparison into accurately prioritized weights on the criteria. Because the objective of this research is prioritizing the pipeline maintenance, AHP will create a prioritization that fairly and accurately reflects point of view of the decision maker in pipeline system. The AHP methodology has proven reliable because in the pair wise comparison, a decision maker should reach a consistency.

CHAPTER 3
PIPELINE SYSTEM

This chapter presents a brief description of pipeline system selected for this research. The selected pipeline systems are Kertih and Kutai Basin pipeline. Both pipelines are selected because they are important, the largest and available at the main area of oil and gas production in the country. Kertih is an infrastructure project Phase 1 known as Peninsular Gas Utilisation (PGU I) or the main constructed facilities comprise the first gas processing plant (Thong, 2007). It is an export terminal and a 32 km main pipeline from the Gas Processing Plant (GPP) to the export terminal, power and industrials end users in the East Coast of Peninsular Malaysia. The Kutai Basin block covering approximately 344.14 square kilometers is located in East Kalimantan Province, approximately one kilometer south of Samarinda city. The Kutai Basin is one of the largest and most important oil and gas producing basins in Indonesia (Koh, 2008).

A step by step methodology is applied by a case study application. This research applied the methodology to the oil and gas pipelines; first it is applied on gas pipeline in Kertih and for the second it is applied on oil pipeline in Kutai Basin (refers to figure 3.1) and the details of Indonesia gas industry can be seen in figure below.

Figure 3.1. Location of The Pipeline Under Study

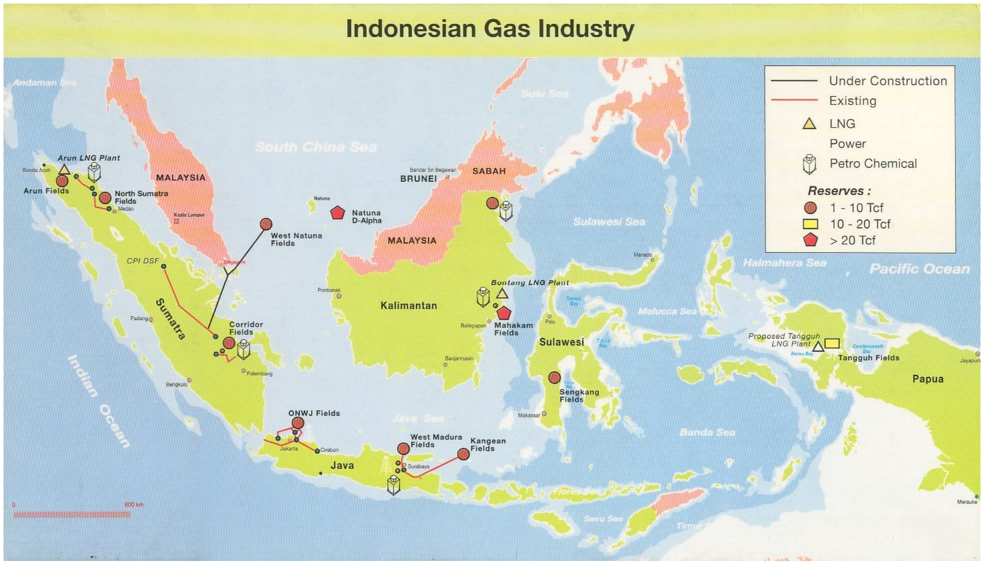

Figure 3.2. Indonesian Gas Industry (Soegiono, 2005)

3.1. Kertih Pipeline

The pipeline system in Kertih is 26 years old, with a capacity of 250 million standard cubic feet per day (mmscfd) of gas transportation. The pipeline is 32 km long with an export terminal located at Kertih. The pipeline under this study is classified into three pipeline stretches. Table 3.1 shows the characteristic and data information for 3 pipelines designated as Pipeline 1, Pipeline 2, and Pipeline 3.

Table 3.1. The Characteristic of Kertih Pipeline

Pipeline ID	Product	Year Install	Material Pipe	OD (mm)	WT (mm)	ID (mm)	Length (km)	D.P (bar)
Pipeline 1	GAS	1982	5LX-60	610	14.3	581.4	48.7	131
Pipeline 2	GAS	1982	5LX-60	762	17.1	727.1	155.7	131
Pipeline 3	GAS	1982	5LX-60	762	17.1	727.1	14	131

During the pipeline observation in Kertih, the primary and secondary data are collected. The primary data consists of list of several causes and the impact of pipeline failure. It is reviewed and discussed with the pipeline engineers to categorize the causes and impact of pipeline failure in pipeline system in Kertih. Eight pipeline engineers are involved in discussion in Kertih. Then list of factors is refined into major factors, and are broken down into sub factors of probability and impact failure. The secondary data consists of history of the pipeline, characteristic of design pipeline and maintenance report.

Here are the factors that may cause probability of pipeline failure, defined by associated mechanisms and failure mode.

Table 3.2. Pipeline damage causes associated to failure modes

Damage Cause	Degradation Mechanisms	Failure Mode
Internal Corrosion	• Internal corrosion due to fluid composition • Improper chemical treatment of fluid	• Burst / leakage
External Corrosion	• External corrosion due to damaged coating and damaged/depletes anodes and defect from construction	• Increased or abnormal consumption of anodes and possible corrosion
Internal Erosion	• Internal corrosion due to fluid composition and flow characteristic • Pipeline design eg. angle and number of bends	• Burst / leakage
External Impact	• Impacts from dropped objects, anchors, trawls, debris, fish bombing	• Pipeline not piggable • Local buckling (collapse) • Dent/gouge and possible crack
On Bottom Stability	• Lateral pipeline movement	• Global buckling / Burst / leakage • Ovalisation due to overloading of pipeline
Free span	• Seabed scouring • Pipeline on bottom instability • Seabed undulations	• Global buckling • Burst / leakage

3.1.1. Factor Causing the Probability of Failure in Kertih Pipeline

Probability of failure is degree of belief regarding the probability of an event occurring in a specified future period. Determining the factors causing probability of pipeline failure is one of the parts to identify the risk failure.

3.1.1.1. Internal Corrosion

Internal corrosion is a common damage cause in pipelines. The presence of corrosion and the rate of corrosion are difficult to predict, as there are many different products, each with different and sometimes varying composition, and different flow regimes. The internal corrosion damage cause includes a large variety of corrosion degradation mechanisms. In hydrocarbon pipeline systems, corrosion damage may be due to:

- CO_2 corrosion
- Bacteria
- H_2S cracking

Water must be present to support the electrochemical reactions causing corrosion. Temperature is another important parameter as it affects water condensation and has an effect on the electrochemical reactions.

3.1.1.2. External Corrosion

External corrosion is applicable mostly to risers in splash zone and onshore part of pipeline. However, this mechanism can also be important to submarine pipelines where anti corrosion measures, such as coating, impressed current etc, are not used, damaged or are ineffective. Inspections are used for:

- Inspection of coating
- Inspection for anode potential
- Inspection for anode depletion
- Wall thickness loss measurements

3.1.1.3. Internal Erosion

Internal erosion in pipeline can be caused by high fluid velocity containing sand particles. Sand is a prerequisite for erosion of the material inside a pipeline, and the velocity of the sand has to be above a certain level. Erosion appears in bends, at reduced diameter, connection of pipelines or other geometrical details. Usually erosion is not a problem if the velocity is less than about 3-4 meters per second. Erosion rate is proportional with the mass of sand in the pipeline, and large particles are more severe than smaller particles. The velocity is a very important parameter as the erosion rate is proportional to the power of 2.5 – 3.0 for the velocity. Erosion could cause 8 days shutdown (Astana, 2004).

3.1.1.4. External Impact

The initial assessment identifies pipelines subjected to high risk of external impact. Inspection cannot be used to avoid damage due to event based mechanisms such as external impact. If an external impact event occurs, it can either cause immediate failure of the pipeline or result in damage to the pipeline. The value of inspection is to identify any significant damage already occurred.

3.1.1.5. On Bottom Stability

The correctly designed pipelines for on bottom stability will only experience stability problems if it is subject to parameters outside the design range. Factors affecting the on bottom stability include:

- Change in design conditions
- Change in pipeline weight
- Loss of weight coating
- Corrosion
- Loss of pipeline cover
- Seabed movement

Designing for on bottom stability is not normally a problem for pipelines below 150 m water depth. Pipelines in water depths of 50 – 150 m require more attention due to stronger wave and current action. The most difficult zone with respect to design for on bottom stability is the region between 0 – 50 m water depths, where combined wave and current effects can be large and highly non linear. In identifying the cause of the stability problem, it may be necessary to recheck the design. In doing so the following needs to be checked:

- The correct input data in use (pipe properties, soil properties and environmental data)
- The appropriate design method used (i.e. whether the method is valid for the actual application or sufficiently accurate)
- Whether the design method has been used correctly

Further, it is important to check if there have been any changes that could cause stability problems. Such changes might be:

- Change in pipe properties (e.g. loss of pipe wall, loss of coating or excessive marine growth)
- Change in environmental conditions (not likely)
- Seabed movements

3.1.1.6. Free Span

Free span is a part of the pipe where the pipe has no support on the seabed. If a free span is too long the pipe might oscillate due to ocean currents. It could also be more exposed to damages from anchors or activities from the fishing industry. From the initial assessment, free spans exceeding a specified length or being defined as "active" in term of length are carried forward to the detailed assessment. Assessment of free spans can be performed to various degrees of complexity, usually requiring a significant amount of input, and the most advanced assessment requires detailed data and can be time consuming and costly.

- Passive (stationary) Free Span

  Passive spans are assessed for fatigue based on an on set criterion. The fatigue check is calibrated to be a safe first pass criterion using information available easily. The maximum allowable free span lengths for passive spans are categorized into 3 levels (see Table 3.3). Free spans less than a specified acceptable length are accepted and no further evaluations are required. When free spans exceeding a specified critical length are determined potential critical based on this conservative first pass check and should be assessed in more detail to assess its criticality.

Table 3.3. Freespan

Span Length	Action
$L < L_{accepable}$	No action, the free span is acceptable
$L_{accepable} < L < L_{potential\ critical}$	Wait and see, monitor the development of the span for the next years, and evaluate the span criticality. Inspection every year.
$L > L_{potential\ critical}$	The span is potential critical, and more detailed assessment is required immediately. Inspection is to be determined based on outcome of the assessment.

- Active (non stationary) Free span

  Active free spans are generally assessed in the same way as the passive free spans, but these free spans are characterized by the change of span length by time. The development of the free spans is usually very difficult to predict, and from surveys the span length seems to develop arbitrary. An active free span can develop due to erosion of the span shoulder and the span length gradually increases. As the length increases, the pipe will deflect more and more and finally the mid span will touch the bottom of the scour hole, and the span is split into two spans or more. The spans can completely vanish in a sort of self burial process due to movements of the soil. The development of active free spans should be assessed based on past inspections, to determine the most likely maximum length of the free spans and if the free spans are concentrated along some sections of the pipeline. In inspections, position and length of free span should be determined in a high degree of accuracy to be valuable for comparison between different inspection surveys.

3.1.2. Impact Factors in Kertih Pipeline

Impact or consequence or outcome is defined for understanding and quantifying potential consequence from a pipeline failure. Based on the probability of pipeline damages mentioned above, it can impact to assets loss due to interruption in production. In this case the impact factors can be classified as follows :

3.1.2.1. Economic Consequences

The economic consequence concerns with repair costs and business loss due to interruption in production.

- Repair Cost: the repair cost is divided into two parts, namely consequence for leak and consequence for burst. Also location of failure should be considered i.e. which is above water, splash zone or underwater. Repairs cost for one incident may cost 25 million dollars (Huebler, 2002).
- Business loss: related to the cost due to shutdown of the pipeline. The pipeline shutdown will push the gasoline prices to raise 3 to 5 cents a gallon as happened in Alaska (Isidore, 2006).

3.1.2.2. Safety Consequences

Safety consequence concerns with personnel injury or loss of life and the possible damage in products being transported.

- Transported product : various types of products such as gas, well fluid, semi processed or dry. Pipeline gas may potentially create an explosive mix if air make its way into the pipes and mixed with gas. Restoration of the gas flow must be controlled by the specialists (Sochi, 2007).
- Manning on Installation covers personnel injury or loss of life. In order to minimize risk of pipeline failure, the most instructive approach is to examine specific incidents and try to learn from the failure (Palmer, 2004).

3.1.2.3. Environmental Consequences

Environmental consequence concerns with the impact of various types of product releases to the environment and the how big the pipeline size may effect to the environment if an incident happened.

- Pollution: The release of substance to environment has to be considered. The release of toxic or harmful substances may alter environment conditions such as impact to fish stocks and bird life (Friedrich, 2007).
- Pipeline Size: Diameter of pipeline has to be considered. Larger diameter will release gases in a more prolonged time for a sustained rate. Small holes can cause leaks and produce dangerous clouds of gas. It can saturate the ground around the pipe and migrate along any conduit to other locations if gas escapes from a pipeline (Loth, 2004).

3.2. Kutai Basin Pipeline

A crude oil pipeline with the length of 533 km in Kutai Basin is studied. The pipeline network under study is 24 years old, with total daily production 34.000 barrels of liquids (18.000 net). The pipeline is classified into five pipeline stretches. Nine pipeline engineers are involved in discussion in Kertih. The list of factors is refined into major factors, and broken down into sub factors of probability and impact failure. The secondary data consists of history of the pipeline, characteristic of pipeline design and maintenance report. Essential data and characteristics of five types of pipelines chosen in Kutai Basin is given in Table 3.4.

Table 3.4. The Characteristic of Kutai Basin Pipeline

Pipeline ID	Product	Year Install	Material Pipe	OD (mm)	WT (mm)	ID (mm)	Length (km)	D.P (bar)
Pipeline 1	OIL	1984	5LX-52	203.2	12.7	177.8	0.4	100
Pipeline 2	OIL	1984	5LX-52	152.4	10.97	130.4	0.4	100
Pipeline 3	OIL	1984	5LX-52	101.6	8.56	84.5	0.4	100
Pipeline 4	OIL	1984	5LX-52	203.2	12.7	177.8	0.5	100
Pipeline 5	OIL	1984	5LX-52	101.6	8.56	84.5	0.5	100

The Kutai Basin consists of six fields, onshore and offshore: Serang, Kerindingan, Melahin, Santan field, Attaka, and Santan terminal. There are 17 platforms in this area in which some are manned and some are un-manned. Pipeline lay out of Kutai Basin pipeline is illustrated in figure 3.3 below:

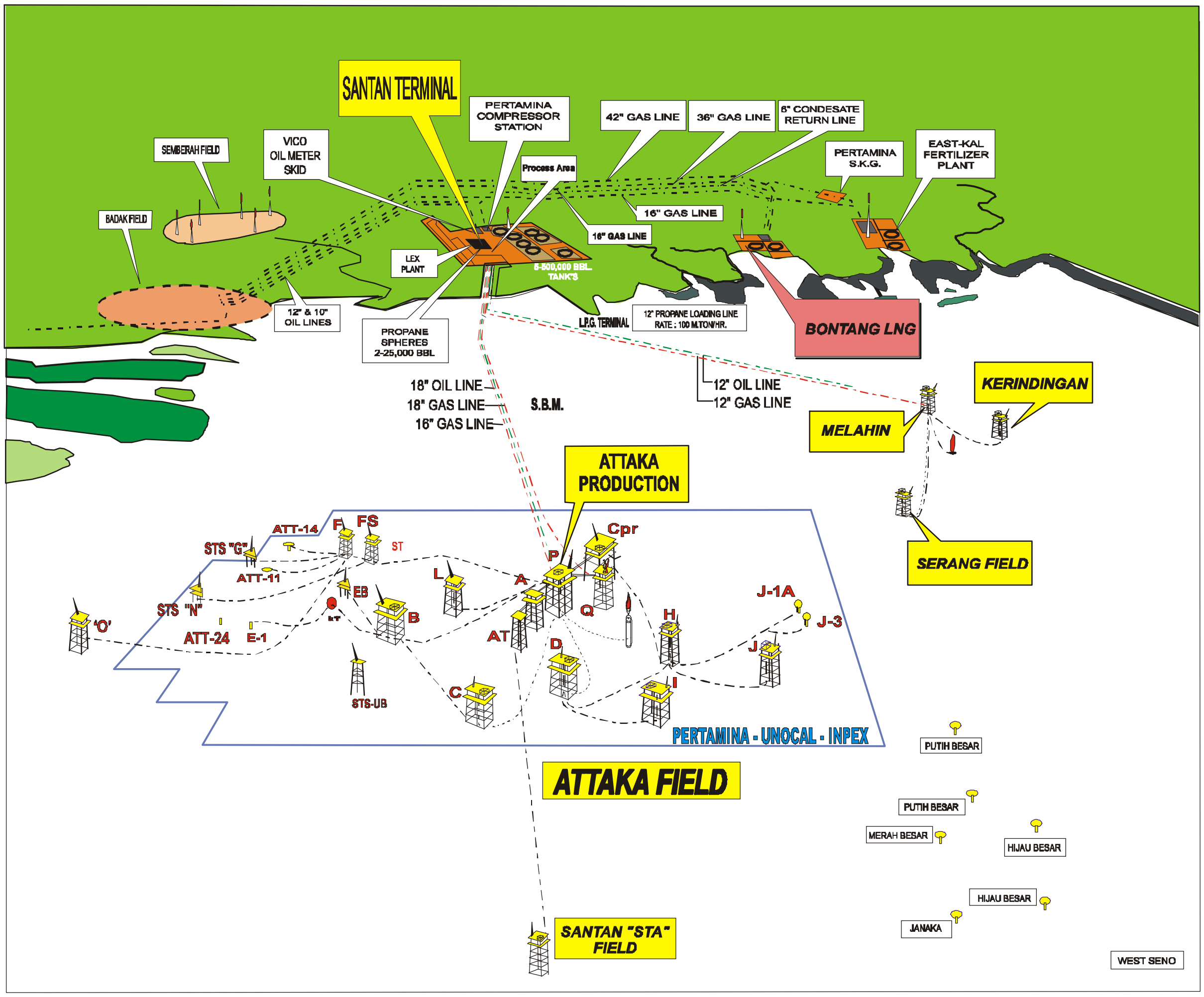

Figure 3.3. Pipeline lay out of Kutai Basin Pipeline

Pipelines are assessed under the basis of threat and consequences. Factors assessed as threats to pipeline are design factor, third party factor, system operation, and maintenance. Consequences are assessed based on the impact to business, environment and population. This basic of risk assessment is illustrated in Figure 3.4 below:

3.2.1. Factors Causing Probability of Failure in Kutai Basin Pipeline

In Kutai Basin, the factors of pipeline failure are further broken into four indexes, as shown in figure below :

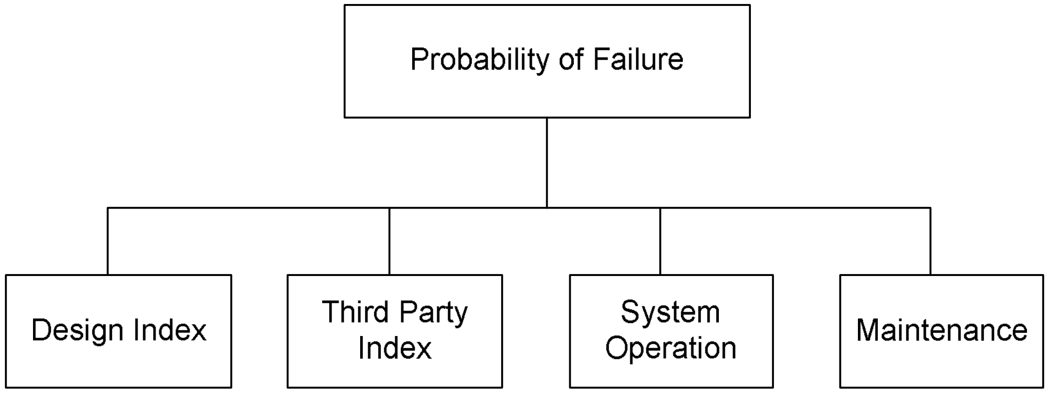

Figure 3.4. Probability of Failure in Kutai Basin

3.2.1.1. Design Index

Design index is the basis for pipeline design consisting of the basic requirements to functionality, so that the pipelines can be a medium of transport from one location to another. The basic requirements in design include :

- Age

  Offshore steel pipelines are normally designed for a life ranging from 10 to 40 years. In this area the maximum life time of pipelines is 33 years.

- Operating Pressure

  Operating pressure can be described as maximum operating pressure (MOP), maximum allowable operating pressure (MAOP), maximum permissible pressure and design pressure. They are often used interchangeably, and they all imply an internal pressure level that comforts with design intent and safety considerations, whether the latter stem from regulatory requirements, industrial standards or company internal policies.

3.2.1.2. Third Party Index

Third party index means accidental damage occurring to the pipe as a result of activities of personnel not associated with the pipeline. This failure mode is also sometimes called outside force or external force, but those descriptions would presumably include earth movements causing the damage.

- ROW Condition

  Right of way condition is a measure of the recognizability and inspectability of the pipeline corridor. A clearly marked, easily recognized ROW reduces the susceptibility of third party intrusions and aids in leak detection.
- Patrol Frequency

  Patrolling the pipeline is a proven effective method of reducing third-party intrusions. The frequency and effectiveness of the patrol should be considered in assessing the patrol value. Patrolling becomes more necessary where third-party activities are largely unreported.
- Above Pipeline Activity

  Above pipeline activity includes in the third party damage potential because the area of opportunity is strongly affected by the level of activity near the pipeline. More people in a pipeline area means more activities of fence building, gardening, water well construction, ditch digging, etc.

3.2.1.3. System Operation

The system operation concerns with the pipeline condition including cathodic protection, coating condition, metal loss defect, fluid properties and internal corrosion.

- Cathodic Protection

  Corrosion is another serious problem plaguing the industry. Corrosion is a sneaky enemy. Until it has caused obvious damage, corrosion is very difficult to detect and locate accurately. Metal pipe corrodes when water or other conditions in the ground create electrical differences between the pipe and the surrounding soil. Corrosion damage can take many forms, including pitting and cracking. A phenomenon called stress corrosion cracking is especially hard to detect and can be dangerous if left uncorrected. To minimize corrosion, pipeline companies install electrical devices called cathodic protection systems, which inhibit electrochemical reactions between the pipe and surrounding materials.
- Coating Condition

  Coating means to isolate the metal from the offending environment, it includes paint, tape wraps, waxes, asphalts and other specially designed coatings. Typical coating faults include cracking, pinholes, impacts (from sharp objects), compressive loadings (stacking of coated pipes, for instances), disbandment, softening or flowing and general deterioration (for example ultraviolet degradation).

- Metal Loss Defect

  Coupon (metal samples) can measure a corrosion rate placed near the pipe wall. From these measurements, actual corrosion on a pipeline can be inferred at least for the portions close to the measuring devices.

- Fluid Properties

  Properties of the transported fluid according to hazard potential are as defined bellow (DNV, 2003).

Table 3.5. Properties of Fluids

Properties of Fluids	
Category	Description
A	Typical non flammable water based fluids
B	Flammable and/or toxic substances which are liquids at ambient temperature and atmospheric pressure conditions for example methanol
C	Non flammable substances which are non toxic gases at ambient temperature and atmospheric pressure conditions, for example nitrogen, carbon dioxide, argon and air.
D	Non toxic, single phase natural gas
E	Flammable and or toxic fluids which are gasses at ambient temperature and atmospheric pressure conditions and which are conveyed as gases and or liquids.

- Internal Corrosion

  Internal corrosion in pipelines is influenced by temperature, CO_2, H_2S, water chemistry, flow velocity and surface condition of the steel. A small change in one of these parameters can change corrosion rate considerably, due to changes in the properties of the thin layer of corrosion products that accumulates on the steel surface.

3.2.1.4 Maintenance

Improper maintenance is a type of error that can occur at several levels in the operation. Lack of management attention to maintenance, incorrect maintenance requirements or procedures, and mistakes made during the actual maintenance activities are all errors that may directly or indirectly lead to pipeline failure.

- Pigging is chosen for the pipeline maintenance because pigging can clear construction of debris, remove rust, dirt and mill scale adds corrosion inhibitor.
- Debris may cause damage to the pipeline or external corrosion protection system. Small amounts of debris can be tolerated, but it is important to keep the construction free of debris. Debris can cause damage to the operation of the pipeline by blocking downstream filters, damaging pump impellers, jamming valves open.
- Corrosion Inhibitor is used to control corrosion, primarily in up stream pipelines carrying oil and gas from the wells to the processing plants.

3.2.2. Impact Factors in Kutai Basin Pipeline

The impact factors concern with the damage that may affect business, environment and population. The impacts of pipeline failure are determined by the following factors:

3.2.2.1. Impact to Business

Impact to business here covers sales line, redundancy line, oil flow and volume of the pipeline.

- Sales Line here means type of line, whether flow line or export line. Flow line means transporting oil or gas from satellite sub sea wells to sub sea manifolds and production facility platforms. Export pipeline means transporting oil or gas from production facility platform to beach for further processing. The damage of export pipeline may cause millions of dollars to retrieve (Frans et all., 2004).
- Redundancy Line whether the pipeline has back up line or not such as storage facilities. It may cause the shutdown of pipeline for two days and the project cost to construct the additional capacity is approximately $27 million (Lowery, 2001).

- Oil Flow is one of the important parts of the production profiles. Any disturbance to this profile will make huge impact to business aspect. Consistency of these oil flow line needs to be maintained. Any errors on this line will cause financial loss due to shutdown the pipeline. As in Brazil, the oil flow was uncontrolled due to human and mechanical errors and it cost $ 100 million for recovery (U.S. Chemical, 2002).
- Volume refers to the volume of pipe or the pipeline capacity. High capacity pipeline may have considerable market power by requiring a minimum batch size. As examples for 30” diameter crude line TransCanada pipeline cost of $1.7 billion. Mardi Gas Pipeline construct 16” and 28” diameter segments cost $1 billion (Hull, 2005).

3.2.2.2. Impact to Environment : Property Damage

The impact to environment will be considered upon the possibility of property damage around pipeline area, such as degradation of landscape, sediment dispersion, and degradation of corrosion protection. This activity must be taken seriously because it lies down general obligation of the states to notify and consult a significant adverse environmental impact across boundaries (UNECE, 1999).

3.2.2.3. Impact to Population : Population Class

Impact to the population class around pipelines will be higher if levels of activities of the people also become higher. As defined by Department of Transportation (DOT, 2008):

1. A Class 1 population is an offshore area.
2. A Class 2 population is low activity level or location unit that has more than 10 but fewer than 46 buildings intended for human occupancy.
3. A Class 3 population is medium activity level or location unit that has 46 or more buildings intended for human occupancy.
4. A Class 4 population is high activity level or location unit where buildings with four or more stories above ground are prevalent.

3.3. Moderation of Pipeline Risk Failure in Indonesia & Malaysia

The pipeline risk failures commonly have similar causes and impact in every pipeline area. Eventhough sometimes the term is different, usually the definition is similar. Regarding the risk failure from pipeline industries as explained above, it can be put into moderation as follows:

a. Probability of Failure

b. Consequence of Failure

Table 3.6. Moderation of Probability of Failure

Pipeline Area	Years	Researchers	Factor	Sub Factors
Indonesia & Malaysia	2008	Silvianita, et all.	1. Internal Corrosion	1.1. Fluid Composition
				1.2. Improper Chemical
			2. External Corrosion	2.1. Damage Coating
				2.2. Damage Anodes
				2.3. Metal Loss Defect
			3. Internal Erosion	3.1. Flow Characteristic
				3.2. Operating Pressure
			4. External Impacts	4.1. Impact from Dropped Objects
				4.2. Fish Bombing
			5. On Bottom Stability	5.1. Seabed Movement
				5.2. Loss of Weight Coating
			6. Free span	6.1. Seabed Scouring 6.2. Pipeline On Bottom Instability 6.3. Seabed Undulations

Table 3.7. Moderation of Consequence of Failure

Pipeline Area	Years	Researchers	Factor	Sub Factors
Indonesia & Malaysia	2008	Silvianita, et all.	1. Economic	1.1. Repair Cost
				1.2. Business Loss
			2. Safety	2.1. Loss of Life
				2.2. Loss of Properties
				2.3. Metal Loss Defect
			3. Environment	3.1. Pollution
				3.2. Oil Spill

The failure characteristics of various pipeline areas have also been studied by some researchers from India, Thailand and Saudi Arabia. Here is the failure characteristic:

Table 3.8. Failure Characteristic of Various Pipeline Areas

Pipeline Area	Years	Researchers	Factor	Sub Factors
India	2003	Dey	1. Corrosion	1.1. External Corrosion
				1.2. Internal Corrosion
			2. External Interference	2.1. Third Party Activities
				2.2. Pilferage
			3. Construction and Materials Defect	3.1. Construction Defect
				3.2. Poor Materials
			4. Natural Hazards	4.1. Earthquake
				4.2. Floods
			5. Others	5.1. Human Error
				5.2. Operational Error
Thailand	2004	Dey, Ogunlana and Naksuksakul	1. Corrosion	1.1. External Corrosion
				1.2. Internal Corrosion
			2. External Influence	2.1. Third Party Activities
				2.2. Free span
			3. Construction and Materials Defect	3.1. Poor Construction
				3.2. Low Grade Material
			4. Error	4.1. Human Error
				4.2. Operational Error
			5. Other	Natural Hazard
Saudi Arabia	2005	Khalil, Assaf and Anazi	1. Corrosion	1.1. External Corrosion
				1.2. Internal Corrosion
			2. External Interference	2.1. Sabotage
				2.2. Other
			3. Structural Defect	3.1. Construction Defect
				3.2. Materials Defect
			4. Mid wall Defect	4.1. Stress Corrosion Cracking
				4.2. Hydrogen induced Cracking
			5. Operational Problems	5.1. Human Error
				5.2. Operational Error
			6. Loss of Ground	-
			7. Other	-

Table 3.9. Consequence of Pipeline of Various Pipeline Areas

Pipeline Area	Years	Researchers	Factor	Sub Factors
Thailand	2004	Dey, Ogunlana and Naksuksakul	1. Economic Loss	1.1. Total Amount of Reserve
				1.2. Operation/flow rate
				1.3. Possible product loss
				1.4. Function
				1.5. Other
			2. Environment and Social Effects	2.1. Severity to Ecology
				2.2. Severity to People
				2.3. Quantity of Leak
				2.4. Affected Area
Texas	2006	Isidore	1. Economic Loss	1.1. Repair and Replace Pipeline
				1.2. Product Loss
			2. Safety	2.1. Loss of Life
				2.2. People Injured

From both Table 3.8 and 3.9 it can be summarized than the risks of pipeline failure gathering from both pipeline industry in Indonesia and Malaysia have been consistent from the literature review. The other researchers have determined the probability of pipeline failure in Thailand, India and Saudi Arabia. Generally the probability factors of failure are similar eventhough sometimes stated in different term. The moderation factors of probability of failure are corrosion, external impacts, defect construction, natural hazards and others. Corrosion always becomes major factor that causes probability of pipeline failure in various pipeline areas.

The pipeline failure would bring impact or consequence due to interruption in production. Impact of pipeline failure is magnitude of potential loss or consequence of an event. The consequence of failure always involves three factors namely economy impact, environment impact and safety impact. The highest factor of consequence of failure always involves the economic loss, whether for repair and replacement costs of pipeline or business loss due to interruption in production.

CHAPTER 4
RESEARCH METHODOLOGY

4.1. Introduction

Research methodology is usually defined as a process of investigation that leads to obtain reliable results. In general these are three categories of a research methodology for example qualitative, quantitative and triangulation. For the purpose of achieving the objectives of this research study that is aimed on knowledge acquisition, therefore a quantitative approach is adopted that involved the main process of sample survey with the help of questionnaires and interviews from experienced pipeline engineers associated with the selected sites.

4.2. Methodological Approach

Probabilities of pipeline system failure are determined by the construction of Analytical Hierarchy Process (AHP). The AHP model consists of various hierarchical levels. The first level referred to the goal, which is the determination of the probabilities of failure, where as the lowest level is the formulation of inspection and maintenance plans for pipeline system under consideration. The intermediate levels are the components those are related to the causes of failure and hence influence the determination of the goal.

For this study a member of factors that could cause the causes of failure for the two pipelines systems ie the Kertih West Malaysia network and the Kutai Basin, Indonesia are obtained by filling in the survey questionnaire and interviewing the senior pipeline engineers associated with the selected sites. The factors are categorized as major factors and each of the major factors is further categorized as sub factors. According to AHP that the elements of each level of the hierarchy are required to be compared in pairs, which is performed using the Expert Choice software.

4.2.1. Analytic Hierarchy Process

For the development of an AHP model these are three basic activities, which are:

i. The first activity involved the construction of hierarchy. In order to develop hierarchies, it is essentials the essential relevant details must be included.

ii. The second activity involved evaluation of hierarchy that is built as activity, for this purpose Expert Choice software is used. This comparison is intended to determine how much various elements are related to each other and to what extent the particular level influences the elements of the next higher level, therefore, it can be used to calculate the relative strength of the impact of the element in the lower level on the overall hierarchy.

iii. In the final activity sensitivity analysis is performed.

4.3. Flowchart Applying to the Pipeline Calculation

The overall process is illustrated in Figure 4.1 in the form of flowchart.

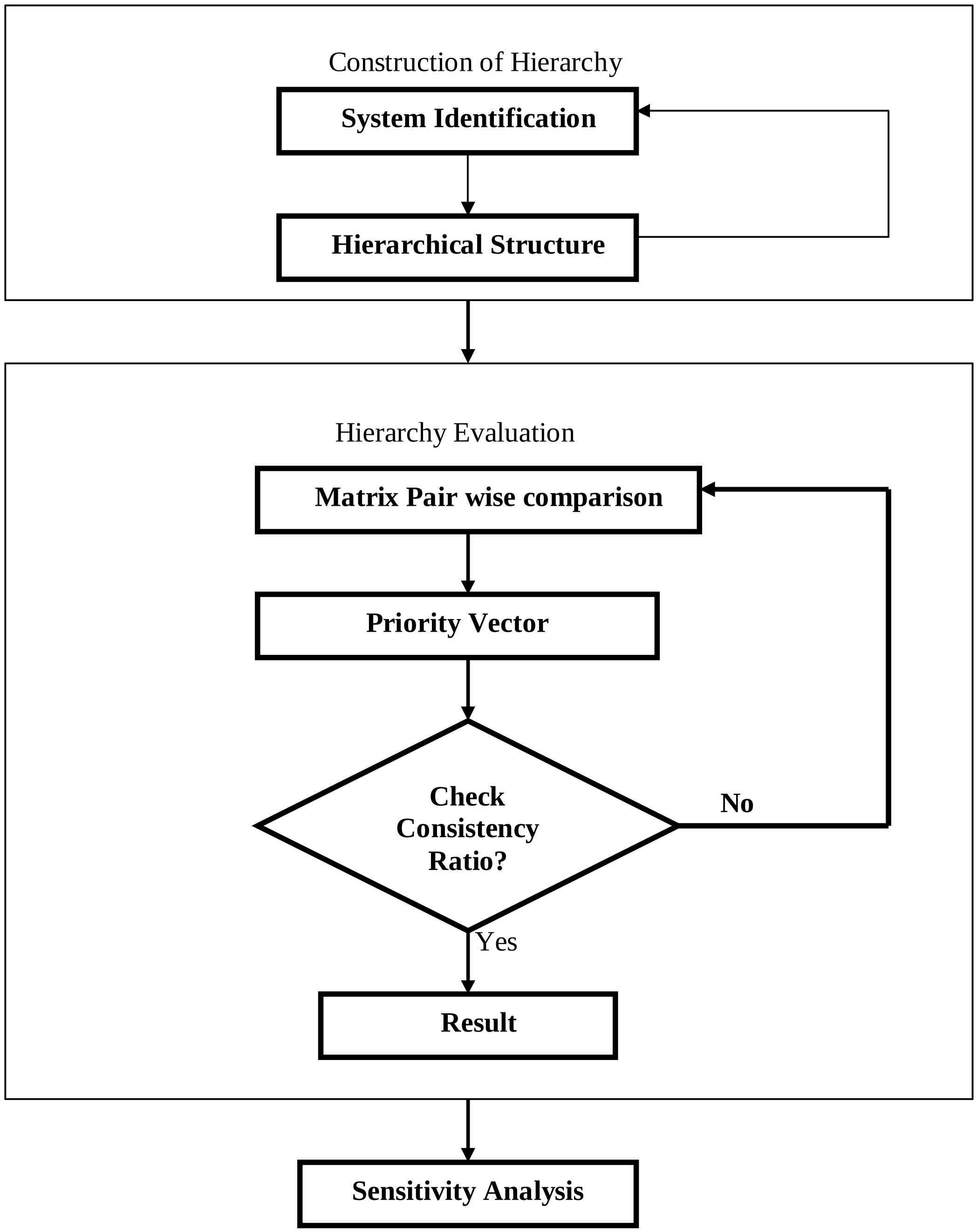

Figure 4.1. Flowchart of AHP

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Here are the steps of applying Analytic Hierarchy Process;

a. Construction of Hierarchy

Construction of hierarchy in AHP is starting with system identification and hierarchical structure. Here are the definitions of each step;

1. System Identification

   The first step to applying AHP is by identification the system. In this framework the information is gathered to develop the hierarchy. The information may consist of primary data and secondary data of the system under study. The primary data is involved the decision maker to make the judgments. And the secondary data can be the history, report of the system under study.

2. Hierarchical Structure

   Based on the system identification, the information can be constructing to a hierarchy. The hierarchy of AHP usually involved four levels;

   i. First level is the goal that need to be achieved
   ii. Second level is the criteria of the factor to enable the goal to be achieved
   iii. Third level is the sub factor of the factor in the previous level
   iv. Fourth level is the alternatives of the pipeline under study.

b. Hierarchy Evaluation

Hierarchy evaluations consists with calculation of matrix pair wise comparison, priority vector completed with the consistency ratio then investigate the result with the sensitivity analysis. Here are the definitions for each step;

1. Matrix Pair Wise Comparison

   The judgments of the relative importance of the elements with respect to the overall goal of prioritizing the pipeline maintenance are made. The judgment is made on numerical scale ranging from 1 to 9 (Table 2.1.). Elements at each level of hierarchy are compared with each other in pairs with their respective parents in the next higher level. For example, for comparing the factors between internal corrosion and external corrosion, a judgment level is chosen as 4 which means that the internal corrosion is 4 times (moderately to strongly) more important than the external corrosion. The same procedure is repeated for both Kertih and Kutai Basin pipeline in each level of the hierarchy. Here is the example :

For both factors below, which one do you think has higher probability of pipeline failure?

absolute ← equivalent → absolute

I.Corrosion	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	E.Corrosion

Process pair wise comparison is used for making judgments regarding the relative importance of the elements in each level with respect to the higher level of the hierarchy, using the AHP pair wise comparison scale, as given in table 4.1. below:

Table 4.1. Matrix Pairwise Comparison Respect to Goal of Kertih Pipeline

Factors	Internal Corrosion	External Corrosion	Internal Erosion	External Impacts	On Bottom Stability	Free span
Internal Corrosion	1	4	5	4	3	3
External Corrosion	1/4	1	1/2	1/3	3	2
Internal Erosion	1/5	2	1	3	2	3
External Impacts	¼	3	1/3	1	2	2
On Bottom Stability	1/3	1/3	1/2	½	1	½
Free span	1/3	1/2	1/3	½	2	1
Total	2.37	10.83	7.67	9.33	13.00	11.50

From the table 4.1 above an n x n matrix is a square matrix, because n is the number of rows and columns, in this level n is 6. An element is equally important when compared to itself therefore the main diagonal must be 1. The reverse comparisons produce the reciprocal of the basic comparison this is called a reciprocal matrix. The next step is normalized the matrix by dividing each value by the column sum. For example:

- First column and first row for internal corrosion, the normalization is come from the value 1 divided by the total value 2.37 then the result is $\frac{1}{2.37} = 0.423$
- Second column and first row for external corrosion, the same way the normalizing is come from the value 4 divided by the total value 10.83 then the result is $\frac{4}{10.83} = 0.3697$

- First column and second row for internal corrosion the normalizing is come from the value ¼ divided by the total value 2.37 then the result is $\frac{1/4}{2.37} = 0.106$

The same procedure of calculation is repeated for the whole factors as summarized in table 4.2.

Table 4.2. Normalize Matrix Respect to Goal of Kertih Pipeline

Factors	Internal Corrosion	External Corrosion	Internal Erosion	External Impacts	On Bottom Stability	Free span	Total
Internal Corrosion	0.423	0.3697	0.652	0.429	0.231	0.261	2.502
External Corrosion	0.106	0.092	0.065	0.036	0.231	0.174	0.642
Internal Erosion	0.085	0.185	0.130	0.321	0.154	0.261	1.146
External Impacts	0.106	0.277	0.043	0.107	0.154	0.174	0.828
On Bottom Stability	0.141	0.031	0.065	0.054	0.077	0.043	0.402
Free span	0.141	0.046	0.043	0.054	0.154	0.087	0.525
Total							6.889

2. Priority Vector

Next step is calculate the synthesis by multiplying the vectors of priority by the weight of the criteria, and taking the sum over all weighted priority entries corresponding to those in the next lower level, and so on. In table 4.2 it can obtain that internal corrosion is the highest with 41.7%. These are the priority vector of the criteria;

- Internal Corrosion : 2.502 / 6 = 0.417
- External Corrosion : 0.642 / 6 = 0.107
- Internal Erosion : 1.146 / 6 = 0.191
- External Impacts : 0.828 / 6 = 0.138
- On Bottom Stability : 0.402/ 6 = 0.067
- Free span : 0.525 / 6 = 0.081

3. Check Consistency Ratio

Measuring Consistency

The AHP provides a theory for checking the inconsistency throughout the matrix, first to compute $Axw = \lambda w$, then find the eigen vector and it will get $\lambda_{\max}$;

$$\begin{pmatrix} 1 & 4 & 5 & 4 & 3 & 3 \\ 0.25 & 1 & 0.5 & 0.33 & 3 & 2 \\ 0.2 & 2 & 1 & 3 & 2 & 3 \\ 0.25 & 3 & 0.33 & 1 & 2 & 2 \\ 0.33 & 0.33 & 0.5 & 0.5 & 1 & 0.5 \\ 0.33 & 0.5 & 0.33 & 0.5 & 2 & 1 \end{pmatrix} \text{x} \begin{pmatrix} 0.417 \\ 0.107 \\ 0.191 \\ 0.138 \\ 0.067 \\ 0.081 \end{pmatrix} = \begin{pmatrix} 2.851 \\ 0.739 \\ 1.332 \\ 0.968 \\ 0.449 \\ 0.549 \end{pmatrix}$$

Eigen Vector

$$\begin{pmatrix} 2.851 \\ 0.739 \\ 1.332 \\ 0.968 \\ 0.449 \\ 0.549 \end{pmatrix} : \begin{pmatrix} 0.417 \\ 0.107 \\ 0.191 \\ 0.138 \\ 0.067 \\ 0.081 \end{pmatrix} = (6.837 ; 6.906 ; 6.974 ; 7.014 ; 6.701 ; 6.778)$$

$$\lambda_{\max} = \frac{6.837 + 6.906 + 6.974 + 7.014 + 6.701 + 6.778}{6} = 6.685$$

After find the $\lambda_{\max}$ = 6.685 then calculate the consistency index (CI), with n = 6.

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

= (6.685 – 6) / (6-1)

= 0.137

To find the Consistency Ratio (CR), must know the random index for n = 6 is 1.24 (refer table 2.2).

CR $= \frac{CI}{RI}$

CR $= \frac{0.137}{1.24}$

= 0.11 (The CR $\leq$ 0.1 indicates sufficient consistency)

4. Result

Based on the calculation above, then it can be summarized the priority of each factor below;

Table 4.3. Comparison of Factors With Respect To Goal of Kertih Pipeline

Factors	Internal Corrosion	External Corrosion	Internal Erosion	External Impacts	On Bottom Stability	Free span	Priority
Internal Corrosion	1	4	5	4	3	3	0.417
External Corrosion	1/4	1	1/2	1/3	3	2	0.107
Internal Erosion	1/5	2	1	3	2	3	0.191
External Impacts	¼	3	1/3	1	2	2	0.138
On Bottom Stability	1/3	1/3	1/2	½	1	½	0.067
Free span	1/3	1/2	1/3	½	2	1	0.081
Consistency Index : 0.137							
Random Index : 1.24							
Consistency Ratio : 0.11							

c. Sensitivity Analysis

Doing the sensitivity analysis, the highest priority is investigated to see how sensitive the parameter of pipeline risk failure. Based on calculation above the highest factor is internal corrosion, here are the sensitivity graphs from the Expert Choice software.

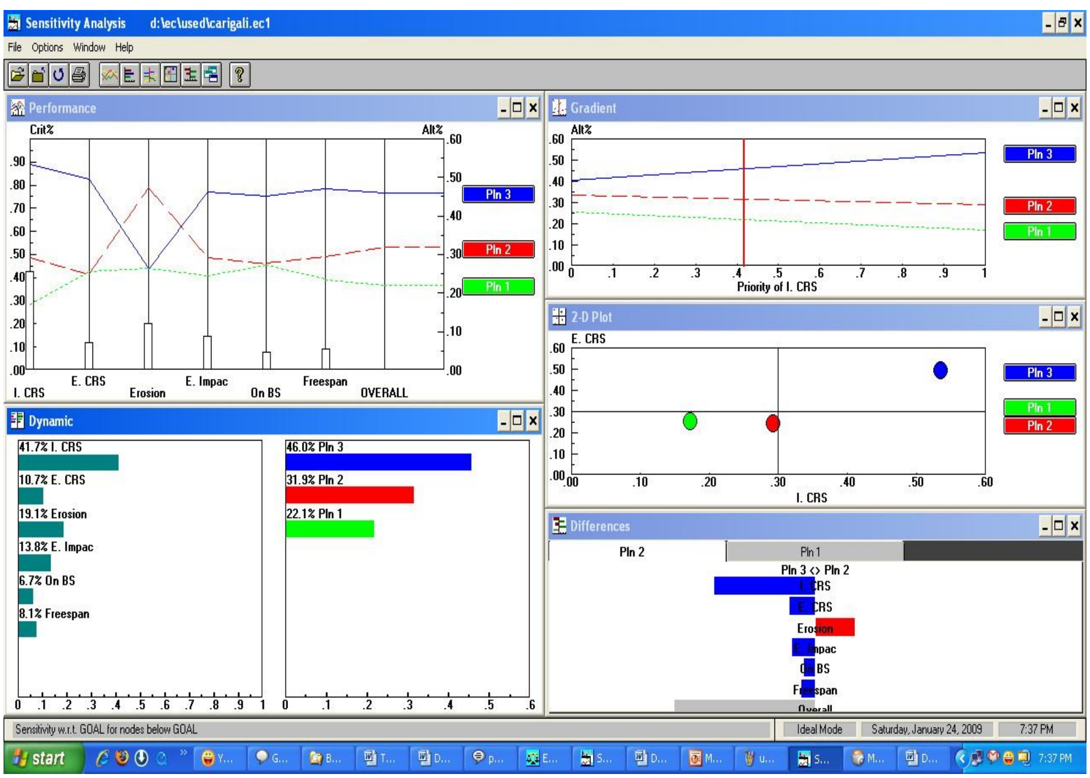

Figure 4.2. Sensitivity Graphs for Internal Corrosion

Then to do the sensitivity analysis some scenarios is applied. The priority of internal corrosion is changed from 41.7 % became 36.7%, 31.7%, 46.4 % and 51.8% by changes the judgments.

Table 4.4. Sensitivity Scenario PoF Kertih Pipeline

Scenario	Weight of Priority (%)				Sensitivity (%)		
	I. Corrosion	PLN 1	PLN 2	PLN 3	PLN 1	PLN 2	PLN 3
- 10%	31.7	22.9	32.3	44.8	3.69	1.26	2.58
- 5%	36.7	22.5	32.1	45.4	1.84	0.63	1.29
Original	41.7	21.7	31.7	46.6	-	-	-
5%	46.4	21.7	31.7	46.6	1.07	0.63	1.38
10%	51.8	21.3	31.4	47.3	2.36	1.26	3.23

Here are the sensitivity graphs for internal corrosion as change scenario:

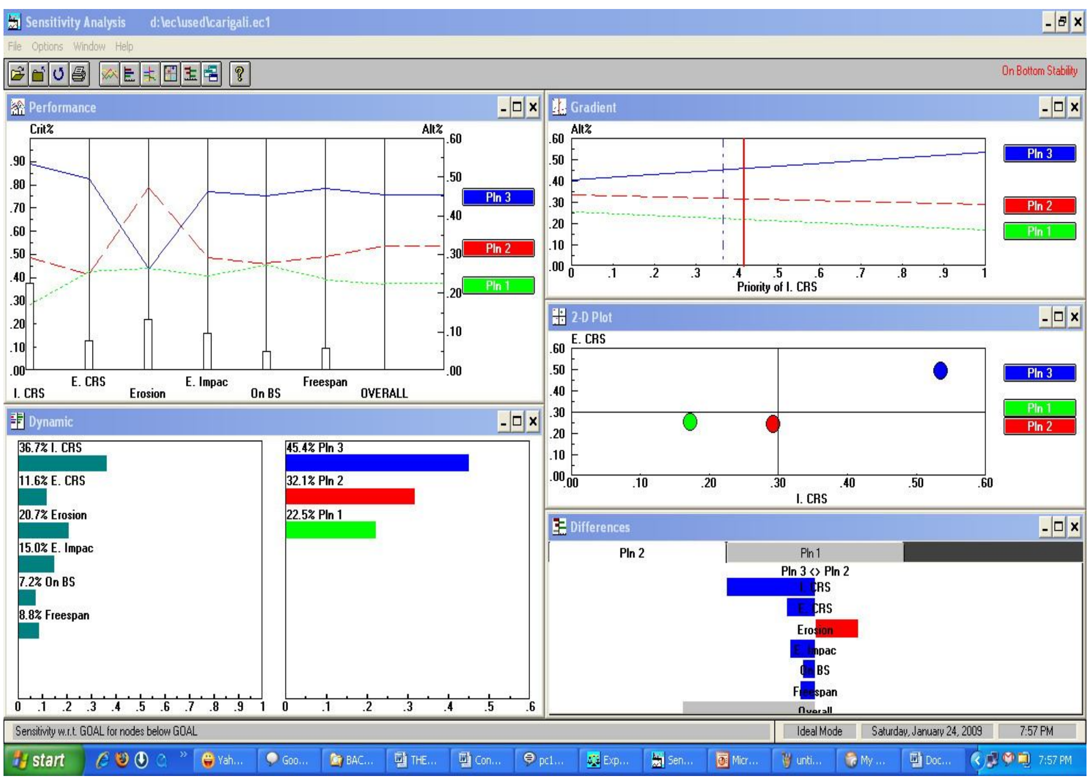

Figure 4.3. Sensitivity Graphs with -5% scenario changes for Internal Corrosion

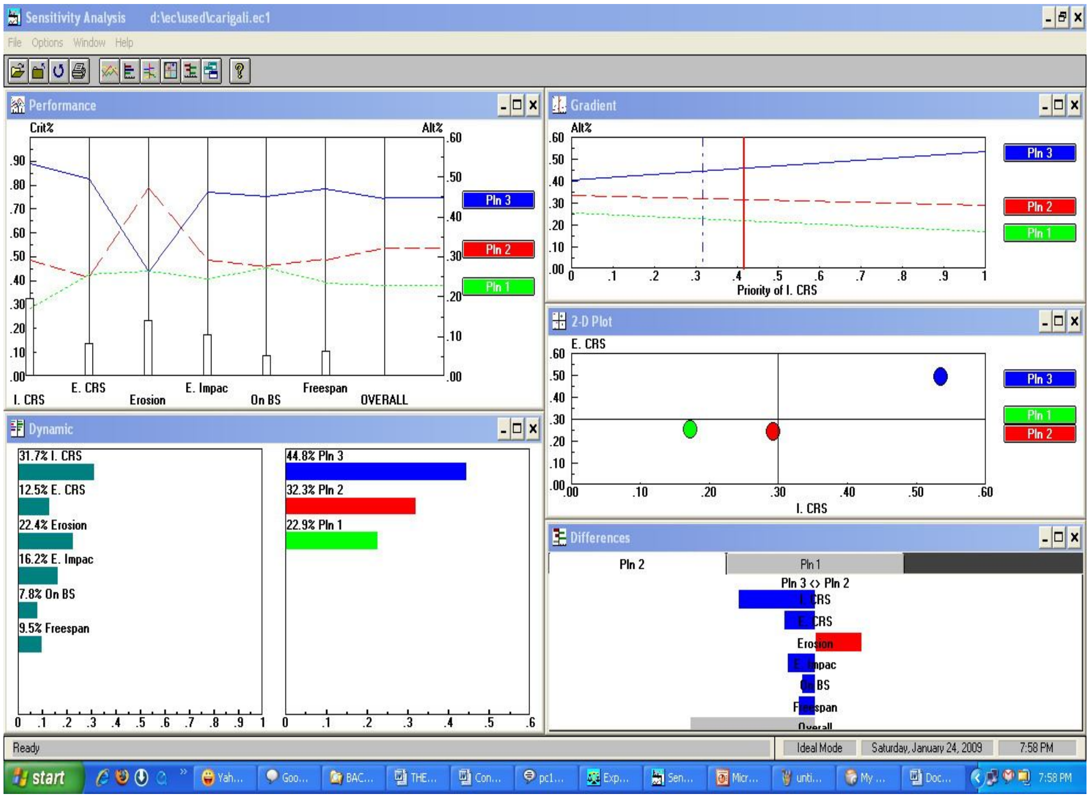

Figure 4.4. Sensitivity Graphs with -10% scenario changes for Internal Corrosion

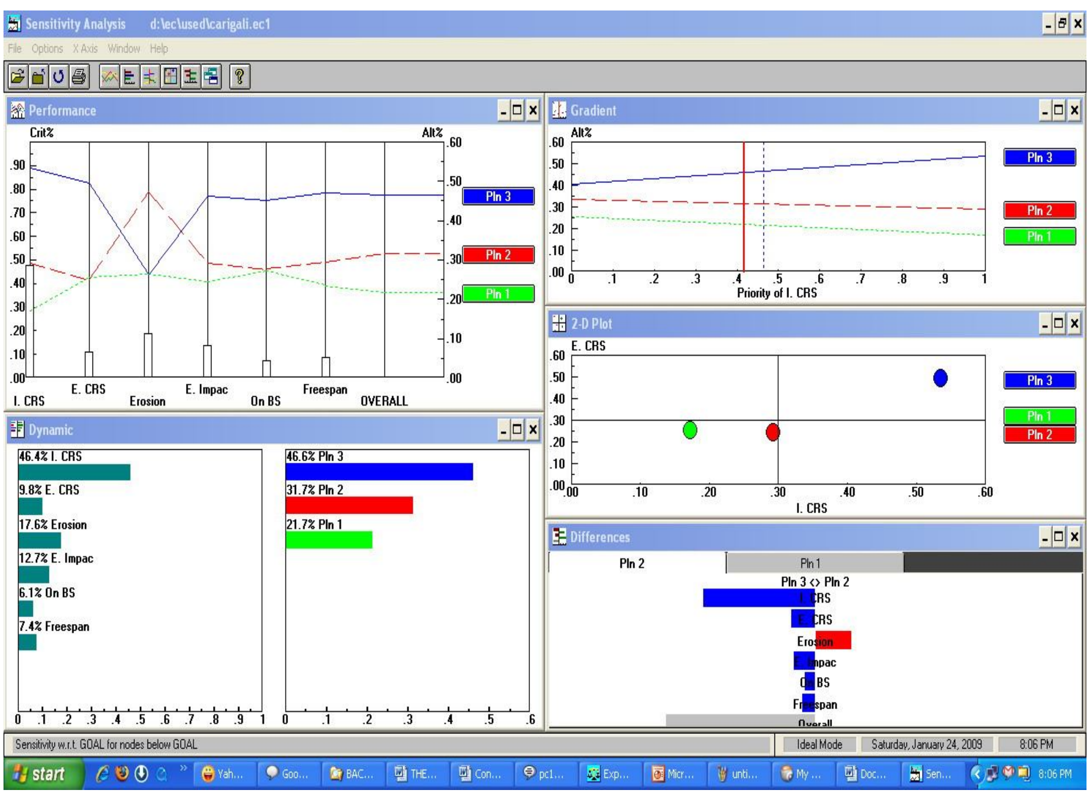

Figure 4.5. Sensitivity Graphs with 5% scenario changes for Internal Corrosion

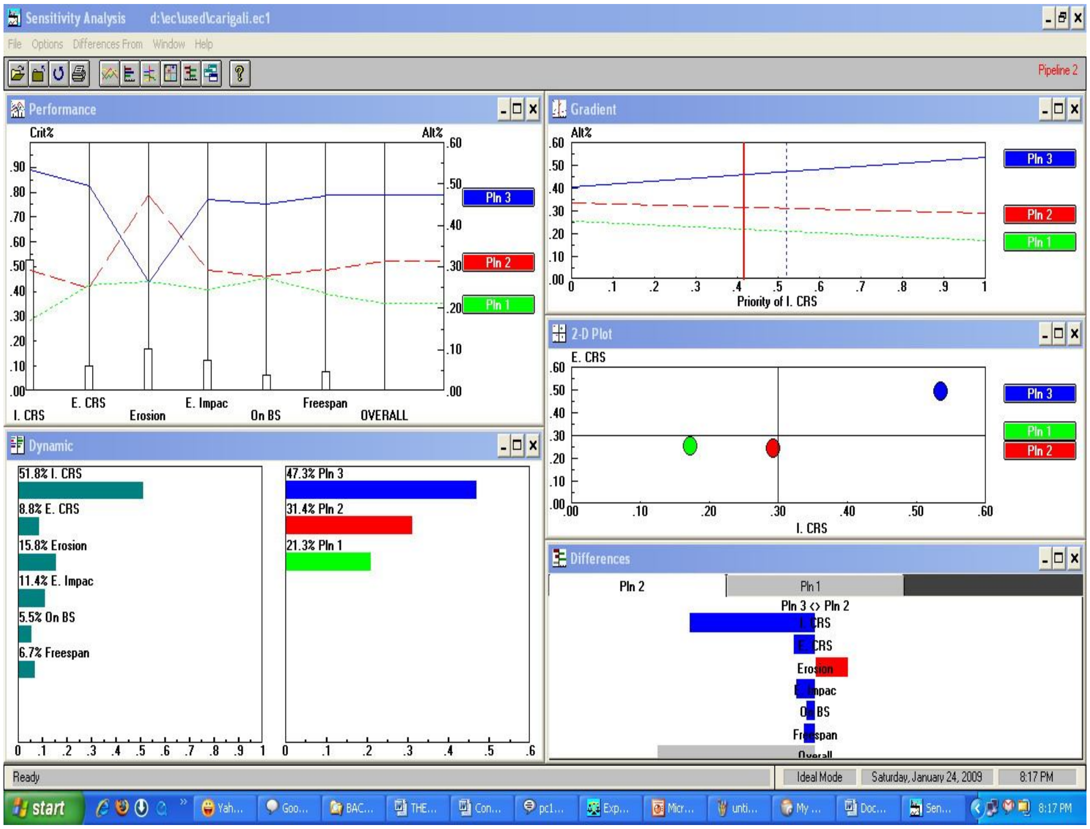

Figure 4.6. Sensitivity Graphs with 10% scenario changes for Internal Corrosion

4.4. Hierarchical Structure

Hierarchical structure is constructed based on the primary and secondary data from each pipeline as explained in previous sentences. Hierarchical structure is function as the initial of Analytic Hierarchy Process evaluation.

4.4.1. Kertih Pipeline

The Analytical Hierarchy Process (AHP) is developed to identify the probability of pipeline failure. The hierarchical structure of probability consist of four levels which are level-1 the goal, level-2 criteria (risk factors), level-3 sub-factors and level-4 alternatives, this structure is illustrated in figure 4.7.

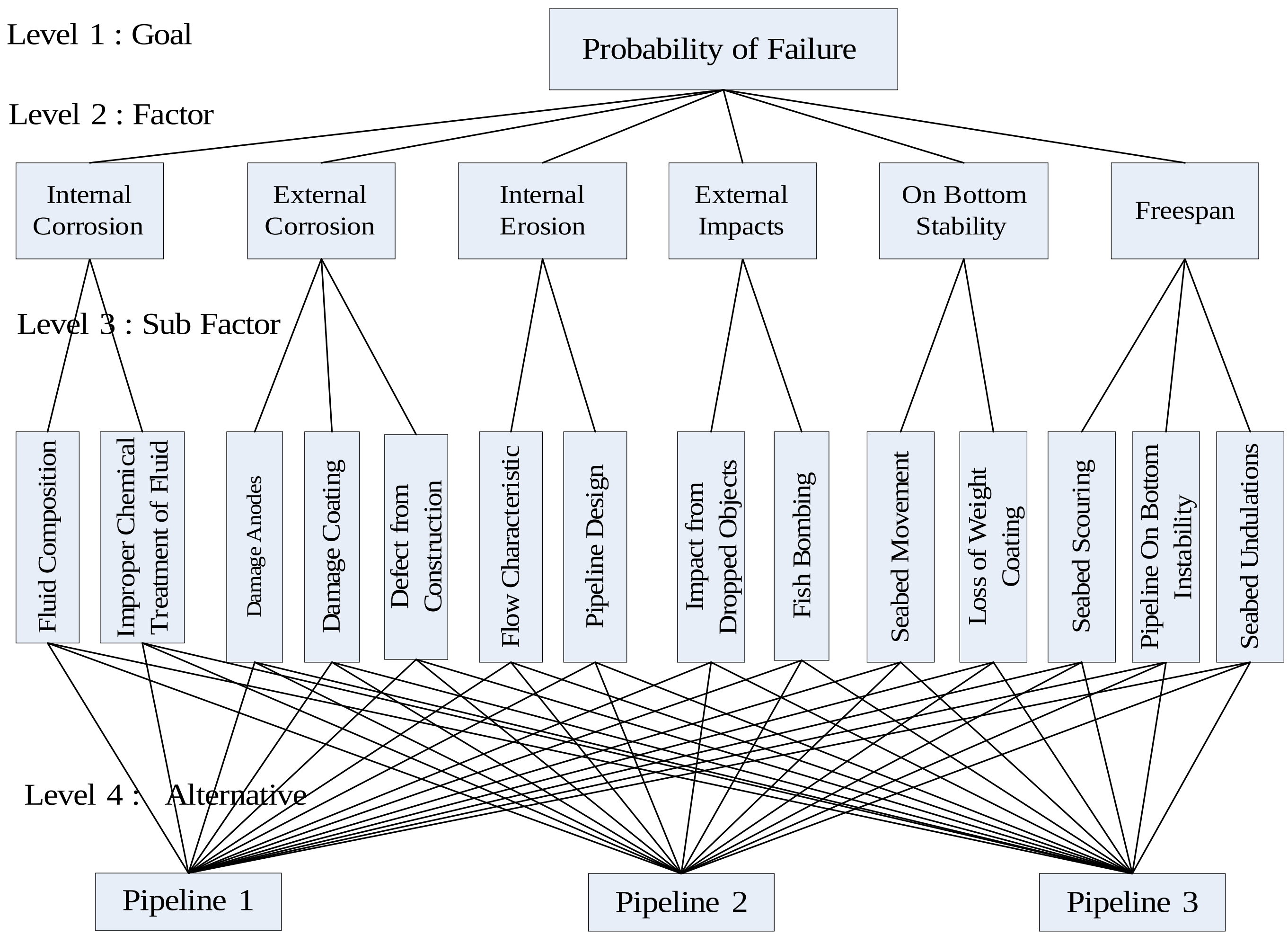

Figure 4.7. AHP Framework for Probability of Failure (PoF) for Kertih Pipeline

After determining the probability of pipeline failure, the next step is to determine the consequence of failure (CoF), which can identify the impact on a range of stakeholders and the assets. The Analytical Hierarchy Process (AHP) structure also developed to identify the consequence of pipeline failure which is illustrated in Figure 4.8.

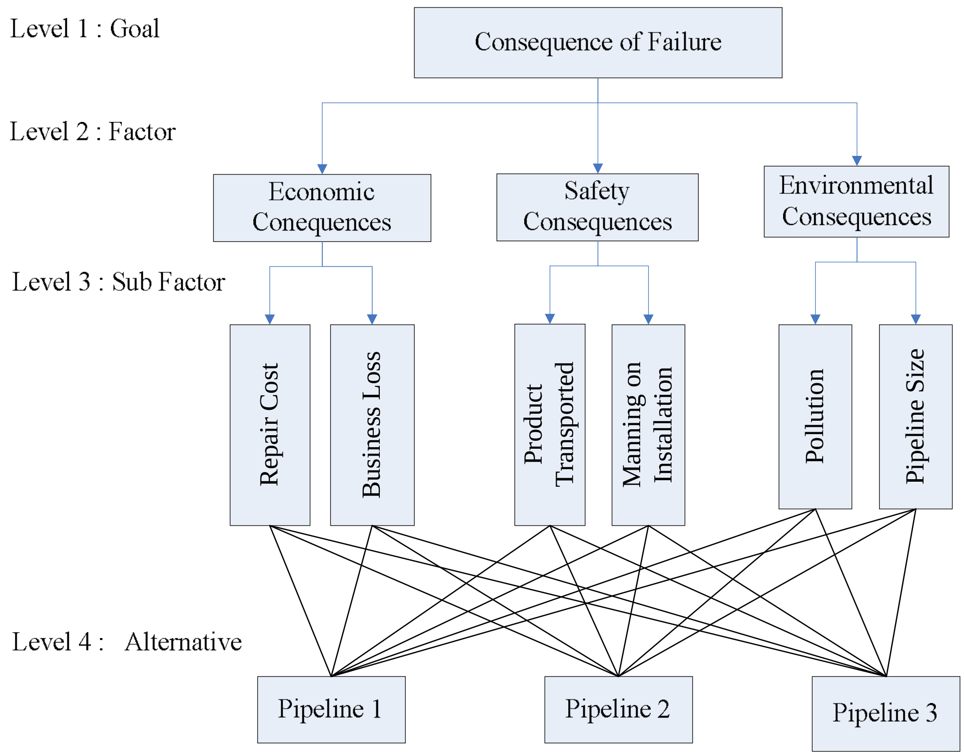

Figure 4.8. AHP Framework for Consequence of Failure (CoF) for Kertih Pipeline

4.4.2. Kutai Basin Pipeline

A multi criteria problem is defined to find out the probability and consequence of pipeline failure. AHP framework for probability of failure (PoF) and the consequence of failure (CoF) for Kutai Basin, Indonesia are illustrated in figure 4.9 and figure 4.10 respectively.

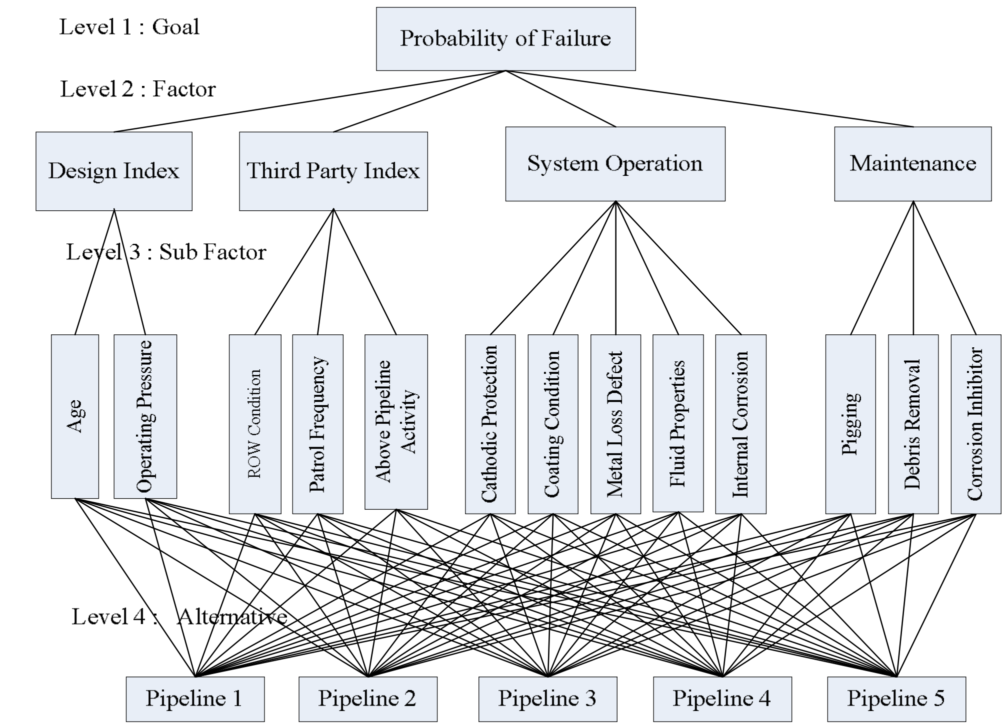

Figure 4.9. AHP Framework for Probability of Failure (PoF) for Kutai Basin Pipeline.

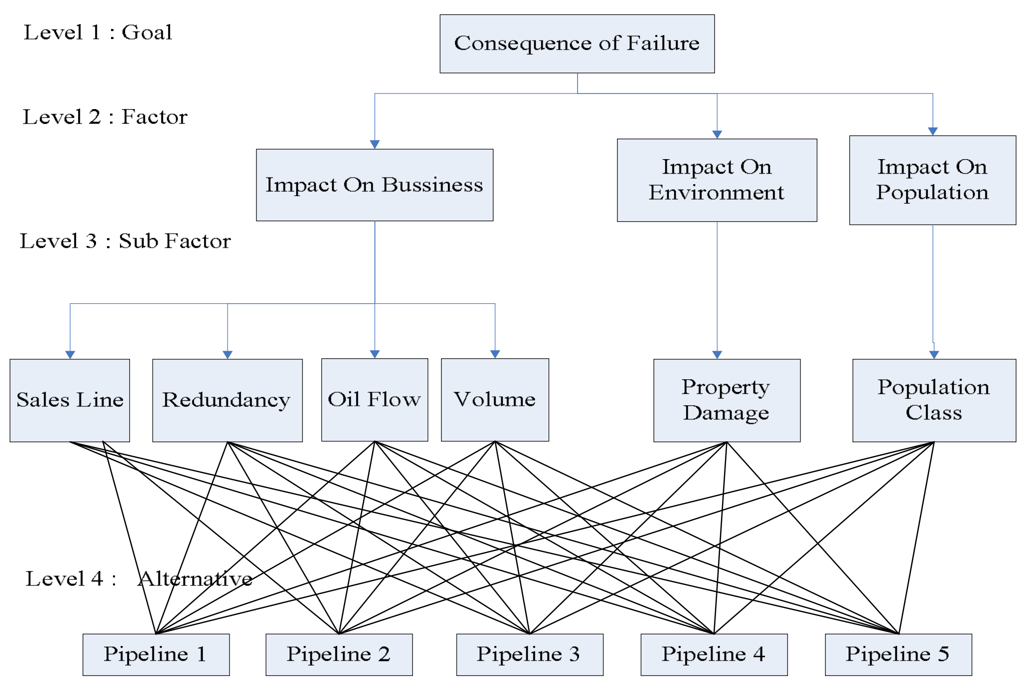

Figure 4.10. AHP Framework for Consequence of Failure (CoF) for Kutai Basin Pipeline

4.5. Comparative Analysis

Since this research involved both pipeline industry in Indonesia and Malaysia then the next analysis is comparing the factor of risk pipeline failure. By comparing both factors in each pipeline area then the moderation factor of risk pipeline failure can be determined. The risks of pipeline failure are divided into two parts;

4.5.1 Comparative Analysis for Probability of Pipeline Failure

Probability is degree of belief of an event that causes a loss occurring in a specified future period. Understanding the factors that may lead to probability of pipeline failure would be important to maximize the pipeline operation.

Table 4.5. Summary of Probability of Pipeline Failure in Kertih and Kutai Basin

Factor Causes the Probability of Pipeline Failure				
No	Kertih Pipelines		Kutai Basin Pipelines	
1.	Internal Corrosion	a. Fluid Composition b. Improper Chemical	Design Index	a. Age Operating Pressure
2.	External Corrosion	a. Damage Anodes b. Damage Coating c. Defect from Construction	Third Party Index	a. ROW Condition b. Patrol Frequency c. Above Pipeline Activity
3.	Internal Erosion	a. Flow Characteristic b. Pipeline Design	System Operation	a. Cathodic Protection b. Coating Condition c. Metal Loss Defect d. Fluid Properties e. Internal Corrosion
4.	External Impacts	a. Fish Bombing b. Impact from Dropped Objects	Maintenance	a. Pigging b. Debris Removal c. Corrosion Inhibitor
5.	On Bottom Stability	a. Seabed Movement b. Loss of Weight Coating	-	-
6.	Free span	a. Seabed Scouring b. Pipeline On Bottom Instability c. Seabed Undulations	-	-

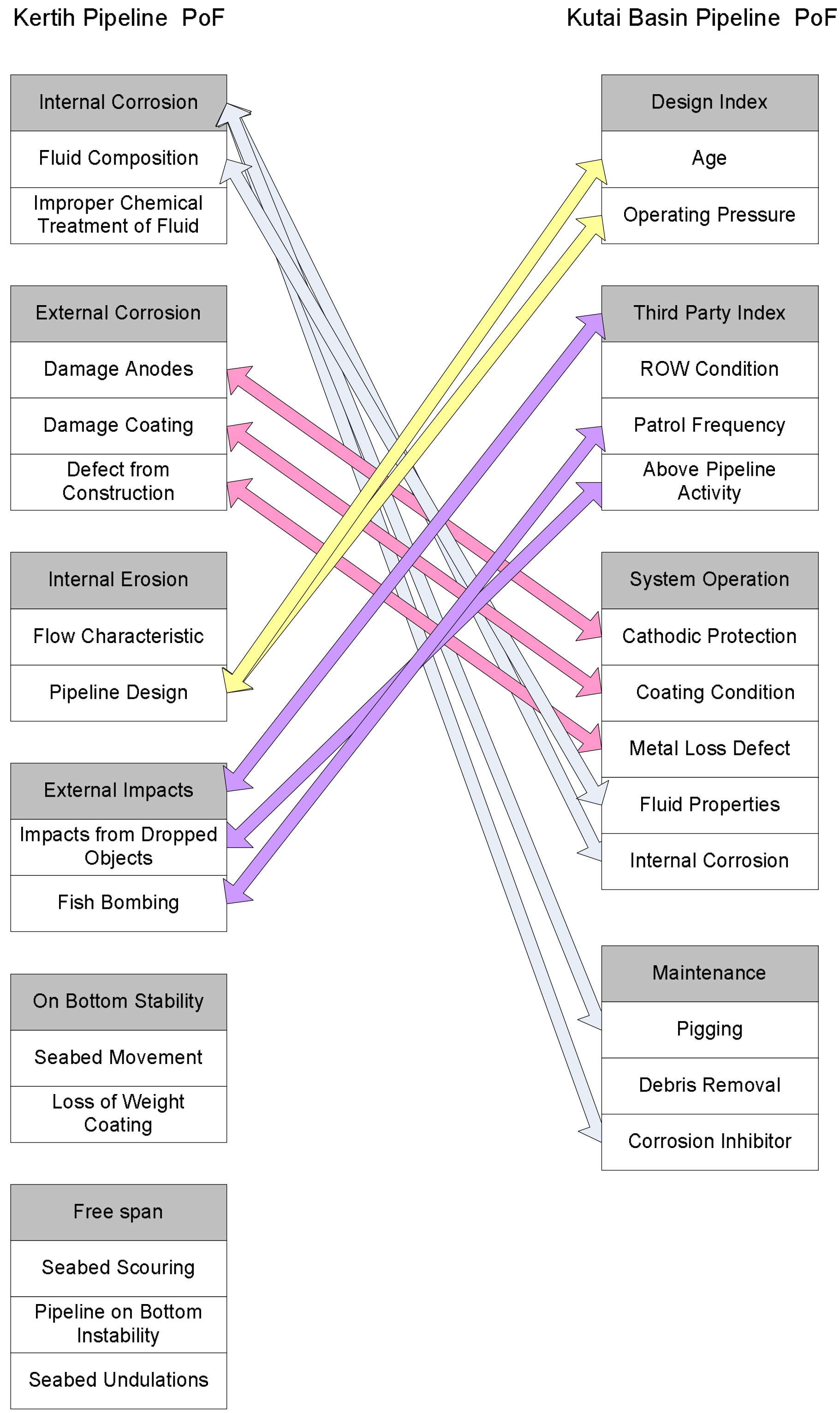

Figure 4.11. Comparative Analysis for Factor Causes the Probability of Pipeline Failure

The probabilities of pipeline failure from both pipeline systems are listed in above Table 4.5. The factors which are lead to cause the probability of failure are gathered from the pipeline engineers of each area based on the history of pipeline under study. From both pipeline under study we can make the moderation of the factor which may cause the probability of pipeline failure. The reason this research study in Kertih Malaysia and Kutai Basin Indonesia pipelines because this is the main area of oil and gas production in their country. Under Peninsular Gas Utilisation (PGU 1) the main facilities constructed comprise the first gas processing plant at Kertih, (Thong, 2007). The Kutai Basin is one of the largest and most important oil and gas producing basins in Indonesia (Koh, 2008).

Kertih pipelines have six factors as causes to make the probability of pipeline failure which are internal corrosion, external corrosion, internal erosion, external impacts, on bottom stability and free span. Whereas Kutai Basin pipelines have four factors as causes which are design index, third party index, system operation and maintenance. On the other hand the factors of both pipelines systems are related even though sometimes their have different terms. Here is the similarity and differences between factors of two pipelines under study:

1. Internal corrosion in Kertih pipeline is a factor of causes that make probability of failure, whereas in Kutai Basin Internal corrosion is in sub factor of system operation. In Kutai Basin it is mentioned corrosion inhibitor and pigging which are the function of this maintenance is to maintain the internal corrosion.
2. Cathodic protection, coating condition and metal loss defect in sub factor of system operation in Kutai Basin pipeline are the preventive of external corrosion.
3. Pipeline Design in sub factor of internal erosion in Kertih can be determine as age and operating pressure of pipeline as mentioned in Design Index of Kutai Basin.
4. External impacts in Kertih are exactly similar with third party index in Kutai Basin.
5. On bottom stability and free span factors is not mentioned in Kutai Basin.

Based on the analysis above, then the moderation factors can be seen in figure 4.12 which is causes the probabilities of pipeline failure are here:

1. Internal Corrosion
    a. Fluid Composition
    b. Improper Chemical Treatment of Fluid

2. External Corrosion
    a. Damage Anodes
    b. Damage Coating
    c. Metal Loss Defect
3. Internal Erosion
    a. Flow Characteristic
    b. Operating Pressure
4. External Impacts
    a. Impact from Dropped Objects
    b. Fish Bombing
5. On Bottom Stability
    a. Seabed Movement
    b. Loss of Weight Coating
6. Free span
    a. Seabed Scouring
    b. Pipeline On Bottom Instability
    c. Seabed Undulations

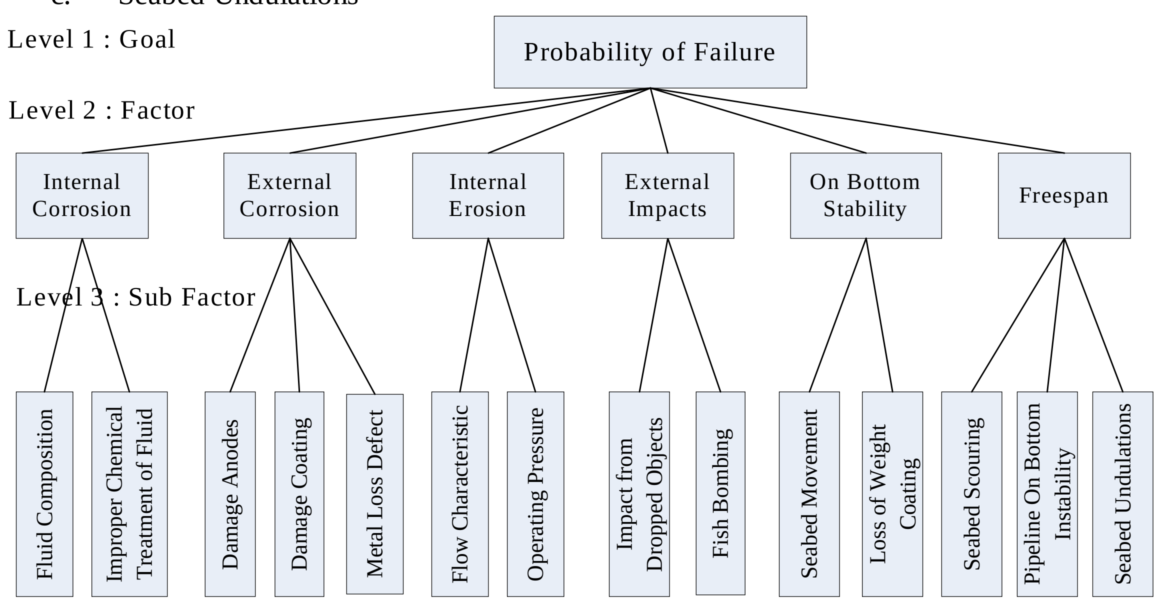

Figure 4.12. Moderation of Probability of Pipeline Failure

4.5.2. Comparative Analysis for Consequence of Pipeline Failure

Consequence is the impact or the potential magnitude of the event loss of pipeline failure and evaluated as the outcome of a failure based on the assumption that such a failure will occur. Knowing the impact of pipeline failure will lead to prevent the causes of pipeline failure by maximize the pipeline maintenance.

Table 4.6. Summary of Consequences of Pipeline Failure in Kertih and Kutai Basin

The Consequences of Pipeline Failure				
No.	Kertih Pipelines		Kutai Basin Pipelines	
1.	Economic :	a. Repair Cost	Business	a. Sales Line
				b. Redundancy
		b. Business Loss		c. Oil Flow
				d. Volume
2.	Safety:	a. Product Transported	Environment	Property Damage
		b. Manning on Installation		
3.	Environmental	a. Pollution	Population	Population Class
		b. Pipeline Size		

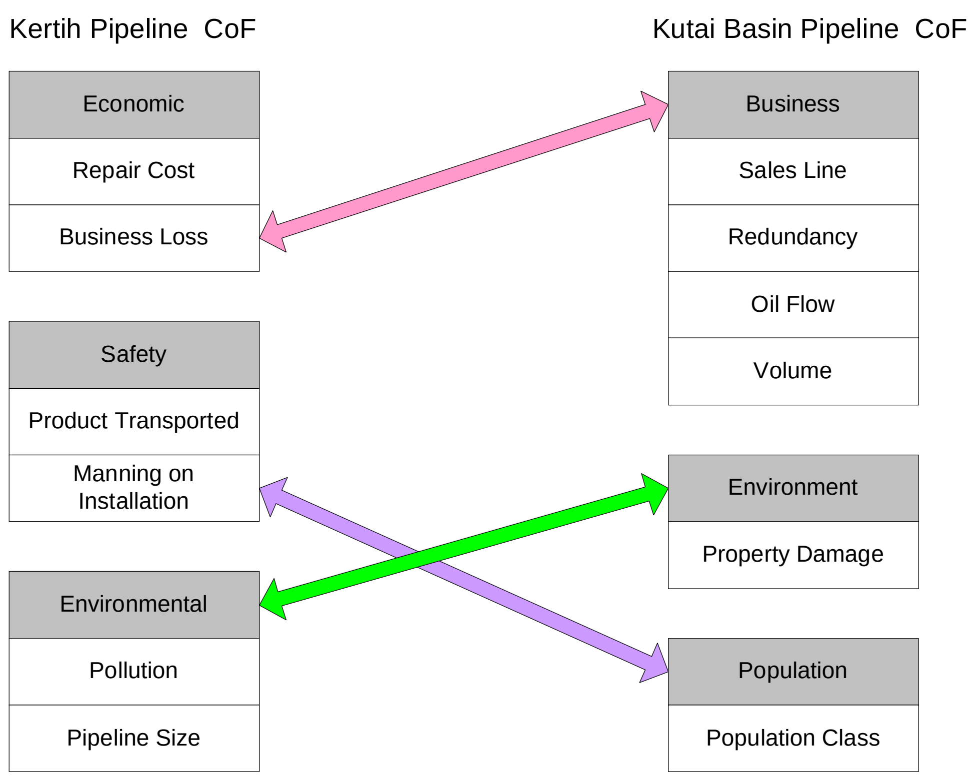

Figure 4.13. Comparative Analysis for Consequence of Pipeline Failure

Kertih pipelines have three factors as the impacts of pipeline failure which are economic, safety and environmental. Similarly Kutai Basin pipelines have three factors as impacts which are business, environment and population. On the other hand the factors of both pipelines systems are related even though sometimes their have different terms. Here is the similarity and differences between factors of two pipelines under study:

1. Business in Kutai Basin pipeline is an impact factor of pipeline failure, whereas in Kertih business is in sub factor of economic.
2. Safety impact in Kertih has similar meaning with population class in Kutai Basin as explain in previous chapter that higher people activity then higher risk to the population class.
3. Environment impact in Kertih and Kutai Basin is exactly similar.

Based on the analysis above, then the moderation factors can be seen in Figure 4.14 which is consequence of pipeline failure are:

1. Economic :
   a. Repair Cost
   b. Business Loss
2. Safety
   a. Loss of Life
   b. Loss of Properties
3. Environment :
   a. Pollution
   b. Oil Spill

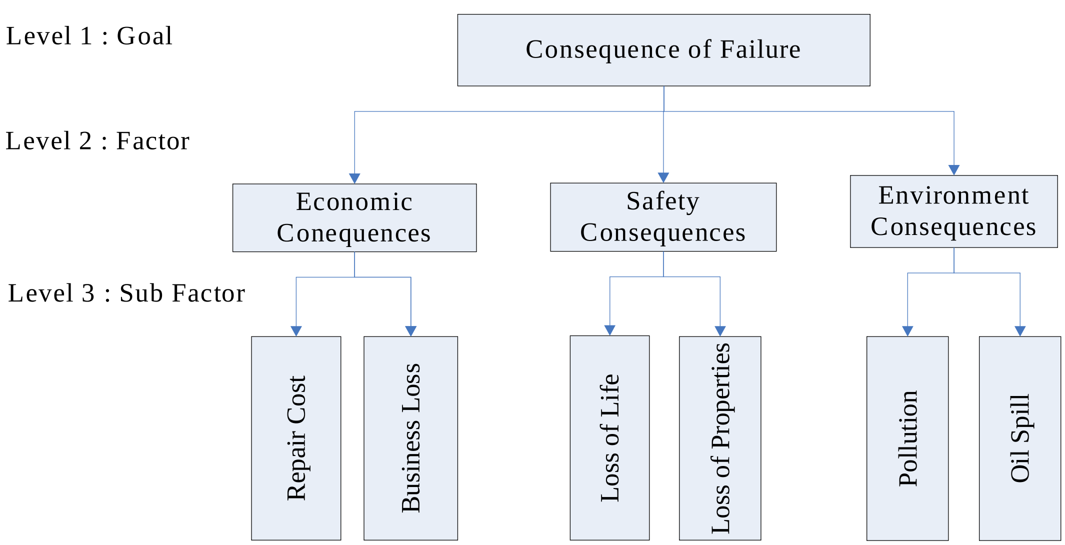

Figure 4.14. Moderation Consequence of Failure

CHAPTER 5
RESULTS & DISCUSSION

5.1. General

This research is based on case study on the two pipeline networks, operated in Kertih Malaysia and in Kutai Basin Indonesia. In Kertih, there are three pipelines included in this research, whereas five pipelines are studied in Kutai Basin. In order to develop the AHP model, the first activity involves setting up of goals in respect to the probability of failure, where various factors and sub factors are identified. For this process data are obtained by interviewing senior pipeline engineers in person related to the systems involved in this study.

During interview they are required to answer questions asked in a questionnaire, a sample of that is given in the Chapter 4. After obtaining the data, it is evaluated and analyzed in order to determine the probability of failure and the respective consequences for each of the pipeline. In the following sections, results of data analysis using the Expert Choice software are presented.

5.1.1. Analysis on Probability and Consequence of Failure

The probability of failure refers to the chance of something happening, whether defined, measured or estimated objectively or subjectively. The consequence of failure refers to outcome or impact of an event. This research is trying to find out the probability and consequence of failure for two case studies as explained before.

5.1.1.1. Analysis on PoF Kertih Pipeline

Eight senior pipeline engineers give their judgments on three pipelines in their areas of responsibility, used to develop the hierarchy. First, the greatest risk factors are determined by the probability of failure (PoF) and the consequence of failure (CoF).

The pipeline engineers give their judgment about the relative importance of the elements in respect to the overall goal of prioritizing the pipeline maintenance, using the pair wise comparison scale based on the hierarchy figure 4.7. Details are given in Appendix A1.

Table 5.1. AHP Output for Probability of Failure (PoF) for Kertih Pipeline

Failure Factor				Analytic Hierarchy Process Output on Probability of Failure		
Major Factor	Probability	Subfactor	Probability	Pipeline 1	Pipeline 2	Pipeline 3
Internal Corrosion	0.417	Fluid Composition	0.278	0.039	0.093	0.147
		Improper Chemical Treatment of Fluid	0.139	0.033	0.029	0.077
External Corrosion	0.107	Damage Coating	0.053	0.017	0.014	0.022
		Damage Anodes	0.033	0.005	0.007	0.021
		Defect from Construction	0.021	0.003	0.005	0.012
Internal Erosion	0.191	Flow Characteristic	0.048	0.007	0.012	0.028
		Pipeline Design	0.143	0.043	0.077	0.023
External Impacts	0.138	Impact from Dropped Objects	0.092	0.018	0.029	0.045
		Fish Bombing	0.046	0.015	0.012	0.019
On Bottom Stability	0.067	Seabed Movement	0.050	0.009	0.013	0.027
		Loss of Weight Coating	0.017	0.008	0.005	0.003
Free span	0.081	Seabed Scouring	0.044	0.007	0.013	0.024
		Pipeline On Bottom Instability	0.017	0.004	0.004	0.009
		Seabed Undulations	0.019	0.004	0.005	0.011
Probability of failure of various Pipeline				0.217	0.317	0.466
Ranking				3	2	1

Table 5.1 shows the AHP output for probability of failure for three pipelines at Kertih. Results of the pair wise comparison for the first level of the hierarchy indicate that internal corrosion has contributed highest probability to pipeline failure, namely 41.7%. The second highest probability is determined by internal erosion of 19.1%, followed by external impact of 13.8% and other factors at the sum of 41.7%. The second highest probability of the cause of pipeline failure is internal erosion of 19.1%. The third highest is external impact of 13.8%, and the other factors are external corrosion of 10.7%, free span of 8.1%, on bottom stability at the sum of 6.7%.

Sub factors are the probable causes attributed to the main factors, for example 41.7% probability of failure due to internal corrosion is caused by 27.8% due to fluid composition and only 13.9% probability of failure is contributed by improper chemical treatment of fluid. It means that the internal corrosion occurring due to the pipe wall loss or damage is caused by reaction between the inside wall of pipe and the transported product depending on fluid composition.

In order to apply chemical treatment to inner side of the pipe, it is necessary that the corrosion mechanism should be fully understood to avoid improper chemical treatment of fluid. For example, oxygen is the main agent that promotes corrosion on steel, therefore oxygen scavenging chemical can be combined with the oxygen in the product to prevent this oxygen from reacting with the pipe wall. Similarly, internal erosion is attributed by two sub factors i.e. flow characteristic and the pipeline design. Pipeline design usually dominates the failure due to internal erosion as the probability obtained in table 5.1.

5.1.1.2. Analysis on CoF Failure Kertih Pipeline

After determining of the probability of pipeline failure the next step is to determine the consequence of failure, intended to identify its impact to a range of stakeholders and the assets. Based on the Figure 4.8 the same analysis is applied to determine the consequence of failure, and the calculations are appended in Appendix A2.

Table 5.2. AHP Output for Consequence of Failure (CoF) for Kertih Pipeline

Impact Factor				Analytic Hierarchy Process Output on Consequence of Failure		
Major Factor	Consequence	Sub factor	Consequence	Pipeline 1	Pipeline 2	Pipeline 3
Economic	0.249	Repair Cost	0.062	0.009	0.027	0.027
		Business	0.187	0.037	0.075	0.075
Safety	0.157	Product	0.118	0.011	0.026	0.041
		Manning	0.039	0.026	0.026	0.026
Environment	0.594	Pollution	0.297	0.042	0.127	0.127
		Pipeline Size	0.297	0.042	0.127	0.127
Consequence of failure of various Pipeline				0.164	0.409	0.428
Ranking				3	2	1

From the analysis on consequence of failure, it is determined that the highest probability i.e. 59.4% will have significant impact to environment. There are two sub factors namely pollution and pipeline size and both of them will contribute equally with a consequence of 29.7% respectively. As a matter of fact that pollution due to leakage or burst of a pipeline will have an effect to a company's reputation as well as to the surroundings. The size of pipeline indicates that the production throughout the pipeline can affect the environment.

Thus the pipelines can be ranked in respect to their consequence of failure. The probability or consequence cannot identify which pipeline should be maintained in high priority. The next step is to integrate them together. The sum of all weighting coefficients must always be 1.00, so that they can now be divided into 5 risk scores. The new score of each pipeline is set based on risk score as shown in Table 5.3.

Table 5.3. Risk Score

Weight of Priority	Risk Score
0.01 - 0.20	1
0.21 - 0.40	2
0.41 - 0.60	3
0.61 - 0.80	4
0.81 - 1.00	5

Risk ranking is best illustrated in a matrix form that illustrates the probability of failure on one axis and the consequence on the other one. This matrix gives an estimate on risk calculated by multiplying risk score of probability of failure with that of the consequence.

Table 5.4. Risk Value

Category of Risk	Range of Risk Value
High Risk	21 – 25
Medium to High Risk	16 – 20
Medium Risk	10 – 15
Low to Medium Risk	6 – 9
Low Risk	1 – 5

The risk category of each pipeline can be categorized using risk matrix as given in Table 5.4. From the analysis on Kertih network it is determined that all these pipelines fall under low risk category. It is due to the fact that all three pipelines under this study carry gas, usually having high consequence, but having low probability of failure, they fall under low risk category.

The final outcomes of each of the pipeline against the risk factors are summarized in Table 5.5. Both probability and consequence for each of the three pipelines are summed up to determine the risk level of pipeline. The weight of probability and consequence in Kertih pipeline changes because the risk score matrix is based on 5x5 matrixes, so to normalize the value, then the weight should be multiplied by 3/5. Multiplying the weight of probability and consequence by 3/5, the risk score is consistent within both pipeline industries because there are five pipelines in Kutai Basin and three pipelines in Kertih. Thus the pipelines can be ranked in respect to their probability and consequence of failure.

Table 5.5. Risk Category of Kertih Pipeline

Name	Probability			Consequence			Risk	Risk Rank	Risk Value	Risk Category
	Weight	Rank	Risk Score (0-5)	Weight	Rank	Risk Score (0-5)				
PLN 1	0.133	3	1	0.098	3	1	0.013	3	1	Low Risk
PLN 2	0.191	2	1	0.245	2	2	0.047	2	2	Low Risk
PLN 3	0.276	1	2	0.257	1	2	0.071	1	4	Low Risk

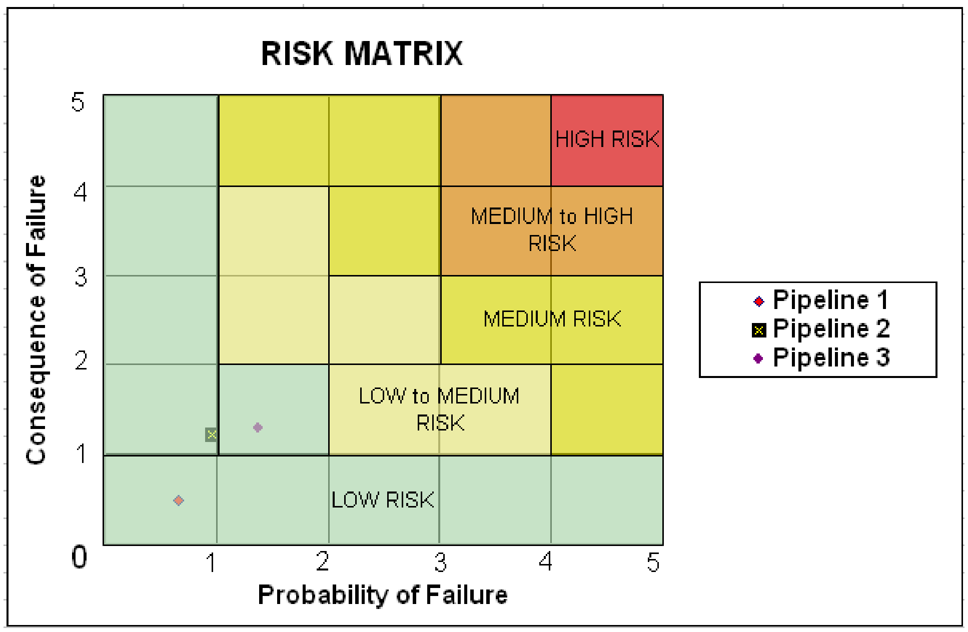

Figure 5.1. Risk Matrix for Kertih Pipeline

5.1.1.3. Analysis on PoF Kutai Basin Pipeline

The pipeline systems in Kutai Basin are to transport oil, under the same procedure as applied in Kertih pipeline. The first analysis is to calculate the risk for pipeline failure in terms of probability and consequence as the hierarchy shown in Chapter 4. As previously discussed, the pipeline engineers gave their judgment about the relative importance of the elements in respect to the overall goal of prioritizing the maintenance of the pipeline, using the pair wise comparison scale. Details are given in Appendix B1. Table 5.6 shows the summary of the probability of pipeline failure in the five pipelines.

Table 5.6. AHP Output of PoF of Kutai Basin Pipeline

Failure Factor				Analytic Hierarchy Process Output on Probability of Failure				
Major Factor	Probability	Sub factor	Probability	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5
Design Index	0.237	Age	0.158	0.013	0.017	0.034	0.060	0.034
		Operating Pressure	0.079	0.026	0.025	0.008	0.008	0.013
Third Party Index	0.180	ROW Condition	0.042	0.008	0.008	0.008	0.008	0.008
		Patrol Frequency	0.033	0.002	0.008	0.008	0.008	0.008
		Above Pipeline Activity	0.105	0.003	0.026	0.026	0.026	0.026
System Operation	0.347	Cathodic Protection	0.044	0.013	0.013	0.013	0.003	0.003
		Coating Condition	0.044	0.009	0.009	0.009	0.009	0.009
		Metal Loss Defect	0.083	0.017	0.017	0.017	0.017	0.017
		Fluid Properties	0.048	0.024	0.006	0.006	0.006	0.006
		Internal Corrosion	0.129	0.026	0.026	0.026	0.026	0.026
Maintenance	0.237	Pigging	0.079	0.016	0.016	0.016	0.016	0.016
		Debris R.	0.079	0.016	0.016	0.016	0.016	0.016
		Corrosion Inhibitor	0.079	0.016	0.016	0.016	0.016	0.016
Probability of failure of various Pipeline				0.187	0.201	0.201	0.216	0.195
Ranking				4	2	2	1	3

The results of the pair wise comparison for the major factor in the hierarchy indicate that the highest contribution to the probability of pipeline failure derives from system operation i.e. 34.7%. The second highest probability causing a pipeline failure is design index and maintenance namely 23.7% and the lowest contribution cause by the third party index is 18%.

The results of the pair wise comparison at the sub factors level of the hierarchy show that the probability derives from a major factor shared by the sub factors. For example, the result of major factor shows that system operation contributes 34.7% probability of failure that would be due to the sub factors which are cathodic protection of 4.4%, coating condition of 4.4%, metal loss defect of 8.3%, fluid properties of 4.8% and internal corrosion of 12.9%.

Corrosion is defined as an electrochemical reaction that involves the loss of metal. To prevent corrosion on parent metal, cathodic protection is used. Corrosion is usually caused by electrons flowing from one point to the other in which pipeline surface consists of randomly distributed cathodic and anodic areas, and seawater is electrolyte that completes the galvanic cell. To create an electrochemical cell, metal with lower potential can become a cathode and is protected by connecting a metal with higher potential to the steel pipeline. Then the pipeline is protected against corrosion by coatings, by attaching anodes which are aluminium and zinc to the steel pipeline. The fluid properties containing CO_2 and H_2S will cause corrosion and affect operations of the pipeline. The last sub factor is internal corrosion related to fluid carried by pipeline or depending upon aggressiveness of the transported medium.

5.1.1.4. Analysis on CoF Failure in Kutai Basin Pipeline

For the analysis on consequence of failure, the highest impact to business is determined at the sum of 60%, whereas impact to environment is calculated at the sum of 20%, and the impact to population is also determined 20%. Details for the pair wise comparison are given in Appendix B2. Impact to business depends on the line type, whether it is a flow line an export line, the redundancy line or oil flow and the volume. All these factors depend on the diameter of the pipe, the larger diameter of the pipeline the higher damage will occur.

Table 5.7. AHP Output of CoF of Kutai Basin Pipeline

Failure Factor				Analytic Hierarchy Process Output on Consequence of Failure				
Major Factor	Consequence	Sub factor	Consequence	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5
Business	0.600	Sales Line	0.249	0.072	0.015	0.085	0.014	0.064
		Redundancy	0.064	0.002	0.018	0.015	0.015	0.014
		Oil Flow	0.176	0.021	0.084	0.026	0.019	0.026
		Volume	0.111	0.019	0.029	0.019	0.022	0.022
Environment	0.200	Property D	0.200	0.096	0.010	0.010	0.042	0.042
Population	0.200	Population C	0.200	0.025	0.099	0.019	0.029	0.029
Consequence of failure of various Pipeline				0.227	0.239	0.190	0.142	0.202
Ranking				2	1	4	5	3

Thus pipelines can be ranked in respect to their consequence of failure. The probability or consequence cannot identify which pipeline should be maintained in high priority. The next step is to integrate them together. The new score of each pipeline is set based on its priority.

The method of risk calculation is based on multiplication the two values: risk score of probability and risk score of consequence. The risk category for each pipeline can be categorized by risk matrix (Table 5.8). It is determined that all five pipelines fall under the low risk category.

Table 5.8. Risk Category of Kutai Basin Pipeline

Name	Probability			Consequence			Risk	Risk Rank	Risk Value	Risk Category
	Weight	Rank	Risk Score	Weight	Rank	Risk Score				
PLN 1	0.189	4	1	0.227	2	2	0.043	2	2	Low Risk
PLN 2	0.203	2	2	0.239	1	2	0.049	1	4	Low Risk
PLN 3	0.203	2	2	0.190	4	1	0.039	4	2	Low Risk
PLN 4	0.219	1	2	0.142	5	1	0.031	5	2	Low Risk
PLN 5	0.198	3	1	0.202	3	1	0.040	3	1	Low Risk

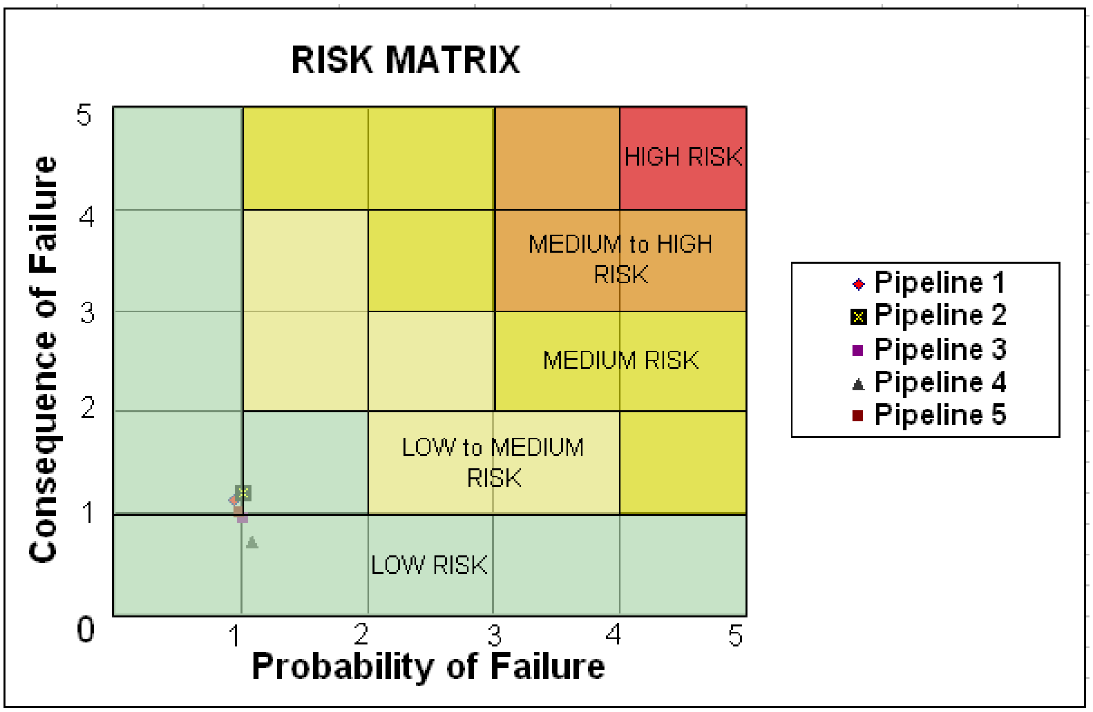

Figure 5.2. Risk Matrix in Kutai Basin Pipeline

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5.2. Analysis on Moderation Probability of Failure

Based on the comparative analysis between the factor of probability of failure in Kertih and that in Kutai Basin pipeline as described Chapter 4, the next step is to analyze the risk category of each pipeline in new hierarchy (see Figure 4.12).

From the analysis shown in Table 5.9 there are some value changes, because compare to Table 5.1. and Table 5.6 some of the factors are eliminated and modified by other factors. The internal corrosion in Kertih pipeline, the value still remains the same with the value in previous analysis, namely 41.7%, whereas in Kutai Basin pipeline, the internal corrosion changes from 12.9% to 28.7%. It is because the internal corrosion in Kutai Basin can be classified based on other factors namely pigging and corrosion inhibitor. And the value of internal corrosion in Kutai Basin has been higher than in previous analysis.

Table 5.9. Moderation on Probability of Pipeline Failure

Moderation Criteria	Kutai Basin								Kertih					
	Probability	Sub factor	Probability	PLN 2a	PLN 2b	PLN 2c	PLN 2d	PLN 2e	Probability	Sub factor	Probability	PLN 1a	PLN 1b	PLN 1c
Internal Corrosion	0.287	Pigging	0.079	0.016	0.016	0.016	0.016	0.016	0.417	Fluid Composition	0.278	0.039	0.093	0.147
		Corrosion Inhibitor	0.079	0.016	0.016	0.016	0.016	0.016		Improper Chemical	0.139	0.033	0.029	0.077
		Internal Corrosion	0.129	0.026	0.026	0.026	0.026	0.026		-	-	-	-	-
External Corrosion	0.171	Cathodic Protection	0.044	0.013	0.013	0.013	0.003	0.003	0.086	Damage Coating	0.053	0.017	0.014	0.022
		Coating Condition	0.044	0.009	0.009	0.009	0.009	0.009		Damage Anodes	0.033	0.005	0.007	0.021
		Metal Loss	0.083	0.017	0.017	0.017	0.017	0.017		-	-	-	-	-
Internal Erosion	0.079	Operating Pressure	0.079	0.026	0.025	0.008	0.008	0.013	0.048	Flow Characteristic	0.048	0.007	0.012	0.028
External Impacts	0.138	Above Pipeline Activity	0.105	0.003	0.026	0.026	0.026	0.026	0.138	Impact Dropped Objects	0.092	0.018	0.029	0.045
		Patrol Frequency	0.033	0.002	0.008	0.008	0.008	0.008		Fish Bombing	0.046	0.015	0.012	0.019
On Bottom Stability	-	-	-	-	-	-	-	-	0.067	Seabed Movement	0.050	0.009	0.013	0.027
										Loss of Weight Coating	0.017	0.008	0.005	0.003
Free span	-	-	-	-	-	-	-	-	0.081	Seabed Scouring	0.044	0.007	0.013	0.024
										Pipeline On Bottom Instability	0.017	0.004	0.004	0.009
										Seabed Undulations	0.019	0.004	0.005	0.011
Probability of Failure of Kutai Basin Pipeline				0.128	0.156	0.139	0.129	0.134	Probability of Failure of Kertih Pipeline			0.166	0.236	0.433
Ranking				5	1	2	4	3	Ranking			3	2	1

Table 5.10. Moderation on Probability of Pipeline Failure

Moderation Criteria	Kutai Basin								Kertih					
	Consequence	Factor/ Sub factor	Consequence	PLN 2a	PLN 2b	PLN 2c	PLN 2d	PLN 2e	Consequence	Factor/ Sub factor	Consequence	PLN 1a	PLN 1b	PLN 1c
Economy	0.600	Sales Line	0.249	0.072	0.015	0.085	0.014	0.064	0.249	Repair Cost	0.062	0.009	0.027	0.027
		Redundancy	0.064	0.002	0.018	0.015	0.015	0.014		Business	0.187	0.037	0.075	0.075
		Oil Flow	0.176	0.021	0.084	0.026	0.019	0.026		-	-	-	-	-
		Volume	0.111	0.019	0.029	0.019	0.022	0.022		-	-	-	-	-
Safety	0.200	Property D	0.200	0.096	0.010	0.010	0.042	0.042	0.039	Manning	0.039	0.026	0.026	0.026
Environment	0.200	Oil Spill	0.200	0.025	0.099	0.019	0.029	0.029	0.297	Pollution	0.297	0.042	0.127	0.127
Consequence of Failure of Kutai Basin Pipeline				0.227	0.239	0.190	0.142	0.202	Consequence of Failure of Kertih Pipeline			0.114	0.255	0.255
Ranking				2	1	4	5	3	Ranking			2	1	1

Table 5.11. Moderation on Risk Category of Kertih Pipeline

Name	Probability			Consequence			Risk	Risk Rank	Risk Value	Risk Category
	Weight	Rank	Risk Score (0-5)	Weight	Rank	Risk Score (0-5)				
PLN 1a	0.099	3	1	0.068	3	1	0.007	3	1	Low Risk
PLN 1b	0.142	2	1	0.153	1	1	0.022	2	1	Low Risk
PLN 1c	0.260	1	2	0.153	1	1	0.040	1	2	Low Risk

Table 5.12. Moderation on Risk Category of Kutai Basin Pipeline

Name	Probability			Consequence			Risk	Risk Rank	Risk Value	Risk Category
	Weight	Rank	Risk Score (0-5)	Weight	Rank	Risk Score(0-5)				
PLN 2a	0.128	5	1	0.227	2	2	0.029	2	2	Low Risk
PLN 2b	0.156	1	1	0.239	1	2	0.037	1	4	Low Risk
PLN 2c	0.139	2	1	0.190	4	1	0.026	4	2	Low Risk
PLN 2d	0.129	4	1	0.142	5	1	0.018	5	2	Low Risk
PLN 2e	0.134	3	1	0.202	3	1	0.027	3	1	Low Risk

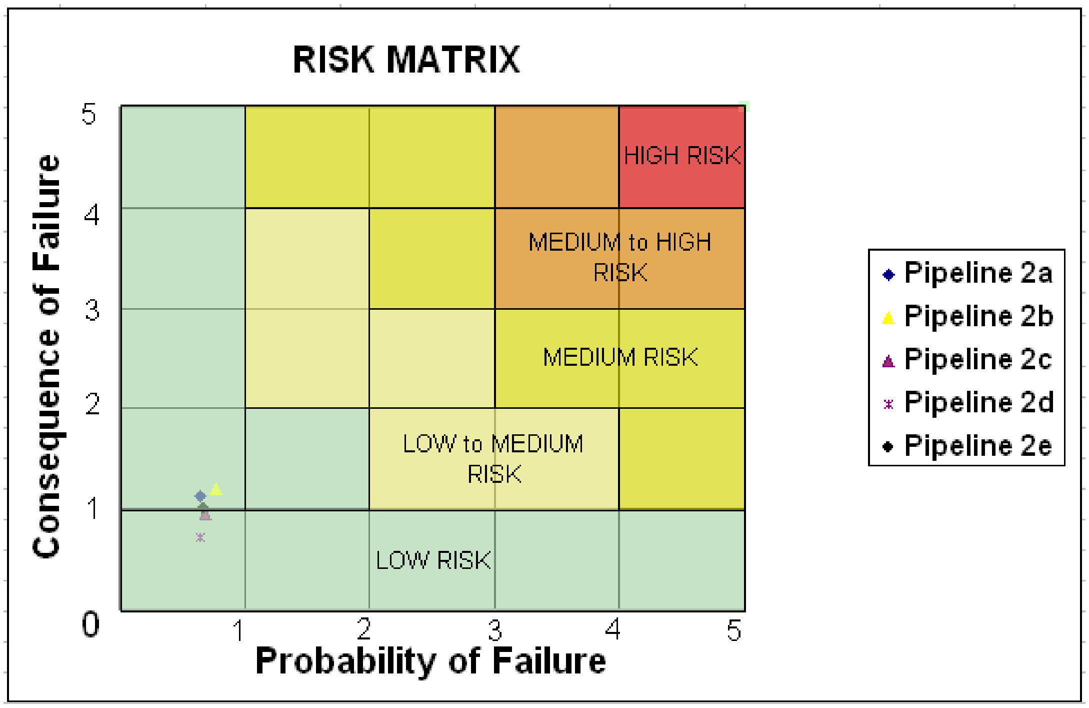

Figure 5.3. Moderation on Risk Matrix for Kutai Basin Pipeline

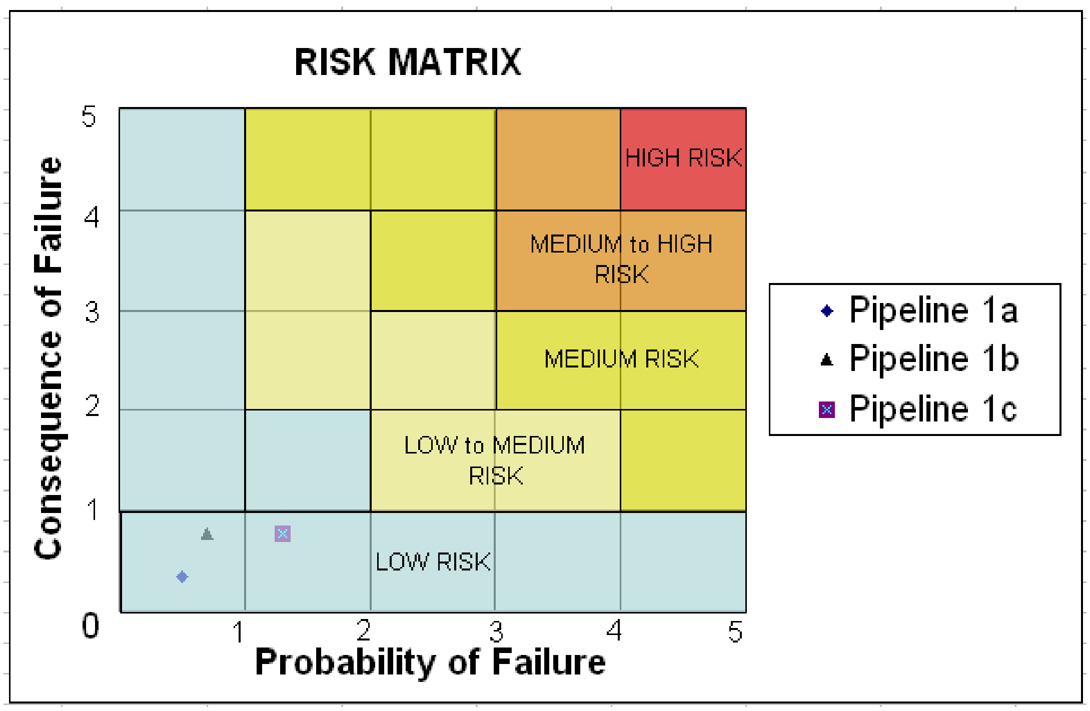

Figure 5.4. Moderation on Risk Category of Kertih Pipeline

5.3. Analysis on Moderation Consequence of Failure

It is the same analysis with moderation probability of pipeline failure. The next step is also moderation consequence of pipeline failure for both Kertih and Kutai Basin pipeline as described in Chapter 4, with new hierarchy (see Figure 4.14).

From the analysis shown in Table 5.13 there are some value changes, because compare to Table 5.2. and 5.7 some of the factors are eliminated and modified with other factors. For example safety consequence, in Kutai Basin pipeline the value still remains the same with the value in previous analysis namely 20%, whereas in Kertih pipeline, the safety impact changes from 15.7% to 3.9%. The transported product factor is eliminated because of moderation in safety factor in Kutai Basin pipeline. Table 5.13 is the summary of moderation for both pipelines with new hierarchy as shown in Figure in 4.12 and 4.14. After identifying the risk category, the risk matrix in Figure 5.5 can be determined.

Table 5.13. Summary of Moderation for Pipeline Risk Category

Name	Probability			Consequence			Risk	Risk Rank	Risk Value	Risk Category
	Weight	Rank	Risk Score	Weight	Rank	Risk Score				
PLN 1a	0.099	3	1	0.068	3	1	0.007	3	1	Low Risk
PLN 1b	0.142	2	1	0.153	1	1	0.022	2	1	Low Risk
PLN 1c	0.260	1	2	0.153	1	1	0.040	1	2	Low Risk
PLN 2a	0.128	5	1	0.227	2	2	0.029	2	2	Low Risk
PLN 2b	0.156	1	1	0.239	1	2	0.037	1	4	Low Risk
PLN 2c	0.139	2	1	0.190	4	1	0.026	4	2	Low Risk
PLN 2d	0.129	4	1	0.142	5	1	0.018	5	2	Low Risk
PLN 2e	0.134	3	1	0.202	3	1	0.027	3	1	Low Risk

The objective of risk matrix ranking is to set the inspection priority on pipeline maintenance. The pipeline is placed in a 5 X 5 matrix to indicate its relative risk ranking as compared to other pipelines. Inspection can help reduce the probability of failure whereas engineering changes are usually required to reduce consequence of failure. When reviewing pipeline inspection schedule and performing turnaround planning it is helpful to record the overall risk of each pipeline (see Table 5.13).

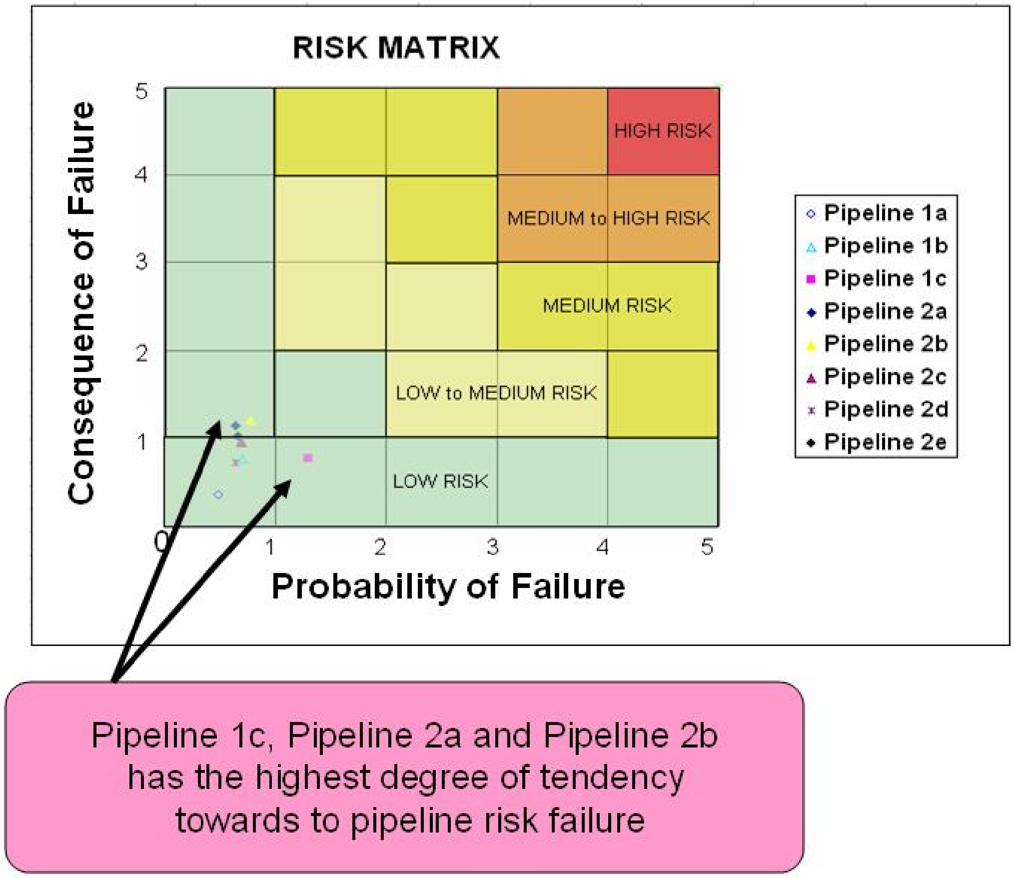

Figure 5.5. Summary of Moderation for Pipeline Risk Category

Figure 5.5 shows the distribution of pipelines by risk in 5 X 5 risk matrix. The distribution is based on the weight of priority of probability of failure in X axis and consequence of failure in Y axis. From Figure 5.5 it can be seen that Pipeline 1c has the tendency towards the highest degree to pipeline risk failure.

The result of analysis in Table 5.9 and Table 5.10 shows that pipeline 1c, 2a and 2b have the highest probability of failure with 43.3%, 12.8%, 15.6% and the consequence is 25.5%, 22.7%, 23.9% respectively. There are six factors in probability of failure namely internal corrosion, external corrosion, internal erosion, external impacts, on bottom stability and free span. Whereas in consequence of failure there are three factors i.e. economy, safety and environment.

Based on moderation of probability of pipeline failure in Table 5.9, the highest factor that contributes in pipeline 1c, 2a and 2b have tendency towards pipeline failure which is internal corrosion. For example pipeline 1c of 22.4% is contributed by fluid composition of 14.7% plus improper chemical of 7.7%. Internal corrosion is related to fluid being carried by pipeline. Internal corrosion can cause wall thinning in every pipeline system during its operating life. In pipeline systems, corrosion damage may due to CO_2 corrosion, bacteria and H_2S cracking.

In Table 5.10 moderation of consequence of pipeline failure, indicates that the highest factor in pipeline 1c, 2a and 2b is impact to economy. For example the economic impact in pipeline 1c is 10.2% contributed by repair cost of 2.7% and business value of 7.5%. The internal corrosion as highest factor of probability of pipeline failure will impact to economy depending on the repair cost of pipeline and the business loss due to interruption in production. Here is the estimation of economic impact in pipeline industry:

Table 5.14. Leak Repair Cost

CoF Leak Repair Cost		
Pipe Diameter	Cost	Duration of Repair
> 24"	US $ 100,000	30 days
> 12" = 24"	US $ 70,000	30 days
= 12"	US $ 60,000	30 days

Table 5.15. Leak Repair Cost

CoF Burst Repair Cost		
Pipe Diameter	Cost	Duration of Repair
> 24"	US $ 2,000,000	180 days
> 12" = 24"	US $ 1,500,000	180 days
= 12"	US $ 1,000,000	180 days

5.4. Existing Method Compare to Analytic Hierarchy Process

The pipeline maintenance in Kutai Basin uses pipeline integrity method. This method consider the pipeline systems as having design features and operating characteristic, which are unique for each individual system. Although those pipelines are unique, the frameworks for developing pipeline integrity are similar.

5.4.1. Existing Method in Kutai Basin Pipeline

Pipeline systems have design features and operating characteristic, which are unique for each individual system. Here is the existing method of pipeline maintenance in Kutai Basin pipeline system. The framework is illustrated below:

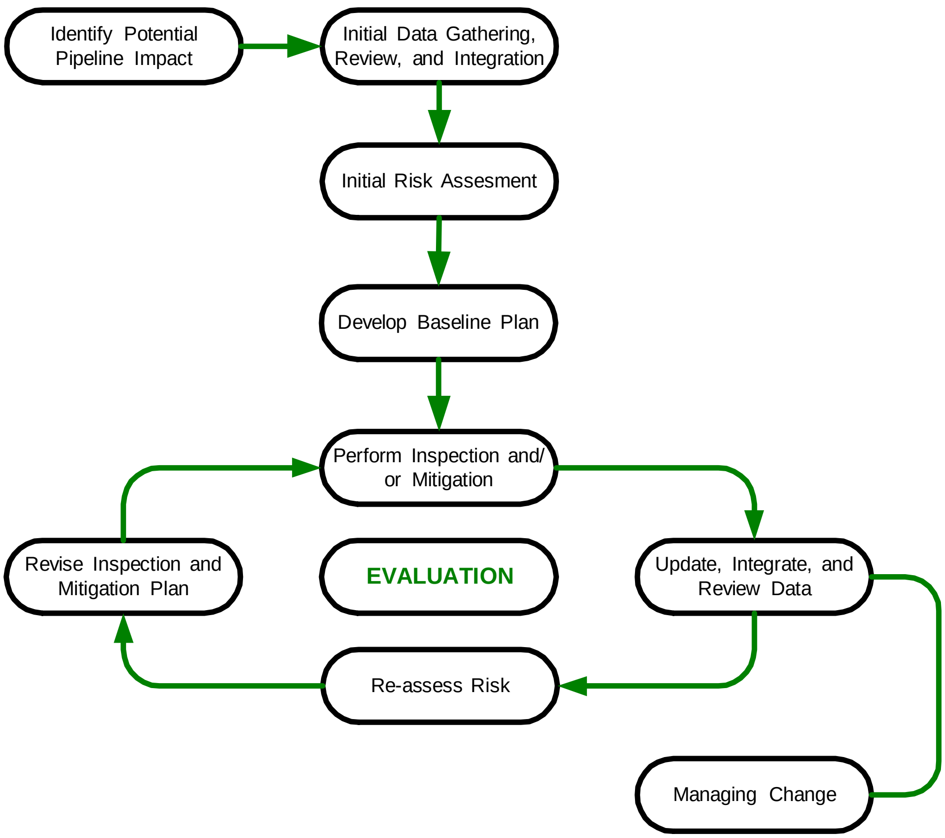

Figure 5.6. Frameworks of Pipeline in Kutai Basin

Identifying Potential Pipeline Impact

This framework involves the identification of pipeline that has significant impact to the event of failure. Impact identification involves impact to business, environment, population and areas affected within the pipeline where it lies or near the pipeline system corridor.

Initial Data Gathering Review, and Integration

The first step in understanding the potential integrity threats along the pipeline system is to assemble information about potential risks. The types of data to support a risk assessment include information on the operation, maintenance, and surveillance practices, pipeline design, operating history, and the specific failure modes and concerns that are unique for each pipeline.

Initial Risk Assessment

In this framework, the data assembled from the previous step is used to conduct a risk assessment of the pipeline system. The risk assessment begins with a systematic and comprehensive search for possible threats to pipeline or to facility integrity with its consequences to the event of failure.

Developing Baseline Plan

Based on output of the risk assessment, a plan shall be developed to address the most significant risks and assess the integrity of the pipeline system. The plan shall include the preventive and mitigate risk control actions, as well as integrity assessment activities (e.g., internal and external corrosion survey, inline inspection, pressure testing).

Inspection and or Mitigation.

In this frame, the baseline assessment plan activities are implemented, the results are evaluated, and the necessary repairs are made to assure defects that might lead to pipeline failure are eliminated.

Updating, Integrating, and Reviewing the Data

The improved and updated information about condition of the pipeline information shall be retained and added to the database information. The information in database will be used to support future risk assessment and integrity evaluations.

Revising Inspection and Mitigation Plan

Risk assessments should be performed periodically. New information on the pipeline includes recent operating data, changes in the pipeline system design and operation, external change that may have occurred, inspection results, etc.

Revising Mitigation and Inspection Plan

The on-going integrity and mitigation plan should be periodically updated to reflect new information and the current understanding of integrity threats. As new risks or new manifestations of previously known risks are identified, additional preventive or mitigate actions to address these risks should be performed, as appropriate.

Evaluating Program.

The pipeline engineers in charge should collect performance information and periodically evaluate the success of its inspection and monitoring techniques, pipeline repair activities, and other preventive and mitigate risk control activities.

Managing Change

The last framework is managing change applicable to all individual frameworks above repectively. The maintenance is not a one-time process, it is a continuous process during the lifetime of the pipeline, which includes monitoring pipeline condition, identifying and assessing risks, and taking action to minimize the most significant threats.

5.4.2. Analytic Hierarchy Process Method

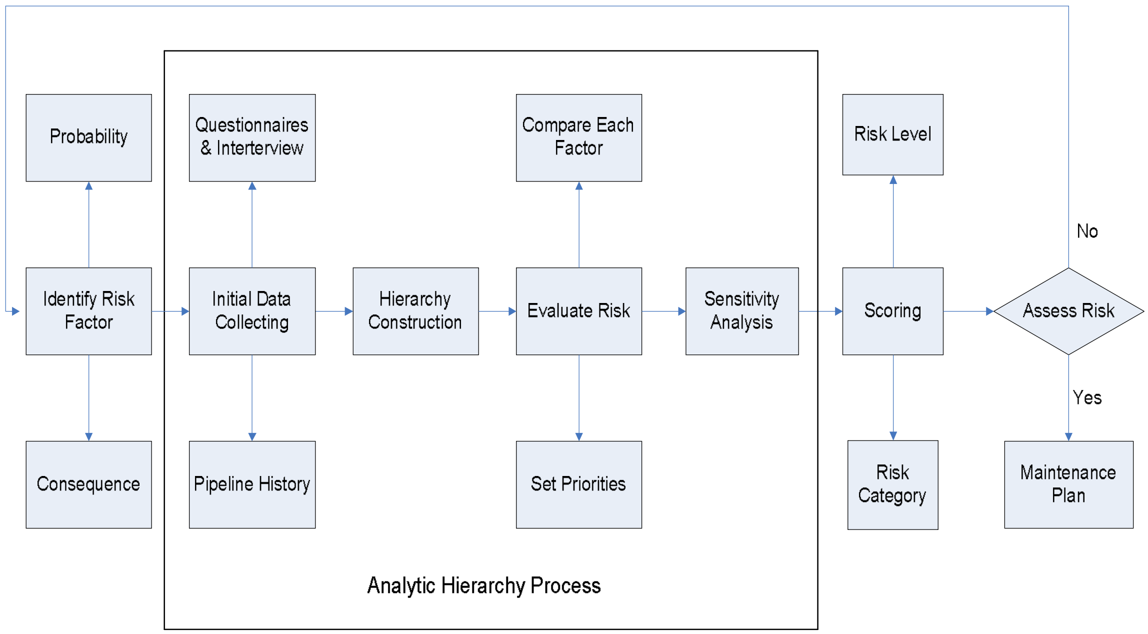

Figure 5.7. Analytic Hierarchy Process Method

Identifying Risk Factor

This framework involves identification of pipeline that has significant risk on the event of failure. Risk factor identification involves factors which may cause probability of pipeline failure and the consequence affected within the pipeline where it lies or near the pipeline system.

Initial Data Collecting

The first step in understanding the potential integrity threats along the pipeline system is to assemble information about potential risks. In this framework, we should perform the initial data collection, review, and integration of data needed to understand condition of the pipe and identify the location of the specific threats to its integrity. The types of data to support a risk assessment include primary and secondary data. The primary data is developed by using questionnaire and interviewing the pipeline engineers for the pipeline system. The information gathered concerns with the operation, maintenance, pipeline design, operating history, and the specific failure modes and those that are unique for each pipeline. The secondary data is a database and maintenances during the lifetime of the pipeline.

Hierarchy Construction

In this framework, the data assembled from the previous step is used to construct a hierarchy of the pipeline system. The construction of hierarchy consists of four levels which are:

i. First level is the goal that needs to be achieved.

ii. Second level is the criteria of the factor to make the goal achieved.

iii. Third level is the sub factor of the factor in the previous level.

iv. Fourth level is the alternatives of the pipeline under study.

In this research, the hierarchy is constructed in systematic and comprehensive ways for probability damage to pipeline and the impact or the consequence to pipeline failure.

Evaluating Risk

Based on the hierarchy construction, risk can be evaluated by analysis hierarchy process. In this analysis, the decision maker carries out matrix pair wise comparison based on the hierarchy. By comparing each element, the priority for each factor will be found. The result of priority factor must consider consistency ratio which is less than 10%. The function of consistency ratio is to check whether the judgments from the respondent have adequately structured the problem in question. The detailed calculation can be seen in Chapter 4.

Sensitivity Analysis

Sensitivity analysis is a procedure to describe analytically the effects of uncertainty on one parameter or more, involved in the analysis of a risk failure of the pipeline. The Analytic Hierarchy Process (AHP) is completed with five sensitivity graphs, as follows:

1. Performance Graphs
2. Dynamic Graphs
3. Gradient Graphs
4. Two-dimensional Graphs
5. Difference Graphs

Scoring

Scoring systems here use a summation of numbers assigned to conditions and activities expected to influence risks. This step consists of risk level divided into a matrix form illustrating the probability of failure on one axis and the consequence on the other. This matrix gives an estimate on risk calculated by multiplying risk score of probability of failure with that of the consequence. The next step is risk categories which are low risk, low to medium risk, medium risk, medium to high risk and high risk category.

Maintenance Plan

Maintenance plan are to ensure that the physical assets continue to fulfill the pipeline process for increasing the operational, design life, availability of the pipeline system. Pipeline systems and the environment in which they operate are never static. Therefore maintenance or repair can be reduced during the detailed design phase by the selection of appropriate engineering concept, equipment and materials.

The existing method for pipeline maintenance in Kutai Basin generally applies risk assessment and the inspection, whereas in AHP method it is added by comparing the risk factors, sensitivity analysis and risk scoring. Compared to the existing method for pipeline maintenance in Kutai Basin, the AHP method has additional advantages, i.e.:

a. AHP can include both intangible and tangible elements in hierarchy
b. The ability of AHP to incorporate both objective and subjective
c. Possible to compare risk factors in hierarchy
d. The sensitivity or effect of result calculation can be analyzed by using sensitivity analysis
e. Possible prioritization on pipeline maintenance based on risk category

5.5. Sensitivity Analysis

The next step of analysis performed after finding the risk level is sensitivity analysis. Sensitivity analysis is used to investigate the sensitivity of the alternatives in order to apply changes in the priorities of the criteria. In the application of Expert Choice software there is a tool that is used to determine sensitivity of the priority. There are five graphical sensitivity analyses, namely:

5.5.1. Performance

The performance graph displays all the information about the criteria value on a single screen. The priority of each criterion is shown by rectangular box on the each criterion vertical line. Here are the four performance graphs for each hierarchy structures;

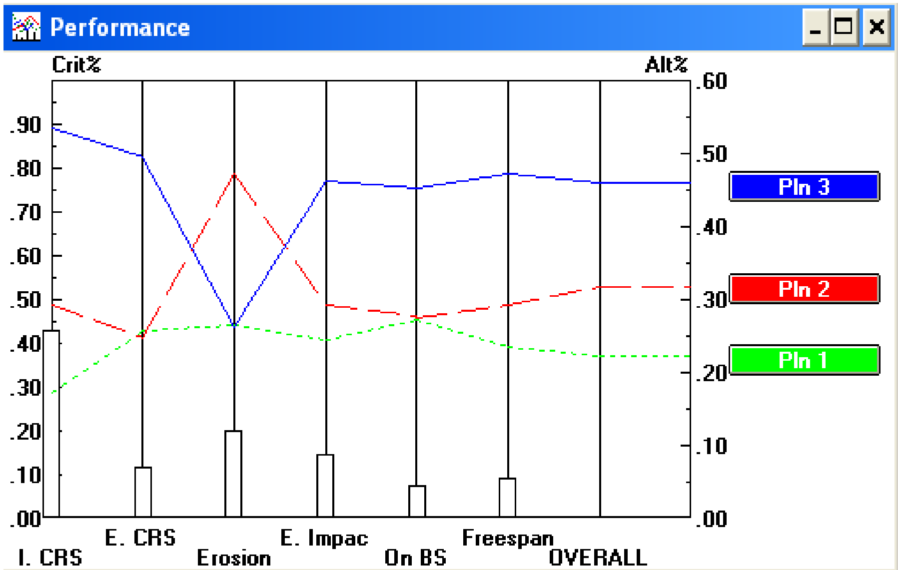

Figure 5.8. Performance Sensitivity Graphs for PoF of Kertih Pipeline

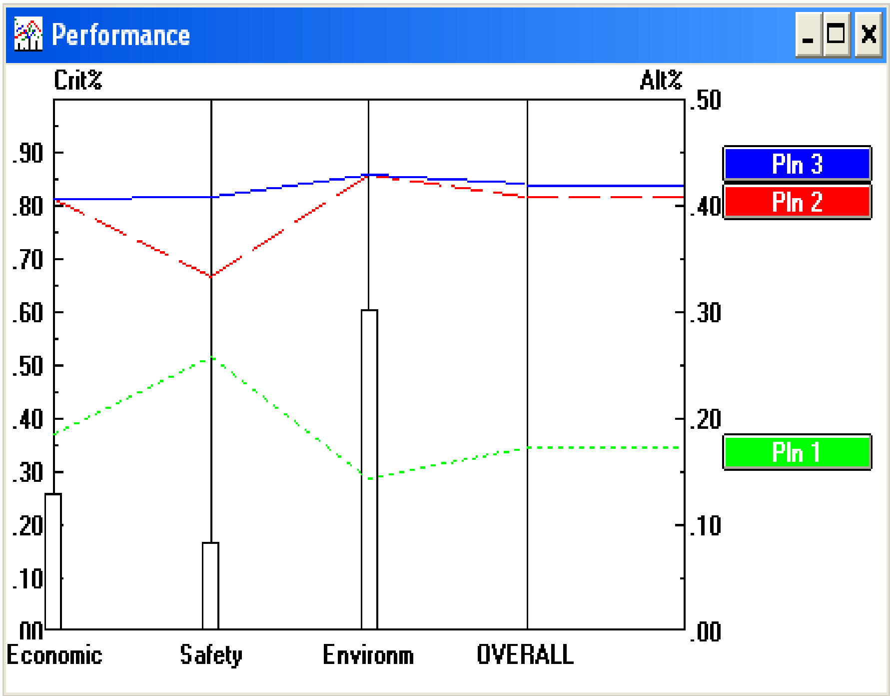

Figure 5.9. Performance Sensitivity Graphs for CoF of Kertih Pipeline

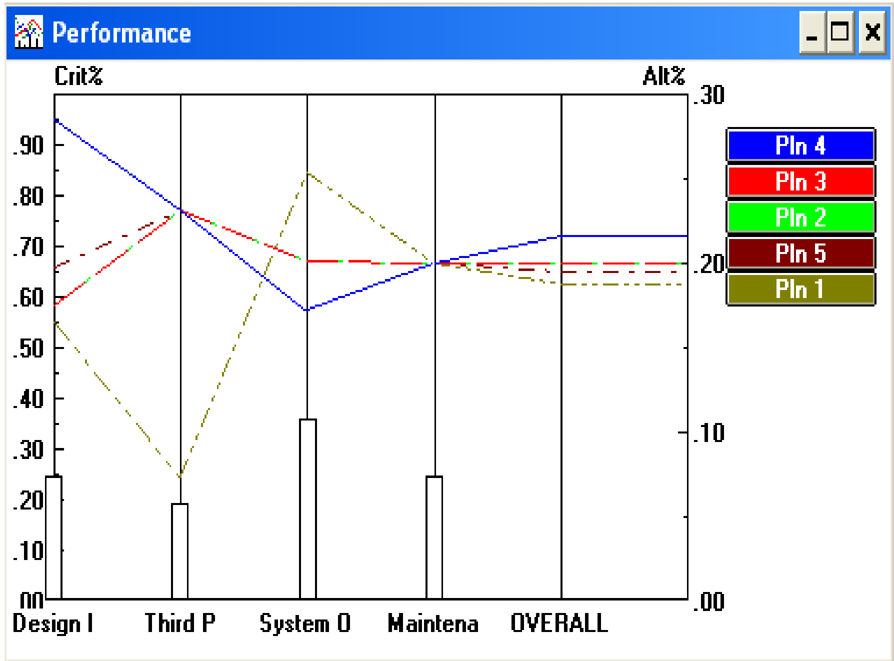

Figure 5.10. Performance Sensitivity Graphs for PoF of Kutai Basin Pipeline

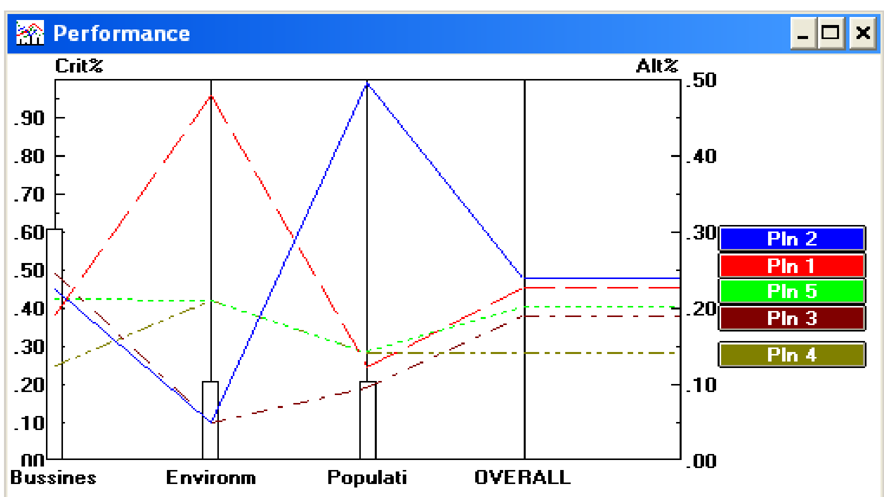

Figure 5.11. Performance Sensitivity Graphs for CoF of Kutai Basin Pipeline

Figure 5.8 – 5.11 shows the performance of sensitivity analysis in respect to the alternatives prioritized in relation to the others either individual or respect to as whole. The criteria bars can be drag up or down which can temporarily alter the relationship between the alternatives and criteria. The lines for the alternatives between the vertical criterion lines have no meaning, they help find particular alternative.

5.5.2. Dynamic

The second graph to perform sensitivity analysis is to use dynamic sensitivity. From the dynamic display it can be seen how the change of priority in one criterion affects priorities of the others. Here are the four dynamic graphs for each hierarchy:

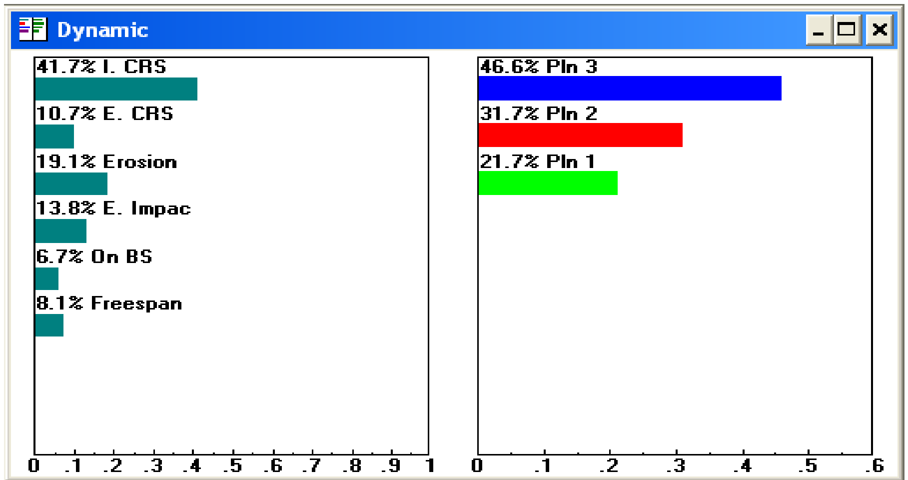

Figure 5.12. Dynamic Sensitivity Graphs for PoF Kertih Pipeline

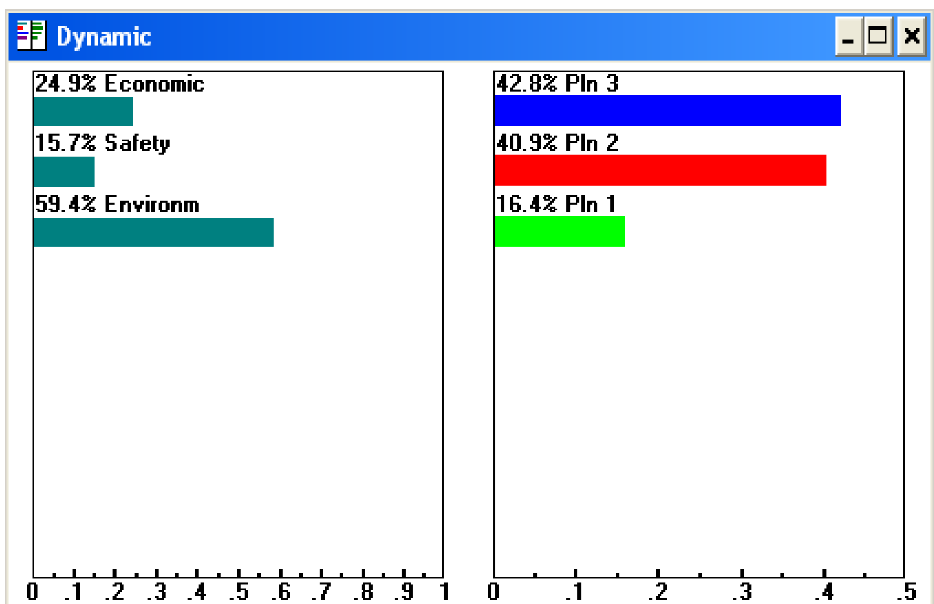

Figure 5.13. Dynamic Sensitivity Graphs for CoF Kertih Pipeline

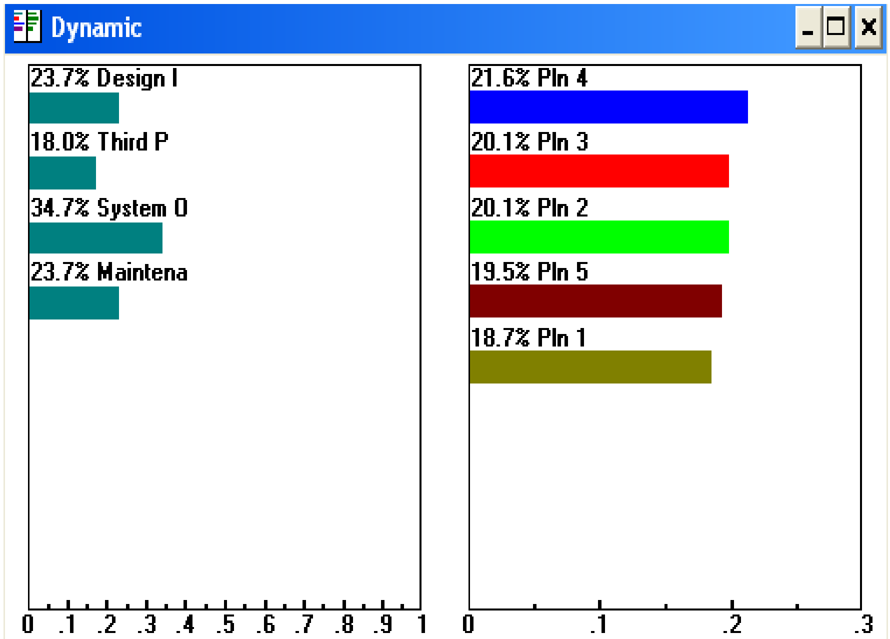

Figure 5.14. Dynamic Sensitivity Graphs for PoF Kutai Basin Pipeline

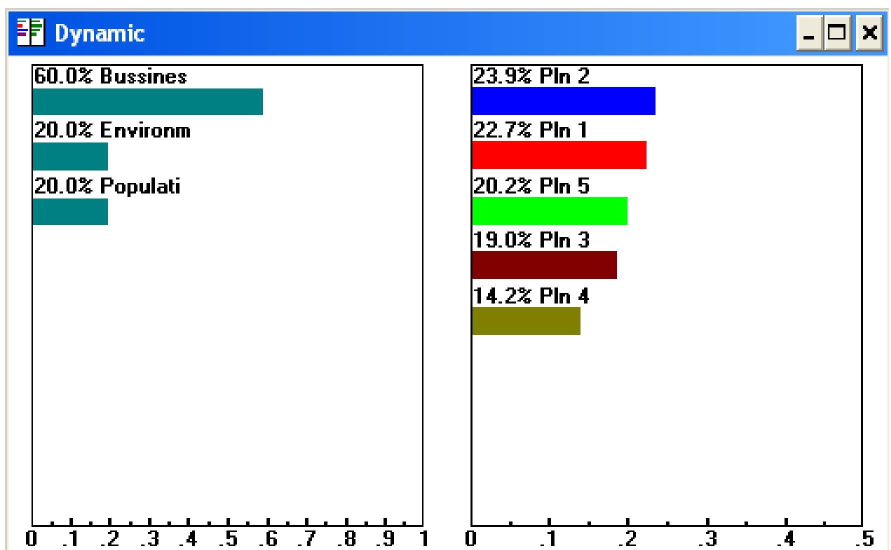

Figure 5.15. Dynamic Sensitivity Graphs for CoF Kutai Basin Pipeline

To view the dynamic changes from priorities of the objectives, dynamic sensitivity analysis is performed for this study as given in Figure 5.12 – 5.15. It shows how changes affect priorities of the alternative. The priority criterion can be drag back and forth in the first column, the priorities of the alternatives will change in the second column.

5.5.3. Gradient

The third way to know sensitivity is through Gradient Sensitivity. This graph explains the composite priority of the alternatives in respect to the priority of a single criterion. Here are the four gradient graphs for each hierarchy:

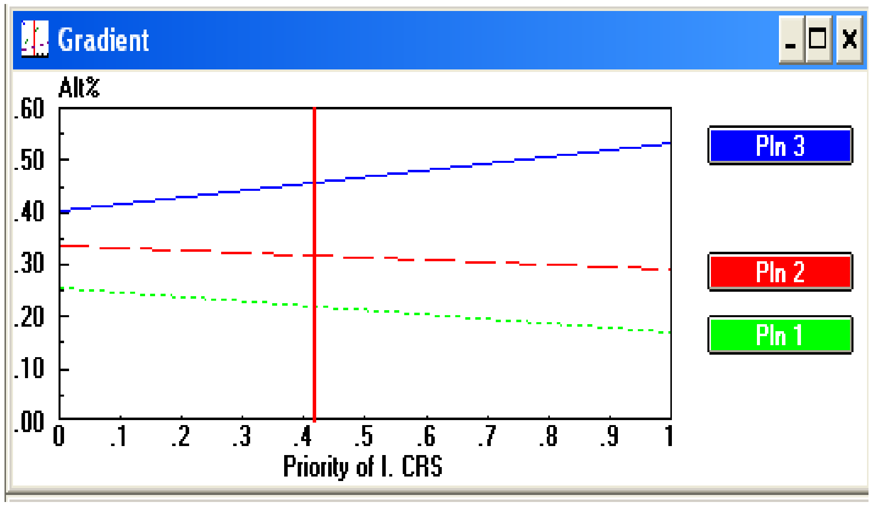

Figure 5.16. Gradient Sensitivity Graphs for PoF Kertih Pipeline

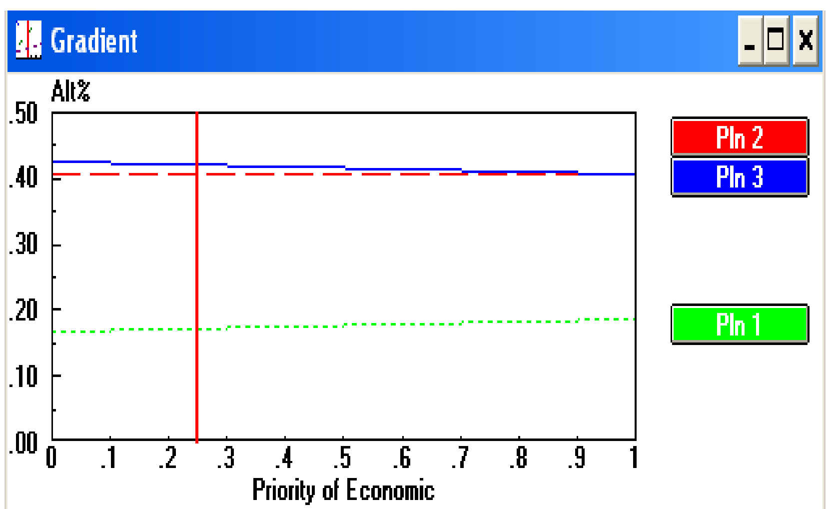

Figure 5.17. Gradient Sensitivity Graphs for CoF Kertih Pipeline

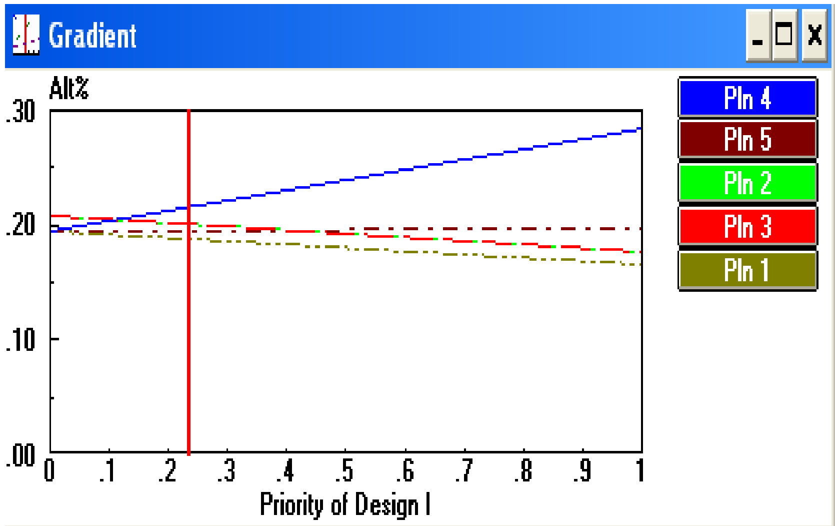

Figure 5.18. Gradient Sensitivity Graphs for PoF Kutai Basin Pipeline

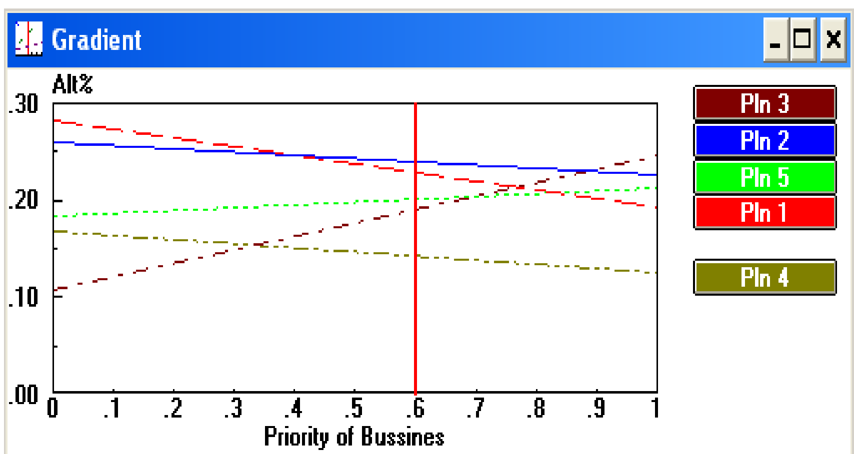

Figure 5.19. Gradient Sensitivity Graphs for CoF Kutai Basin Pipeline

These above graphs 5.16 – 5.19, show that two criteria are mutually compared to each other against the alternatives in a decision. The vertical line represents priority of criterion selected for x axis, and the diagonal lines represent the linear relationships among alternatives in regards to the priority selected for the x axis. Priority of the alternative is the height on y axis in the intersection of the alternative line with the criterion line.

5.5.4. Two Dimensional Plot

The fourth graph to perform the sensitivity analysis is Two Dimensional Plot. The two dimensional plot shows how well the alternatives perform in respect to any two criteria. Here are the four two dimensional plots for each hierarchy:

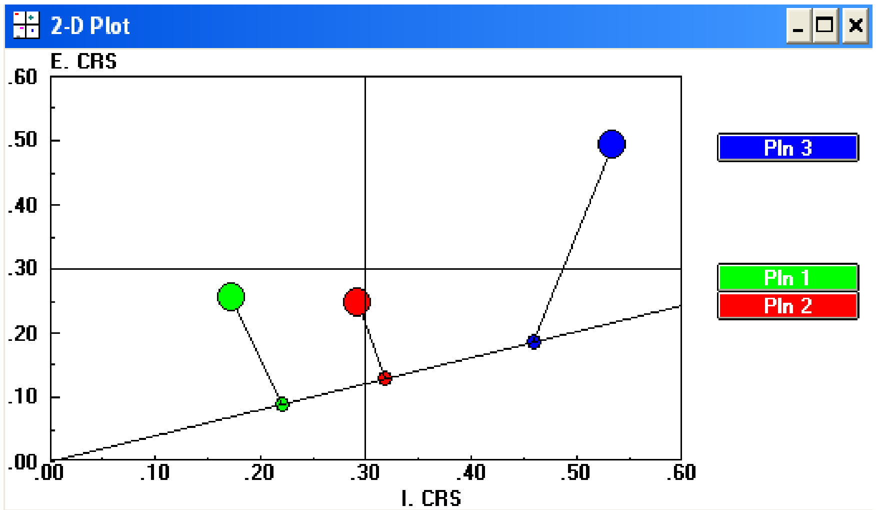

Figure 5.20. Dimensional Plot Sensitivity Graphs for PoF Kertih Pipeline

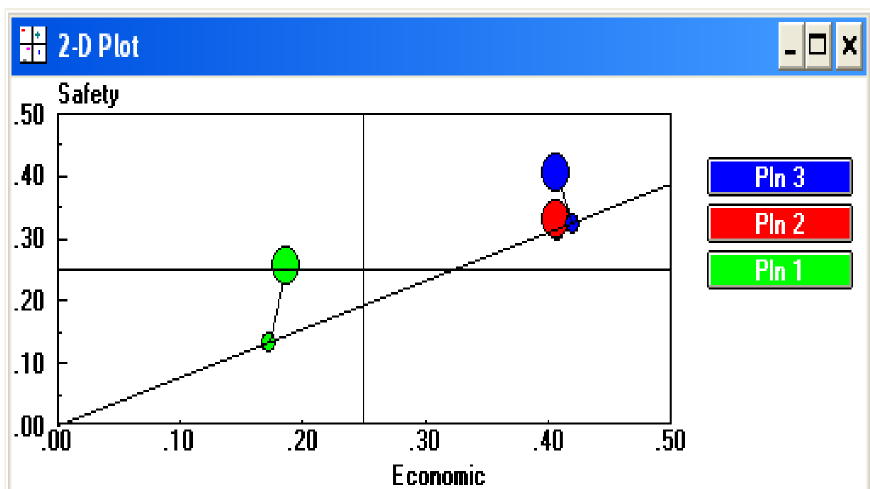

Figure 5.21. Dimensional Plot Sensitivity Graphs for CoF Kertih Pipeline

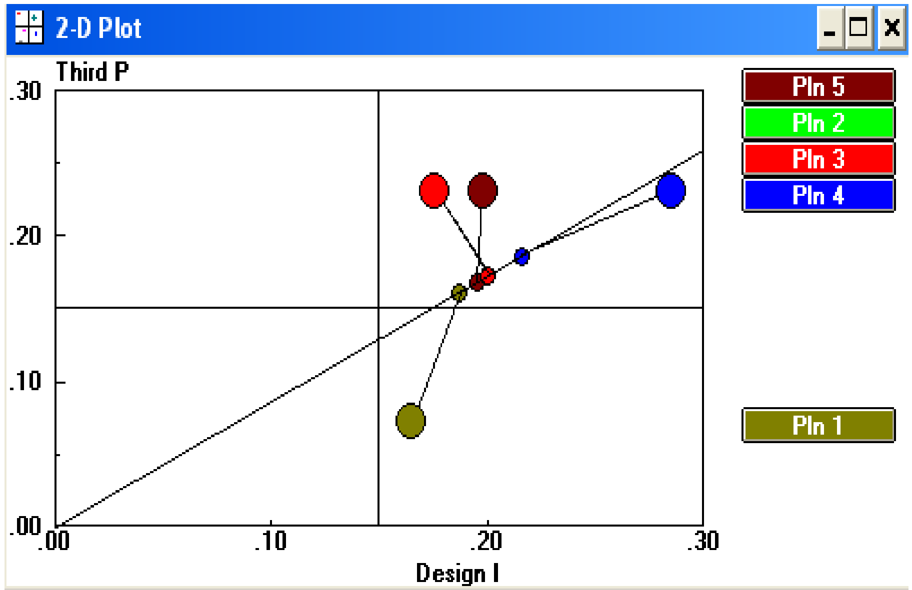

Figure 5.22. Dimensional Plot Sensitivity Graphs for PoF Kutai Basin Pipeline

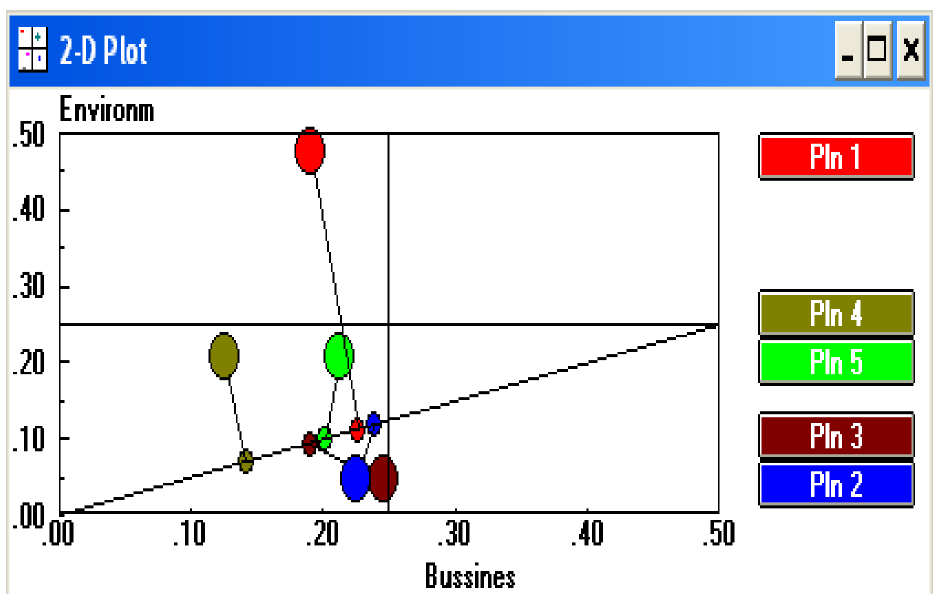

Figure 5.23. Dimensional Plot Sensitivity Graphs for CoF Kutai Basin Pipeline

The two dimensional plot graphs as shown in Figure 5.20 – 5.23 constitute two criteria compared to each other against the alternatives in a decision. Circles represents the alternatives, Y axis represents one criterion and the other on the X axis. The above figure shows the alternatives from the pipeline system in respect to Internal Corrosion and External Corrosion.

5.5.5. Differences

The last graph to investigate the sensitivity analysis is Differences Sensitivity. In the differences graph one of the alternatives is selected in order to be compared against each of the other alternative. Here are the four differences graphs for each hierarchy:

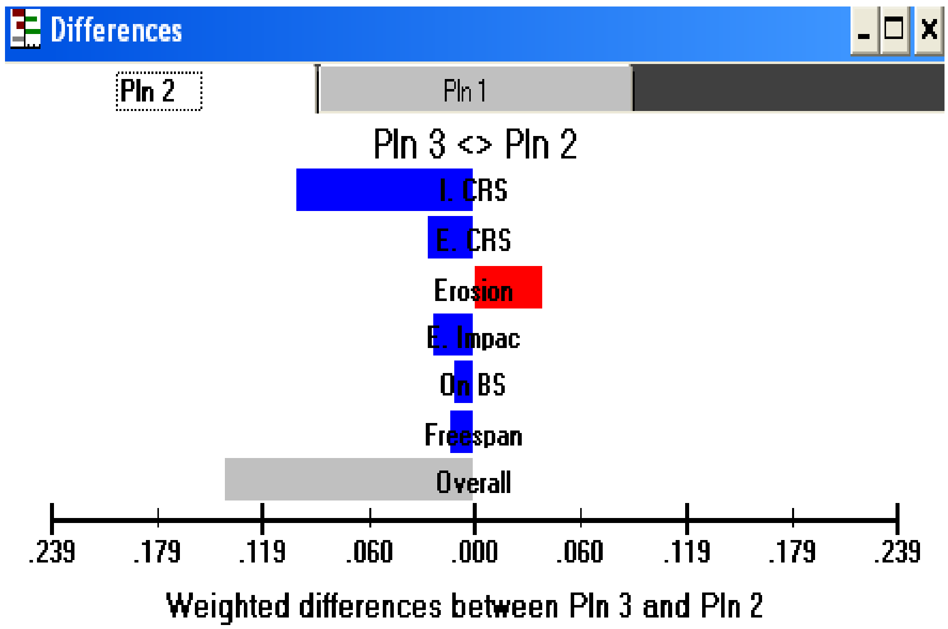

Figure 5.24. Differences Graphs for PoF Kertih Pipeline

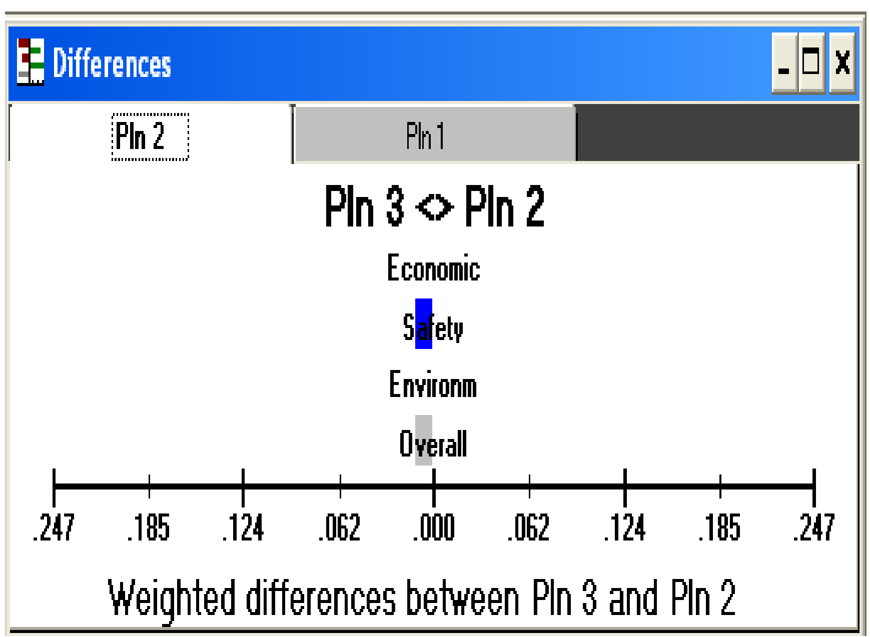

Figure 5.25. Differences Graphs for CoF Kertih Pipeline

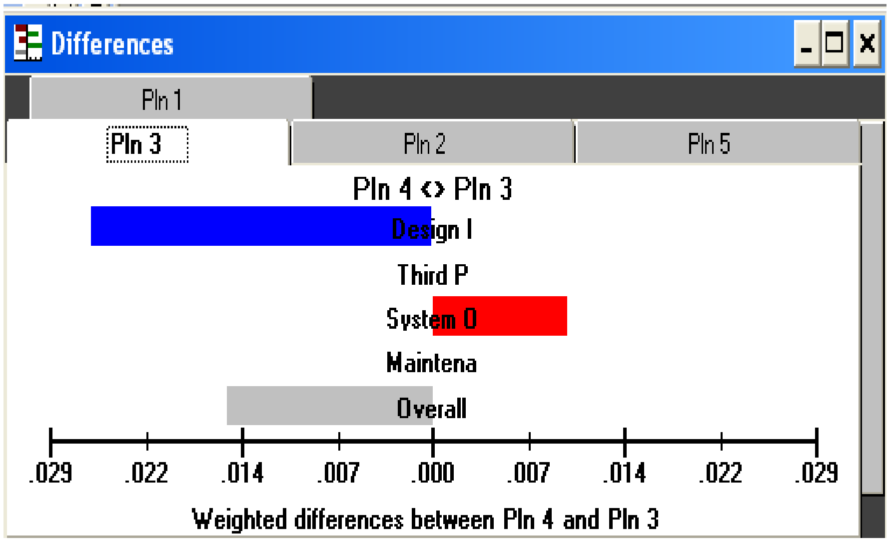

Figure 5.26. Differences Graphs for PoF Kutai Basin Pipeline

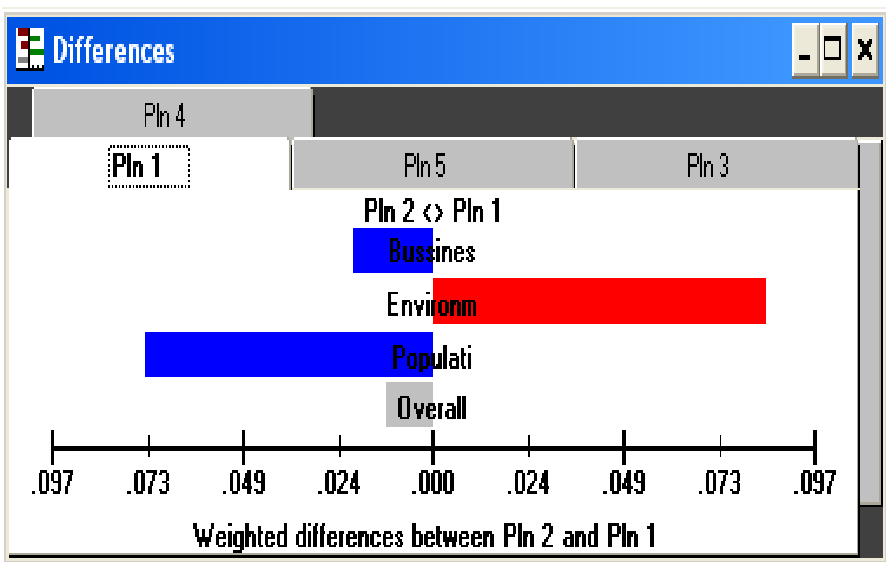

Figure 5.27. Differences Graphs for CoF Kutai Basin Pipeline

In the differences graphs, one of the alternatives is selected to be compared to the rest of the other alternatives. The criteria are differentiated by current node. A bar appears on the graph for each criterion. If two criteria are equal, no bar is displayed. The overall result is displayed at the bottom of the graph and shows the overall percentage with one alternative is better than the other. In figure 5.27 pipelines 2 has higher probability to fail than pipeline 1.

5.5.6. Sensitivity Analysis on PoF Kertih Pipeline

To carry out the performance sensitivity analysis, some scenarios are required to be applied to find the alternatives by increasing or decreasing the priorities. Sensitivity analysis is applied to the Internal Corrosion having the highest weight of 41.7% in respect to the goal. These are four scenarios used to find the priority changes which are 5%, -10%, 5% and 10%. Table 5.15 shows the sensitivity on the amount of changes that may occur.

Table 5.15. Sensitivity Scenario PoF Kertih Pipeline

Scenario	Weight of Priority (%)				Sensitivity (%)		
	I. Corrosion	PLN 1	PLN 2	PLN 3	PLN 1	PLN 2	PLN 3
- 10%	31.7	22.5	32.1	45.4	3.69	1.26	2.58
- 5%	36.7	22.1	31.9	46.0	1.84	0.63	1.29
Original	41.7	21.7	31.7	46.6	-	-	-
5%	46.4	21.4	31.5	47.1	1.07	0.63	1.38
10%	51.8	21.0	31.3	47.7	2.36	1.26	3.23

Table 5.15 shows that by changing the scenario the results obtained have shown the same priority, namely less than 10%. It shows that the results obtained from the analysis are suitable with the condition of the pipeline.

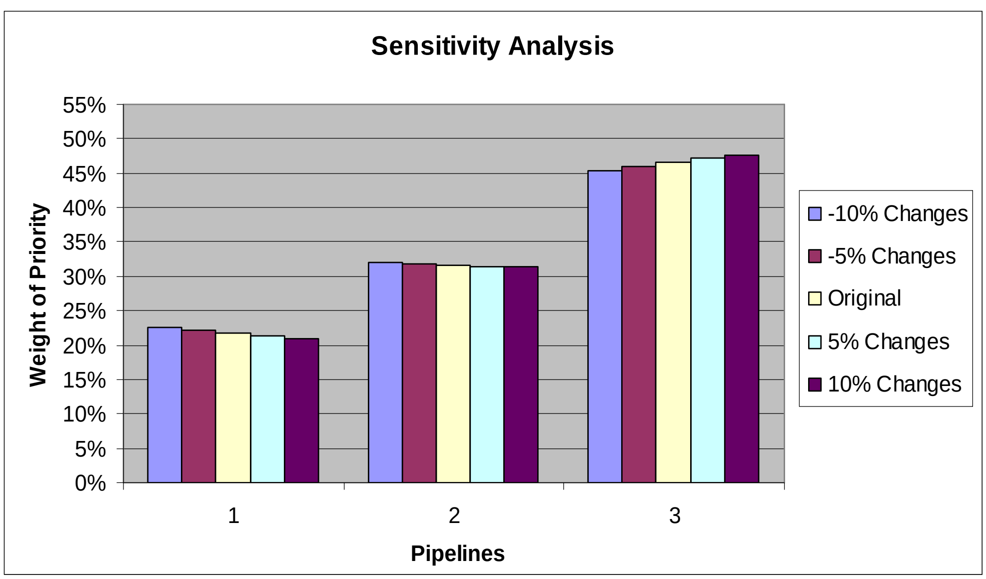

Figure 5.28. Sensitivity Analysis on PoF Kertih Pipeline

5.5.7. Sensitivity Analysis on CoF Kertih Pipeline

Sensitivity analysis is performed on the major factors of Environment, having the highest weight of 59.4% in respect to the goal. These are four different scenarios with the changes of -5%, -10%, 5% and 10% to find the effects on the priority. Table 5.16 shows the sensitivity on the amount of changes that may occur.

Table 5.16. Sensitivity Scenario CoF Kertih Pipeline

Scenario	Weight of Priority (%)				Sensitivity (%)		
	Environment	PLN 1	PLN 2	PLN 3	PLN 1	PLN 2	PLN 3
- 10%	49.4	16.9	40.4	42.7	3.05	1.22	0.23
- 5%	54.4	16.6	40.7	42.7	1.22	0.49	0.23
Original	59.4	16.4	40.9	42.8	-	-	-
5%	64.4	16.1	41.1	42.8	1.83	0.49	-
10%	69.4	15.9	41.4	42.8	3.05	1.22	-

Table 5.16 shows that by changing the scenario the results obtained on Environment have shown the same priority of pipeline alternatives, namely less than 10%. It shows that the results obtained from the analysis are suitable with the condition of the pipeline.

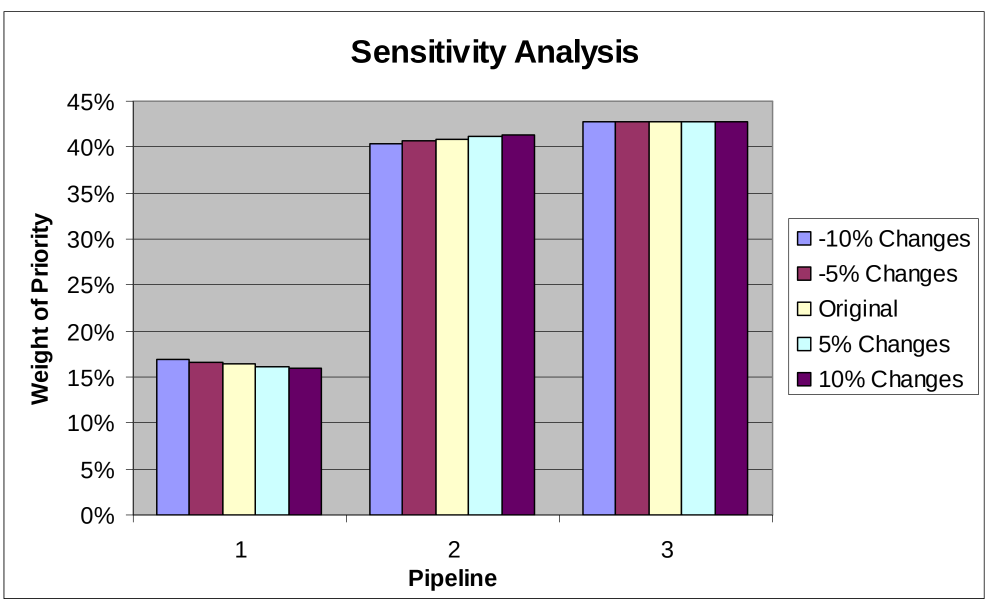

Figure 5.29. Sensitivity Analysis on CoF Kertih Pipeline

5.5.8. Sensitivity Analysis on PoF Kutai Basin Pipeline

Sensitivity analysis is performed on the major factors of System Operation, having the highest weight of 34.7% in respect to the goal. These are four different scenarios with the changes of -5%, -10%, 5% and 10% to find the effects on the priority. Table 5.17 shows the sensitivity on the amount of changes that may occur.

Table 5.17. Sensitivity Scenario PoF Kutai Basin Pipeline

Scenario	Weight of Priority (%)						Sensitivity (%)				
	S. Operation	PLN 1	PLN 2	PLN 3	PLN 4	PLN 5	PLN 1	PLN 2	PLN 3	PLN 4	PLN 5
-10%	24.7	17.7	20	20	22.3	19.9	5.35	0.50	0.50	3.24	2.05
-5%	29.7	18.2	20	20	22	19.7	2.67	0.50	0.50	1.85	1.03
Original	34.7	18.7	20.1	20.1	21.6	19.5	-	-	-	-	-
5%	39.7	19.2	20.1	20.1	21.3	19.4	2.67	0	0	1.39	0.51
10%	44.6	19.7	20.1	20.1	20.9	19.2	5.35	0	0	3.24	1.54

Table 5.17 shows that by changing the scenario, the results obtained on System Operation have shown the same priority of pipeline alternatives, namely less than 10%. It shows that the results obtained from the analysis are suitable with the condition of the pipeline.

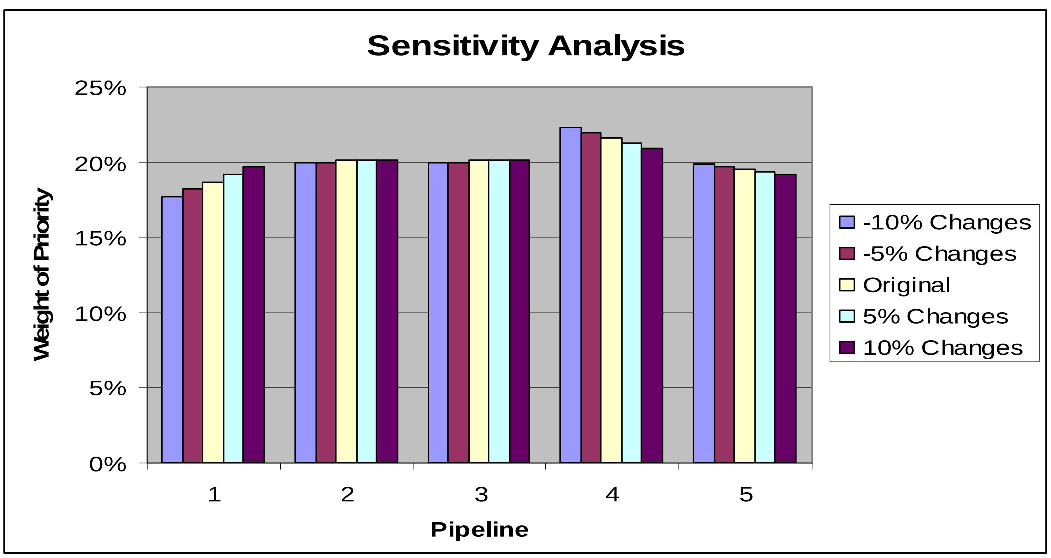

Figure 5.30. Sensitivity Analysis on PoF Kutai Basin Pipeline

5.5.9. Sensitivity Analysis on CoF Kutai Basin Pipeline

Sensitivity analysis is performed on the major factors of Business, having the highest weight of 60% in respect to the goal. These are four different scenarios with the changes of -5%, -10%, 5% and 10% to find the effects on the priority. Table 5.18 shows the sensitivity on the amount of changes that may occur.

Table 5.18. Sensitivity Scenario CoF Kutai Basin Pipeline

Scenario	Weight of Priority (%)						Sensitivity (%)				
	Bussiness	PLN 1	PLN 2	PLN 3	PLN 4	PLN 5	PLN 1	PLN 2	PLN 3	PLN 4	PLN 5
-10%	50	23.8	24.3	17.4	14.7	19.9	4.85	1.67	8.42	3.52	1.49
-5%	55	23.2	24.1	18.2	14.4	20.0	2.20	0.84	4.21	1.41	0.99
Original	60	22.7	23.9	19.0	14.2	20.2	-	-	-	-	-
5%	65	22.2	23.7	19.8	13.9	20.4	2.20	0.84	4.21	2.11	0.99
10%	70	21.7	23.5	20.5	13.7	20.5	4.41	1.67	7.89	3.52	1.49

Table 5.18 shows that by changing the scenario, the results obtained on Business have shown the same priority of pipeline alternatives, namely less than 10%. It shows that the results obtained from the analysis are suitable with the condition of the pipeline.

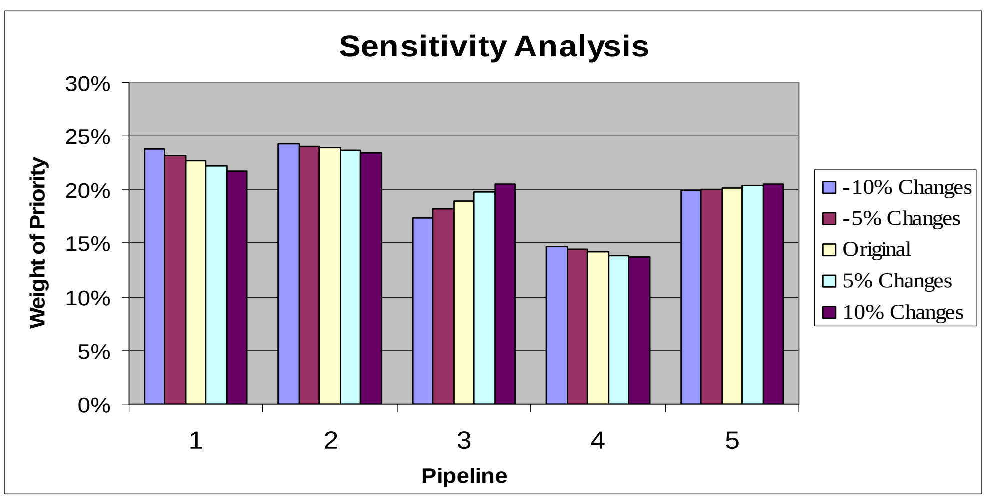

Figure 5.31. Sensitivity Analysis on CoF Kutai Basin Pipelines

5.6. Inspection and Maintenance Plans

The above analysis helps develop a maintenance plans for the entire offshore pipelines network of the pipelines under study. The following maintenances are applied for pipelines under high risk category appropriate for maintenance plans. However based on the research analysis the risk category of both pipeline systems in Kertih and Kutai Basin is low, therefore then the inspection and maintenance below may not be considered or the frequency of inspection may be conducted annually.

Table 5.19. Inspection and Maintenance Plans for Kertih Pipelines

No	Failure Factors	Inspection and Maintenance Plans	Risk	Frequency
1.	Internal Corrosion	• Intelligent pigging	Low	Annual
2.	External Corrosion	• Cathodic Protection • General Visual Inspection (GVI)	Low	Annual
3.	Internal Erosion	• General Visual Inspection (GVI)	Low	Annual
4.	External Impacts	• General Visual Inspection (GVI)	Low	Annual
5.	On Bottom Stability	• General Visual Inspection (GVI)	Low	Annual
6.	Free span	• General Visual Inspection (GVI)	Low	Annual

Table 5.20. Inspection and Maintenance Plans for Kertih Pipelines

No	Failure Factors	Inspection and Maintenance Plans	Risk	Frequency
1.	Design Index	• Intelligent pigging	Low	Annual
2.	Third Party Index	• General Visual Inspection (GVI)	Low	Annual
3.	System Operation	• General Visual Inspection (GVI) • Intelligent pigging	Low	Annual

5.7. Summary of Research Study

This research applies Analytic Hierarchy Process in two different case studies on pipeline systems. The first area is in Kertih, Malaysia carrying gas and the other one is in Kutai Basin, Indonesia carrying oil. As explained in Chapter 4, the first framework in AHP is constructing the hierarchy. There are two hierarchies of each pipeline system. In order to find the risk, the factors that may cause the probability of failure and the impact of pipeline failure must be defined first. Based on the hierarchy, the analysis could be done through matrix pair wise comparison and the highest priority from each hierarchy is found. Sensitivity analysis is used to investigate how the different weight assigned to each factor could affect the outcomes of the hierarchy.

The similarities and the differences between two pipelines can be analyzed by using comparative analysis. The function of comparative analysis is to find the moderation of two different pipeline systems. It is very important to do so because the hierarchy of risk pipeline failure is rather different. By doing comparative analysis, the risk of pipeline failure can be moderate for both pipeline systems.

Analytic Hierarchy Process has been applied in many areas, such as pipeline industry, construction and building, economics, safety and health. This research is trying to find the appropriate maintenance plans of pipeline systems by identifying the risk of pipeline failure. Based on the above analysis it can be seen that AHP is more complete and more accurate analysis than the existing method on one of pipeline system under study.

Based on the previous analysis on moderation of risk pipeline failure as shown in Table 5.9 and Table 5.10, it can be seen that pipeline 1c has tendency towards of pipeline failure. The probability of failure is internal corrosion with 14.7% and would give impact to business at the sum of 7.5%. Using AHP, the factors that lead to pipeline failure can be identified clearly so the proper maintenance can be determined based on the occurring factors. Maintenance plans can be formulated based on the risk category of pipelines. The advantages of pipeline maintenance based on risk analysis are to minimize inspection, maintenance and repair activities which could be dangerous to personnel. The other advantage is to maximize the availability of the pipeline system during its operational life and to maximize the life of pipeline.

CHAPTER 6

RECOMMENDATION & CONCLUSION

6.1. Conclusion

This research is based on case study regarding the prioritization of pipeline maintenance with the help of risk analysis. Two pipeline systems, the one a gas pipeline system operated in Kertih, Malaysia and the second of oil pipeline system operated Kutai Basin, Indonesia are analyzed using Analytic Hierarchy Process (AHP) model. Following are the conclusion drawn in view of the objective of this research.

1. The first objective is to determine the greatest risk factors that govern the pipeline failure. Following are the main findings related to this objective:
   i. Analytical study on three gas pipeline system operated in Kertih Malaysia showed that the Pipeline 3 involved the highest risk factor which is obtained on the basis of calculation of probability and consequence of failure. Internal corrosion is found as the major factor that imposes highest probability of failure i.e. 41.7. The internal corrosion will be promoted by fluid composition and the chemical treatment of fluid. In the event of pipeline failure it will impact upon the environment that will be happened due to pollution and the pipeline size.
   ii. When the five oil pipelines in Kutai Basin are analyzed, it is determined that the Pipeline 2 has the highest risk of failure. The major factor that causes pipeline failure is system operation that is prompted by the cathodic protection, coating condition, metal loss defect, fluid properties and internal corrosion. The consequence of this failure will have significant impact on the business.

   Based on the comparative analysis the moderation of risk pipeline failure can determined for both pipeline system in Kertih and Kutai Basin. The moderation for probability of pipeline failure is internal corrosion, external corrosion, internal erosion, external impact, on bottom stability and free span. And the highest factor that leads to probability of failure is still the same internal corrosion. Moderation for consequence of failure is divided into economy, safety and consequence. The highest impact of pipeline failure is on economy of the pipeline industry.

2. Sensitivity analysis on the major factor of probability of failure and its corresponding consequences are performed using the change of scenario and it is obtained that change in priority as its impact is calculated less than 10%.
3. The final objective is to prioritize the maintenance and inspection of the pipeline system.
   i. For Kertih Malaysia pipeline system maintenance strategy to be formulated based on intelligent pigging, cathodic protection and general visual inspection.
   ii. The maintenance plans for Kutai Basin pipeline will comprise of pigging, debris removal, corrosion inhibitor and general visual inspection.

Since the risk category of pipeline in both pipeline system Kertih and Kutai Basin are into low risk then the inspection and maintenance mentioned above may not be considered or the frequency of inspection may doing annually. The result of moderation Kertih pipeline as pipeline 1 as and Kutai Basin pipeline as pipeline 2 are based on the risk matrix below;

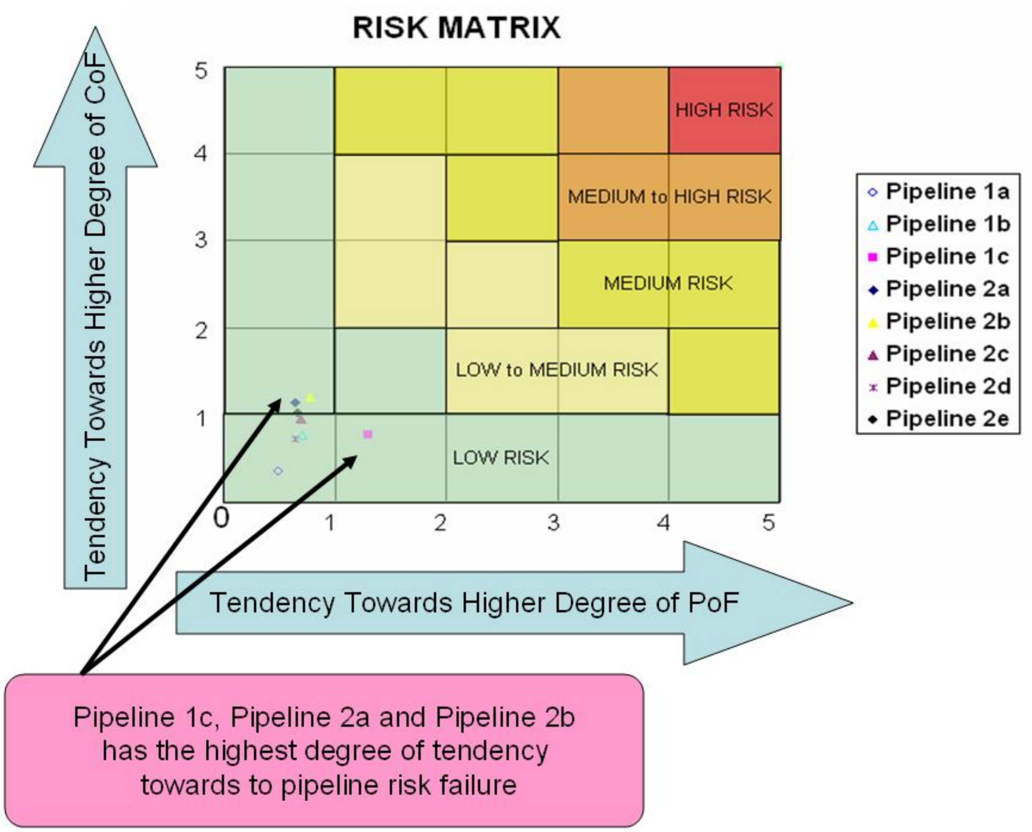

Figure 6.1. Tendency Towards Higher Degree of Pipeline Failure

The highest factor that contributes in pipeline 1c, 2a and 2b have tendency towards of pipeline failure which is internal corrosion. Internal corrosion is related to fluid that is carried by the pipeline. The internal corrosion as highest factor of probability of pipeline failure will be impact on economy of pipeline industry. By knowing and understand the risk of pipeline failure then the maintenance can be determined easily. For example the probability of failure is internal corrosion then the proper maintenance should be pigging.

This research using Analytic Hierarchy Process (AHP) as a tool to decided prioritizing pipeline maintenance. AHP can formulate and calculate the risk pipeline failures which are probability of failure and consequence of failure. After identifying risk pipeline failure has been accomplish then calculate the risk category to formulate the maintenance plans. Compare to the existing method that applied in pipeline industry the maintenance plans only based on inspection and no comparing each factor. This way will performed improper maintenance which may incur unnecessary cost.

6.2. Recommendations

This research used two case studies for the analysis application, where one could develop by reviewing various type of location, company and contractor. This is important to find the probability of pipeline failure because it will depends on the various locations and company to threat the pipeline for maintenance. Other recommendations may include:

1. Carry out research on various type of multi criteria decision making and make comparison to identify the best methodology for determining risk analysis.
2. Adding more information on the pipeline failure causes and the pipeline under study.

PUBLICATIONS

i. 4th Asian Pipeline Conference and Exhibition (APCE) on 19-20 November 2008 at the Berjaya Times Square Hotel, Kuala Lumpur. Prioritizing the Pipeline Maintenance Approach Using Analytical Hierarchy Process (Paper Presented).

ii. International Graduate Conference on Engineering and Science on 23-24 December 2008 at Skudai Campus, Johor Bahru. Prioritizing the Maintenance of Pipelines (Paper Presented).

iii. 7th Asia Pacific Structural Engineering and Construction Conference 2009 (APSEC 2009) and 2nd European Asian Civil Engineering Forum (EACEF 2009) on 4-6 August 2009 in Langkawi. Risk Analysis of Pipelines Maintenance (Paper Accepted).

iv. National Postgraduate Conference 2009 on 25-26 March 2009 in Universiti Teknologi PETRONAS Tronoh Perak Malaysia. Sensitivity Analysis of Pipeline Failure (Paper Accepted).

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APPENDIX A

THE PAIRWISE COMPARISON OF KERTIH PIPELINE

A1. Probability of Failure

Comparison of factors with respect to goal

Factors	Internal Corrosion	External Corrosion	Internal Erosion	External Impacts	On Bottom Stability	Free span	Priority
Internal Corrosion	1	4	5	4	3	3	0.417
External Corrosion	1/4	1	1/2	1/3	3	2	0.107
Internal Erosion	1/5	2	1	3	2	3	0.191
External Impacts	¼	3	1/3	1	2	2	0.138
On Bottom Stability	1/3	1/3	1/2	½	1	½	0.067
Free span	1/3	1/2	1/3	½	2	1	0.081
Consistency Index : 0.137							
Random Index : 1.24							
Consistency Ratio : 0.11							

Comparison of sub factors with respect to Internal Corrosion

Internal Corrosion	Fluid Composition	Improper Chemical Treatment of Fluid	Priority
Fluid Composition	1	2	0.667
Improper Chemical Treatment of Fluid	1/2	1	0.333
Consistency Index : 0			
Random Index : 0			
Consistency Ratio : 0			

Comparison of sub factors with respect to External Corrosion

External Corrosion	Damage Coating	Damage Anodes	Defect From Construction	Priority
Damage Coating	1	2	2	0.493
Damage Anodes	1/2	1	2	0.311
Defect From Construction	1/2	1/2	1	0.196
Consistency Index : 0.03				
Random Index : 0.58				
Consistency Ratio : 0.05				

Comparison of sub factors with respect to Internal Erosion

Internal Erosion	Flow Characteristic	Pipeline Design	Priority
Flow Characteristic	1	1/3	0.25
Pipeline Design	3	1	0.75
Consistency Index : 0			
Random Index : 0			
Consistency Ratio : 0			

Comparison of sub factors with respect to External Impacts

External Impacts	Impacts from Dropped Objects	Fish Bombing	Priority
Impacts from Dropped Objects	1	2	0.667
Fish Bombing	1/2	1	0.333
Consistency Index : 0			
Random Index : 0			
Consistency Ratio : 0			

Comparison of sub factors with respect to On Bottom Stability

On Bottom Stability	Seabed Movement	Loss of Weight Coating	Priority
Seabed Movement	1	3	0.75
Loss of Weight Coating	1/3	1	0.25
Consistency Index : 0			
Random Index : 0			
Consistency Ratio : 0			

Comparison of sub factors with respect to Freespan

Freespan	Seabed Scouring	Pipeline On Bottom Instability	Seabed Undulations	Priority
Seabed Scouring	1	3	2	0.550
Pipeline On Bottom Instability	1/3	1	1	0.210
Seabed Undulations	1/2	1	1	0.240
Consistency Index : 0.0116				
Random Index : 0.58				
Consistency Ratio : 0.02				

Comparison of alternative with respect to Fluid Composition

Fluid C.	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1/3	1/3	0.140
Pipeline 2	3	1	1/2	0.333
Pipeline 3	3	2	1	0.528
Consistency Index : 0.03				
Random Index : 0.58				
Consistency Ratio : 0.05				

Comparison of alternative with respect to Improper Chemical Treatment of Fluid

Improper Chemical	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1	½	0.24
Pipeline 2	1	1	1/3	0.21
Pipeline 3	2	3	1	0.55
Consistency Index : 0.01				
Random Index : 0.58				
Consistency Ratio : 0.02				

Comparison of alternative with respect to Damage Coating

Damage Coating	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1	1	0.327
Pipeline 2	1	1	1/2	0.260
Pipeline 3	1	2	1	0.413
Consistency Index : 0.03				
Random Index : 0.58				
Consistency Ratio : 0.05				

Comparison of alternative with respect to Damage Anodes

Damage Anodes	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1/2	1/3	0.151
Pipeline 2	2	1	1/4	0.218
Pipeline 3	3	4	1	0.630
Consistency Index : 0.06				
Random Index : 0.58				
Consistency Ratio : 0.1				

Comparison of alternative with respect to Defect from Construction

Defect from Construction	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1/2	1/3	0.157
Pipeline 2	2	1	1/3	0.249
Pipeline 3	3	3	1	0.594
Consistency Index : 0.03				
Random Index : 0.58				
Consistency Ratio : 0.05				

Comparison of alternative with respect to Flow Characteristic

Flow Characteristic	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1/2	1/3	0.157
Pipeline 2	2	1	1/3	0.249
Pipeline 3	3	3	12	0.594
Consistency Index : 0.03				
Random Index : 0.58				
Consistency Ratio : 0.05				

Comparison of alternative with respect to Pipeline Design

Pipeline Design	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1/2	2	0.297
Pipeline 2	2	1	3	0.540
Pipeline 3	1/2	1/3	1	0.163
Consistency Index : 0.01				
Random Index : 0.58				
Consistency Ratio : 0.01				

Comparison of alternative with respect to Impact from Dropped Objects

Impact from Dropped O.	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1/2	½	0.196
Pipeline 2	2	1	1/2	0.311
Pipeline 3	2	2	1	0.492
Consistency Index : 0.03				
Random Index : 0.58				
Consistency Ratio : 0.05				

Comparison of alternative with respect to Fish Bombing

Fish Bombing	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1	1	0.327
Pipeline 2	1	1	1/2	0.260
Pipeline 3	1	2	1	0.413
Consistency Index : 0.03				
Random Index : 0.58				
Consistency Ratio : 0.05				

Comparison of alternative with respect to Seabed Movement

Seabed Movement	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1/2	½	0.190
Pipeline 2	2	1	1/3	0.263
Pipeline 3	2	3	1	0.547
Consistency Index : 0.08				
Random Index : 0.58				
Consistency Ratio : 0.13				

Comparison of alternative with respect to Loss of Weight Coating

Loss of Weight Coating	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	2	2	0.493
Pipeline 2	½	1	2	0.311
Pipeline 3	1/2	1/2	1	0.196
Consistency Index : 0.03				
Random Index : 0.58				
Consistency Ratio : 0.05				

Comparison of alternative with respect to Seabed Scouring

Seabed Scouring	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1/2	1/3	0.163
Pipeline 2	2	1	1/2	0.297
Pipeline 3	3	2	1	0.540
Consistency Index : 0.01				
Random Index : 0.58				
Consistency Ratio : 0.01				

Comparison of alternative with respect to Pipeline On Bottom Instability

Pipeline On Bottom Instability	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1	½	0.240
Pipeline 2	1	1	1/3	0.210
Pipeline 3	2	3	1	0.550
Consistency Index : 0.01				
Random Index : 0.58				
Consistency Ratio : 0.02				

Comparison of alternative with respect to Seabed Undulations

Seabed Undulations	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1/2	½	0.190
Pipeline 2	2	1	1/3	0.263
Pipeline 3	2	3	1	0.547
Consistency Index : 0.08				
Random Index : 0.58				
Consistency Ratio : 0.13				

A2. Consequence of Failure

Comparison of alternative with respect to Goal

Goal	Economic	Safety	Environmental	Priority
Economic	1	2	1/3	0.249
Safety	1/2	1	1/3	0.157
Environmental	3	3	1	0.594
Consistency Index : 0.029				
Random Index : 0.58				
Consistency Ratio : 0.05				

Comparison of alternative with respect to Economic

Economic	Repair Cost	Business Loss	Priority
Repair Cost	1	1/3	0.250
Business Loss	3	1	0.750
Consistency Index : 0.0			
Random Index : 0.58			
Consistency Ratio : 0.0			

Comparison of alternative with respect to Safety

Economic	Product Transported	Manning On Installation	Priority
Product Transported	1	3	0.750
Manning On Installation	1/3	1	0.250
Consistency Index : 0.0			
Random Index : 0.58			
Consistency Ratio : 0.0			

Comparison of alternative with respect to Environmental

Environmental	Pollution	Pipeline Size	Priority
Pollution	1	1	0.500
Pipeline Size	1	1	0.500
Consistency Index : 0.0			
Random Index : 0.58			
Consistency Ratio : 0.0			

Comparison of alternative with respect to Repair Cost

Repair Cost	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1/3	1/3	0.143
Pipeline 2	3	1	1	0.429
Pipeline 3	3	1	1	0.429
Consistency Index : 0.0				
Random Index : 0.58				
Consistency Ratio : 0.0				

Comparison of alternative with respect to Business Loss

Business Loss	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1/2	1/2	0.200
Pipeline 2	2	1	1	0.400
Pipeline 3	2	1	1	0.400
Consistency Index : 0.0				
Random Index : 0.58				
Consistency Ratio : 0.0				

Comparison of alternative with respect to Product Transported

Product Transported	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1/3	1/3	0.140
Pipeline 2	3	1	1/2	0.333
Pipeline 3	3	2	1	0.528
Consistency Index : 0.029				
Random Index : 0.58				
Consistency Ratio : 0.05				

Comparison of alternative with respect to Manning On Installation

Manning On Installation	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1	1	0.333
Pipeline 2	1	1	1	0.333
Pipeline 3	1	1	1	0.333
Consistency Index : 0.0				
Random Index : 0.58				
Consistency Ratio : 0.0				

Comparison of alternative with respect to Pollution

Pollution	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1/3	1/3	0.143
Pipeline 2	3	1	1	0.429
Pipeline 3	2	1	1	0.429
Consistency Index : 0.0				
Random Index : 0.58				
Consistency Ratio : 0.0				

Comparison of alternative with respect to Pipeline Size

Pipeline Size	Pipeline 1	Pipeline 2	Pipeline 3	Priority
Pipeline 1	1	1/3	1/3	0.143
Pipeline 2	3	1	1	0.429
Pipeline 3	3	1	1	0.429
Consistency Index : 0.0				
Random Index : 0.58				
Consistency Ratio : 0.0				

APPENDIX B

THE PAIRWISE COMPARISON OF KUTAI BASIN PIPELINE

B1. Probability of Failure

Comparison of factors with respect to goal

Factors	Design Index	Third Party Index	System Operation	Maintenance	Priority
Design Index	1	2	1/2	1	0.237
Third Party Index	1/2	1	1	1/2	0.180
System Operation	2	1	1	2	0.347
Maintenance	1	2	1/2	1	0.237
Consistency Index : 0.081					
Random Index : 0.90					
Consistency Ratio : 0.09					

Comparison of sub factors with respect to Design Index

Design Index	Age	Operating Pressure	Priority
Age	1	2	0.667
Operating Pressure	1/2	1	0.333
Consistency Index : 0			
Random Index : 0			
Consistency Ratio : 0			

Comparison of sub factors with respect to Third Party Index

Third Party Index	ROW Condition	Patrol Frequency	Above Pipeline A.	Priority
ROW Condition	1	1	½	0.232
Patrol Frequency	1	1	1/4	0.184
Above Pipeline Activity	2	4	1	0.584
Consistency Index : 0.029				
Random Index : 0.58				
Consistency Ratio : 0.05				

Comparison of factors with respect to System Operation

System Operation	Cathodic Protection	Coating Condition	Metal Loss	Fluid Properties	Internal Corrosion	Priority
Cathodic Protection	1	1	1/2	1	1/3	0.125
Coating Condition	1	1	1/2	1	1/3	0.125
Metal Loss	2	2	1	2	1/2	0.239
Fluid Properties	1	1	1/2	1	1/2	0.138
Internal Corrosion	3	3	2	2	1	0.373
Consistency Index : 0.011						
Random Index : 1.12						
Consistency Ratio : 0.01						

Comparison of sub factors with respect to Maintenance

Maintenance	Pigging	Debris	Corrosion Inhibitor	Priority
Pigging	1	1	1	0.333
Debris	1	1	1	0.333
Corrosion Inhibitor	1	1	1	0.333
Consistency Index : 0.00				
Random Index : 0.58				
Consistency Ratio : 0.00				

Comparison of alternative with respect to Age

Age	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	1	1/3	1/4	1/3	0.085
Pipeline 2	1	1	1/2	1/3	1/2	0.106
Pipeline 3	3	2	1	1/2	1	0.216
Pipeline 4	4	3	2	1	2	0.377
Pipeline 5	3	2	1	1/2	1	0.216
Consistency Index : 0.012						
Random Index : 1.12						
Consistency Ratio : 0.01						

Comparison of alternative with respect to Operating Pressure

Operating Pressure	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	1	3	4	2	0.325
Pipeline 2	1	1	3	2	3	0.316
Pipeline 3	1/3	1/3	1	1	1/2	0.096
Pipeline 4	1/4	½	1	1	1/2	0.101
Pipeline 5	1/2	1/3	2	2	1	0.161
Consistency Index : 0.0224						
Random Index : 1.12						
Consistency Ratio : 0.02						

Comparison of alternative with respect to ROW Condition

ROW Condition	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	1	1	1	1	0.200
Pipeline 2	1	1	1	1	1	0.200
Pipeline 3	1	1	1	1	1	0.200
Pipeline 4	1	1	1	1	1	0.200
Pipeline 5	1	1	1	1	1	0.200
Consistency Index : 0.0						
Random Index : 1.12						
Consistency Ratio : 0.0						

Comparison of alternative with respect to Patrol Frequency

Patrol Frequency	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	1/4	1/4	1/4	1/4	0.059
Pipeline 2	4	1	1	1	1	0.235
Pipeline 3	4	1	1	1	1	0.235
Pipeline 4	4	1	1	1	1	0.235
Pipeline 5	4	1	1	1	1	0.235
Consistency Index : 0.0						
Random Index : 1.12						
Consistency Ratio : 0.0						

Comparison of alternative with respect to Above Pipeline Activity

Above Pipeline A.	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	1/9	1/9	1/9	1/9	0.027
Pipeline 2	9	1	1	1	1	0.243
Pipeline 3	9	1	1	1	1	0.243
Pipeline 4	9	1	1	1	1	0.243
Pipeline 5	9	1	1	1	1	0.243
Consistency Index : 0						
Random Index : 1.12						
Consistency Ratio : 0.00						

Comparison of alternative with respect to Cathodic Protection

Cathodic Protection	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	1	1	5	5	0.294
Pipeline 2	1	1	1	5	5	0.294
Pipeline 3	1	1	1	5	5	0.294
Pipeline 4	1/5	1/5	1/5	1	1	0.059
Pipeline 5	1/5	1/5	1/5	1	1	0.059
Consistency Index : 0						
Random Index : 1.12						
Consistency Ratio : 0.00						

Comparison of alternative with respect to Coating Condition

Coating Condition	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	1	1	1	1	0.200
Pipeline 2	1	1	1	1	1	0.200
Pipeline 3	1	1	1	1	1	0.200
Pipeline 4	1	1	1	1	1	0.200
Pipeline 5	1	1	1	1	1	0.200
Consistency Index : 0						
Random Index : 1.12						
Consistency Ratio : 0.00						

Comparison of alternative with respect to Metal Loss Defect

Metal Loss Defect	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	1	1	1	1	0.200
Pipeline 2	1	1	1	1	1	0.200
Pipeline 3	1	1	1	1	1	0.200
Pipeline 4	1	1	1	1	1	0.200
Pipeline 5	1	1	1	1	1	0.200
Consistency Index : 0						
Random Index : 1.12						
Consistency Ratio : 0.00						

Comparison of alternative with respect to Fluid Properties

Fluid Properties	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	4	4	4	4	0.500
Pipeline 2	1/4	1	1	1	1	0.125
Pipeline 3	1/4	1	1	1	1	0.125
Pipeline 4	1/4	1	1	1	1	0.125
Pipeline 5	1/4	1	1	1	1	0.125
Consistency Index : 0						
Random Index : 1.12						
Consistency Ratio : 0.00						

Comparison of alternative with respect to Internal Corrosion

Internal Corrosion	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	1	1	1	1	0.200
Pipeline 2	1	1	1	1	1	0.200
Pipeline 3	1	1	1	1	1	0.200
Pipeline 4	1	1	1	1	1	0.200
Pipeline 5	1	1	1	1	1	0.200
Consistency Index : 0						
Random Index : 1.12						
Consistency Ratio : 0.00						

Comparison of alternative with respect to Pigging

Pigging	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	1	1	1	1	0.200
Pipeline 2	1	1	1	1	1	0.200
Pipeline 3	1	1	1	1	1	0.200
Pipeline 4	1	1	1	1	1	0.200
Pipeline 5	1	1	1	1	1	0.200
Consistency Index : 0						
Random Index : 1.12						
Consistency Ratio : 0.00						

Comparison of alternative with respect to Debris Removal

Debris	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	1	1	1	1	0.200
Pipeline 2	1	1	1	1	1	0.200
Pipeline 3	1	1	1	1	1	0.200
Pipeline 4	1	1	1	1	1	0.200
Pipeline 5	1	1	1	1	1	0.200
Consistency Index : 0						
Random Index : 1.12						
Consistency Ratio : 0.00						

Comparison of alternative with respect to Corrosion Inhibitor

Corrosion Inhibitor	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	1	1	1	1	0.200
Pipeline 2	1	1	1	1	1	0.200
Pipeline 3	1	1	1	1	1	0.200
Pipeline 4	1	1	1	1	1	0.200
Pipeline 5	1	1	1	1	1	0.200
Consistency Index : 0						
Random Index : 1.12						
Consistency Ratio : 0.00						

B2. Consequence of Failure

Comparison of alternative with respect to Goal

Goal	Business	Environment	Population	Priority
Business	1	3	3	0.600
Environment	1/3	1	1	0.200
Population	1/3	1	1	0.200
Consistency Index : 0.0				
Random Index : 0.58				
Consistency Ratio : 0.00				

Comparison of alternative with respect to Business

Business	Sales Line	Redundancy	Oil Flow	Volume	Priority
Sales Line	1	3	2	2	0.415
Redundancy	1/3	1	1/3	1/2	0.107
Oil Flow	1/2	3	1	2	0.293
Volume	1/2	2	1/2	1	0.185
Consistency Index : 0.034					
Random Index : 1.12					
Consistency Ratio : 0.03					

Comparison of alternative with respect to Environment (Property Damage)

Property Damage	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	7	7	3	3	0.479
Pipeline 2	1/7	1	1	1/5	1/5	0.049
Pipeline 3	1/7	1	1	1/5	1/5	0.049
Pipeline 4	1/3	5	5	1	1	0.211
Pipeline 5	1/3	5	5	1	1	0.211
Consistency Index : 0.022						
Random Index : 1.12						
Consistency Ratio : 0.02						

Comparison of alternative with respect to Population

Population	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	1/4	1	1	1	0.124
Pipeline 2	4	1	4	4	4	0.495
Pipeline 3	1	1/4	1	1/2	1/2	0.096
Pipeline 4	1	1/4	2	1	1	0.143
Pipeline 5	1	1/4	2	1	1	0.143
Consistency Index : 0.022						
Random Index : 1.12						
Consistency Ratio : 0.02						

Comparison of alternative with respect to Sales Line

Sales Line	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	4	1/2	5	2	0.289
Pipeline 2	1/4	1	1/5	1	1/5	0.060
Pipeline 3	2	5	1	5	1	0.339
Pipeline 4	1/5	1	1/5	1	1/5	0.057
Pipeline 5	1/2	5	1	5	1	0.256
Consistency Index : 0.045						
Random Index : 1.12						
Consistency Ratio : 0.04						

Comparison of alternative with respect to Redundancy

Redundancy	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	1/9	1/9	1/8	1/9	0.027
Pipeline 2	9	1	1	1	2	0.283
Pipeline 3	9	1	1	1	1	0.241
Pipeline 4	8	1	1	1	1	0.236
Pipeline 5	9	1/2	1	1	1	0.213
Consistency Index : 0.011						
Random Index : 1.12						
Consistency Ratio : 0.01						

Comparison of alternative with respect to Oil Flow

Oil Flow	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	1/3	1	1	1/2	0.118
Pipeline 2	3	1	4	4	4	0.477
Pipeline 3	1	1/4	1	2	1	0.146
Pipeline 4	1	1/4	1/2	1	1	0.111
Pipeline 5	2	1/4	1	1	1	0.148
Consistency Index : 0.034						
Random Index : 1.12						
Consistency Ratio : 0.03						

Comparison of alternative with respect to Volume

Volume	Pipeline 1	Pipeline 2	Pipeline 3	Pipeline 4	Pipeline 5	Priority
Pipeline 1	1	1/2	1	1	1	0.171
Pipeline 2	2	1	2	1	1	0.264
Pipeline 3	1	1/2	1	1	1	0.171
Pipeline 4	1	1	1	1	1	0.197
Pipeline 5	1	1	1	1	1	0.197
Consistency Index : 0.022						
Random Index : 1.12						
Consistency Ratio : 0.02						