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Optimizing Pipeline Inspection Program to Balance Safety, Compliance, and Cost Efficiency: A Case Study at Petrotama

Primasatria Zhes Putra, Akbar Adhi Utama
Institut Teknologi Bandung, Indonesia
Email: primasatria_putra@sbm-itb.ac.id, akbar@sbm-itb.ac.id

ABSTRACT

PetroTama operates a vast pipeline network that supports the production of 160,000 barrels of oil per day, accounting for 26% of Indonesia's daily production. These pipelines are vital for PetroTama, making them one of the main critical assets for sustaining production performance. To maintain production capacity, PetroTama must ensure the safety and reliability of its entire pipeline network, which can only be achieved through a robust pipeline inspection program. However, currently, only 37% of the network has been inspected, leaving 5,480 km of pipelines without inspection data. This exposes PetroTama to significant risks concerning safety, compliance, and cost efficiency. This study aims to evaluate the current conditions, identify root causes, and propose solutions for optimizing PetroTama's pipeline inspection program using the DMAIC (Define, Measure, Analyze, Improve, Control) methodology. The analysis using Current Reality Tree (CRT) reveals two main root causes: budgetary constraints and lack of regular improvement in the inspection program. The proposed solution focuses on improving the inspection program, with budget availability assumed as a fixed condition. The Analytical Hierarchy Process (AHP), combined with Spreadsheet Simulation, is used to determine the best business solutions. The solutions are evaluated based on safety, compliance, and cost efficiency criteria. Key recommendations include implementing a combined time-based and risk-based inspection program, supported by an adequate budget, CMMS utilization, inspection contracts, and a continuous improvement program.

KEYWORDS *Pipeline Inspection Program, Operational Safety, Regulatory Compliance, Cost Efficiency, Analytical Hierarchy Process*

INTRODUCTION

The oil and gas industries are at the heart of maintaining the world's energy supply, powering transportation, electricity, and other industrial operations. Despite the increased integration of renewable energy sources, fossil fuels continue to dominate over 80% of the world's total primary energy consumption, as per the International Energy Agency (IEA, 2023). The projected demand for natural gas and oil is likely to remain significant in the coming decades, particularly in developing economies, where industrialization and urbanization processes continue to drive the rise in energy consumption (Khan et al., 2021).

Despite the relevance of oil and gas infrastructure to support energy supply, the sector faces large-scale operational challenges due to aging infrastructure. Most of the assets across the globe were commissioned several decades ago, and as these facilities approach the end of their design life, issues such as structural deterioration, corrosion, and mechanical faults become increasingly common (Iqbal et al., 2017; Burns, 2019). Research by Xie and Tian (2018) points out that a large percentage of the world's pipelines are more than 40 years old, contributing to high maintenance expenditures and operational hazards. The United States alone has over 2.6 million miles of pipeline, much of which was built prior to the 1980s and requires extensive inspection and rehabilitation (American Petroleum Institute, 2020). The dangers posed by the aging infrastructure of oil and gas activities are three-dimensional, including safety risks, environmental damage, and economic liabilities.

One of the most important infrastructures in this industry is the pipeline, which primarily functions as a safe, efficient, and cost-effective means of transporting fluids, such as crude oil, natural gas, and other hydrocarbons, across vast distances. As it surpasses its designed lifespan, pipelines become more susceptible to leakages and accidents, posing serious environmental hazards. Therefore, pipeline integrity plays a very important role in safety and sustainability. This underlines such risks that demand the industry to be aggressive with asset management strategies (Lu et al., 2019).

Failure in pipeline infrastructure can result in catastrophic incidents, including explosions, oil spills, and the release of toxic gases, thereby causing direct harm to human life and environmental ecosystems (Soedarsono et al., 2023). The Deepwater Horizon spill in 2010 and the pipeline burst in North Dakota in 2013 are some of the ravaging effects associated with pipeline failure due to degradation and ineffective maintenance practices (Eskandarzade et al., 2022).

From an economic perspective, unexpected pipeline failure results in sudden operational shutdowns, supply disruption, and huge financial losses to producers and consumers (Khan et al., 2021). With these risks, pipeline integrity management has been an industry priority. Traditionally, inspections were conducted at regular intervals, i.e., time-based inspections, but this method is now becoming more inefficient as it is not able to discriminate between high-risk and low-risk zones (Iqbal et al., 2017; Abbassi et al., 2022; Babayeju et al., 2024). Hence, risk-based inspection (RBI) models have become more significant, enabling operators to prioritize maintenance activities based on the risk profiles (Xie & Tian, 2018; Ali & Sabry, 2019; Chin et al., 2020; Babayeju et al., 2024). This practice delivers enhanced safety while reducing unnecessary expenses.

Indonesia, as one of the major oil and gas producers in Southeast Asia, relies heavily on its network of pipelines to transport hydrocarbons across its archipelago. However, many of these pipelines were built decades ago, raising concerns over their structural integrity and environmental impacts (Soedarsono et al., 2023). PetroTama, the operator of one of Indonesia's biggest oil fields in Riau province, faces similar challenges, particularly with regards to its aging pipeline system.

PetroTama operates an extensive pipeline network to support the production of 160,000 barrels of oil per day, equivalent to 26% of Indonesia’s daily production, generating approximately 11 million USD in daily revenue. These pipelines serve as the main oil transportation system for PetroTama, making it one of the critical assets that sustain production performance. In order to maintain production capacity, PetroTama must ensure that the entire pipeline network operates safely and reliably. This can only be achieved by implementing a robust pipeline inspection program that proactively identifies potential integrity threats such as corrosion, defects, mechanical damage, and others (American Petroleum Institute, 2019). Periodical inspections allow for the detection of anomalies at an early stage, enabling PetroTama to conduct timely proactive maintenance interventions and avoid catastrophic outcomes (Ma et al., 2021). It also provides required information for conducting further assessment or evaluation of pipeline conditions so that anomalies can be identified early before they become failures that disrupt operations.

Research by Iqbal et al. (2017) and Xie & Tian (2018) emphasizes the challenges associated with aging oil and gas pipeline infrastructure and highlights the increasing need for effective pipeline inspection methods. Iqbal et al. (2017) argue that the traditional time-based inspection model is inefficient, particularly for older pipelines, as it does not differentiate between high-risk and low-risk zones. This leads to the need for more advanced risk-based inspection (RBI) strategies. Similarly, Xie and Tian (2018) discuss the large-scale issue of pipeline degradation, citing that many pipelines, particularly those in the U.S., are over 40 years old, which raises concerns about their safety and operational reliability. These findings underscore the importance of implementing effective inspection and maintenance strategies to mitigate the risks posed by aging infrastructure. However, both studies primarily focus on broader global challenges without specifically examining the unique operational dynamics and regulatory frameworks of specific countries, such as Indonesia.

This research focuses on optimizing the inspection program at PetroTama's extensive pipeline network. The scope of the study includes evaluating the existing inspection practices, identifying gaps and areas for improvement, and proposing an optimized framework emphasizing the implementation of risk-based inspection (RBI) methodologies to improve safety, compliance, and cost efficiency. Specifically, the research investigates variables in inspection intervals, inspection methods, and inspection coverage. The proposed framework should be aligned with the available budget and regulatory requirements set by Permen ESDM No. 32 Tahun 2021.

The main limitation of this study is that it is restricted to available data on pipeline conditions and financial constraints, which may limit the viability and actual execution of the recommended system. Furthermore, the research study is limited to only those operational factors of pipeline inspection and maintenance at PetroTama operations, excluding other external factors related to the environment or economic fluctuations that may impact the effectiveness of an inspection program.

The aim of this study is to evaluate the existing pipeline inspection practices at PetroTama, identify gaps in the current system, and propose an optimized inspection framework that incorporates risk-based inspection (RBI) methodologies. By doing so, the study seeks to enhance the safety, efficiency, and cost-effectiveness of the inspection process while ensuring compliance with regulatory requirements. The findings of this study will be beneficial for PetroTama in improving operational safety, reducing potential risks associated with aging pipelines, and ensuring a more efficient maintenance program that contributes to the overall sustainability of Indonesia's energy sector.

METHOD

The research design for this study followed the DMAIC flow process (Figure 1), beginning with problem identification at PetroTama regarding challenges related to aging pipeline inspections. These challenges included inadequate inspection coverage, reduced budgets for these activities, and non-compliance with updated regulations (*Permen ESDM No. 32 Tahun 2021*). The objectives of the research were framed based on these critical issues, aiming to explore better ways to optimize pipeline inspection programs effectively.

The next step involved measuring the current condition and creating baseline metrics that reflected the existing inspection program's performance. A root cause analysis was then conducted, comprising a review of both the current state of pipeline inspection practices and the ideal state of achieving safety, compliance, and cost-efficient inspection strategies. The current reality tree methodology was used to identify shortcomings in coverage, regulatory compliance, and budget allocation.

The improvement stage began with data collection from quantitative sources, such as pipeline data, risk profiles, financial records, and regulatory compliance, followed by qualitative sources from the Manager of Asset Integrity & Reliability and SMEs. Inspection method options were referred to applicable standards, such as American Petroleum Institute (API) 570 and American Petroleum Institute (API) RP 574. Further research focused on the elaboration of alternative solutions by proposing several frameworks: time-based inspection, risk-based inspection, and hybrid approaches.

The proposed alternatives were then tested in the decision analysis phase for feasibility, cost efficiency, and conformance with regulatory mandates. The analysis tools used in this research were Analytical Hierarchy Process (AHP) and spreadsheet simulations. This approach enhanced the overall decision-making process, ensuring a structured evaluation of alternative solutions.

The output was to propose a business solution that incorporated an optimized inspection framework, integrating risk-based methodologies to maximize safety and compliance while minimizing costs. This framework was accompanied by an implementation plan that provided a detailed roadmap for a long-term inspection program, meeting regulatory requirements and operational goals.

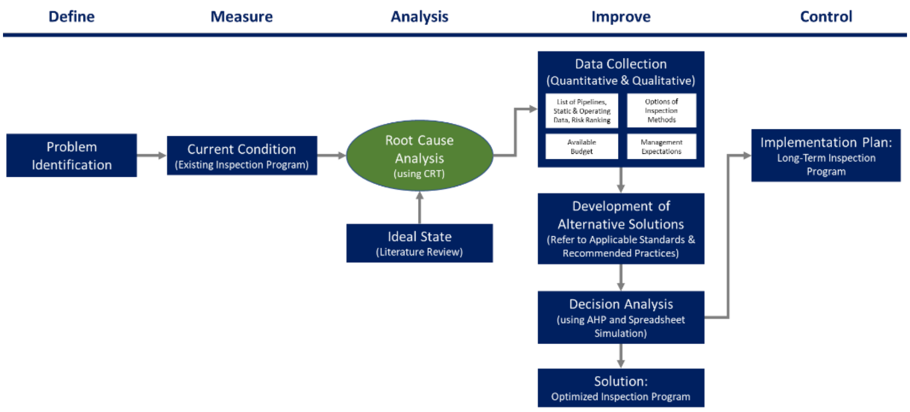

Figure 1. Research Design Process

RESULTS AND DISCUSSION

The first stage of DMAIC framework is to Define the problem. The business issue that is covered in this study is the gap in the inspection program, where only 37% of pipeline in PetroTama's operation area has been inspected to date. The impacts of this gap are significant, which are loss of production opportunity due to pipeline failures that have been happened for years and violation to Government regulation.

The easiest way to accelerate the inspection coverage towards 100% inspected pipelines is by increasing the budget allocation for inspection program, so that PetroTama can utilize much more inspection crew to conduct massive inspection program. But this approach cannot be done due to declining operational expenditure (OPEX) for pipeline integrity management in recent years, as shown in Figure 4. In 2024, the total budget for pipeline integrity management program is about USD 6 million, consist of USD 4.5 million for pipeline inspection activities and USD 1.5 million for other activities.

The existing inspection program implemented for PetroTama's pipeline network is still using the time-based approach, with a 5-years interval applied for all pipeline segments without considering the risk level. This approach incurs an annual OPEX ranging from USD 4 to 5 million, covering pipeline inspection program for 800 – 1000 km in length.

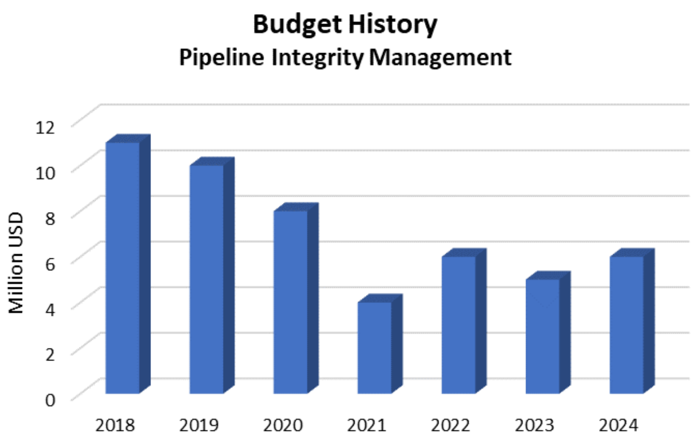

Figure 2. OPEX for Pipeline Integrity Management
(Source: PetroTama's internal data, 2024)

Under this budgetary constraint, time-based inspection approach is no longer relevant and requires transition to risk-based inspection (RBI) which is more efficient and more focus to critical infrastructures (Singh et al., 2018, Leoni et al., 2021, Adewoyin, 2022, Han et al., 2024, Hanson et al., 2024). RBI method set up a more formal and analytical approach, prioritizing risk as the primary driver for inspection planning (Mohamed et al., 2018, Adewoyin, 2022, Han et al., 2024). Pipelines with no inspection data are exposed with high probability of failure. This risk is further heightened by the fact that over 90% of pipelines in PetroTama have been in operation for over their design life (20 years), as shown in Figure 3.

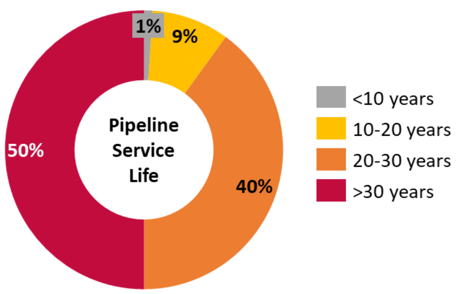

Figure 3. PetroTama's Pipeline Service Life Distribution
(Source: PetroTama's internal data, 2024)

PetroTama has a strong commitment and focus on safety performance. This is demonstrated by the establishment of stringent KPI target related to safety aspect, such as zero tolerance for fatality and number of accident (NoA). However, the absence of inspection data for certain pipelines introduces the risk of safety accidents such as fire or explosion, exposure to hazardous liquid, and potential harm to personnel or community.

The pipeline integrity management cycle consists of 4 major phases, which are Plan-Do-Check-Act. The inspection activities itself is on the "Do" phase, but these activities are relied on what is planned in the "Plan" phase where the Engineers develop the assessment plan that includes the inspection program. RBI mentioned in the previous paragraph is also part of the "Plan" phase and can be the input for inspection program development.

In developing pipeline inspection program, the activities can be divided into 2 types, which are re-inspection activity and baseline inspection activity. Re-inspection activity refer to inspection conducted on pipelines that have been inspected on its previous interval, whereas baseline inspections are performed on pipelines that have not been inspected before.

In existing inspection program, the inspection method is defined based on pipeline category, as shown in Table 1.

Table 1. Pipeline Inspection Method in Existing Inspection Program

Pipeline Category	Inspection Method
Trunkline	ILI, LRUT
Production Line & Gas Line	ILI, LRUT, UT, PECT
Non Hydrocarbon - Large Size	UT, PECT
Flowlines	LRUT, UT
Non Hydrocarbon - Small Size	UT, PECT

Currently there are several options of inspection method supported by PetroTama inspection contracts, where each method has specific cost (unit-rate/pipeline length or segment) as shown in the Table 2.

Table 2. Unit Rate of Pipeline Inspection Method

Method	Unit Rate (per Length-m)	Unit Rate (per Segment)
Ultrasonic Testing (UT)	1.78	
Long-Range Ultrasonic Testing (LRUT)	17.76	
LRUT+UT	6.66	
Inline Inspection (ILI)		310,800
Pulsed Eddy Current Testing (PECT)	13.32	
PECT Partial	8.88	
UT Partial	0.44	
Visual Testing (VT)	0.13	

Assuming that annual budget allocation for inspection activities of USD 4.5 million, the distribution of inspection lengths and corresponding costs of each method are given in Table 3, while the breakdown of inspection lengths and cost by inspection status (re-inspection or baseline) is provided in Table 4.

Table 3. Current Inspection Program based on Method

Inspection Method	Total Length (m)	Total Cost (USD)
UT	804,425	1,428,660
LRUT	64,659	1,148,340
LRUT+UT	-	-
ILI	81,468	1,838,843
PECT	6,318	84,158
PECT Partial	-	-
UT Partial	-	-
VT	-	-
Total	956,871	4,500,000

Table 4. Current Inspection Program based on Status

Inspection Status	Total Length (m)	Total Cost (USD)
Re-inspection	459,684	3,246,552
Baseline Inspection	497,187	1,253,448

Based on above data, baseline inspection activities can only cover ~497 km of pipeline per year in average, which means that it will need 11 years to inspect all 63% (5,480 km) of uninspected pipeline if PetroTama maintain to use current inspection strategy without any improvement. To prevent such undesirable accidents, PetroTama must undertake an acceleration of the baseline inspection activities to ensure that all pipelines have inspection data.

In addition to safety aspect, the business issue discussed also impact the company compliance to regulation. Pipelines without valid technical inspection data cannot proceed the issuance of "persetujuan layak operasi" (PLO) as mandated by Permen ESDM No. 32 Tahun 2021. This condition indicates that currently PetroTama is violating regulatory requirements, potentially exposing it to sanctions by the Government such as partial operational suspension or even a complete shutdown. Moreover, this regulation also requires oil and gas pipelines which are already in operation should be regularly inspected at a certain interval and will have maximum validity of 4 years from the latest inspection period. This requires PetroTama to review the inspection intervals for hydrocarbon pipelines in order to align with regulation.

In existing inspection program, hydrocarbon pipelines use 5 years intervals indicating the necessity for improvement initiative. Based on the data base, total length of pipelines included in the scope of this regulation is 6,889 km. Under the existing program, there are only 3,741 km of pipelines in scope that can be inspected in the next 4 years, as shown in Table 5. Since the validity of PLO is limited up to 4 years, then this coverage is not enough to fully comply with the regulations.

Table 5. Total of Inspected Pipeline (PLO Scope) in the Next 4 years

Total Inspected Pipeline (PLO Scope) in the Next 4 Years (m)	**3,740,872**
Total Pipeline (PLO Scope) (m)	6,889,661
% Compliance in the Next 4 Years	54%

In terms of cost efficiency, the performance is often measured using a unit cost metric, such as cost per length of pipeline inspected (meter or miles). Ossai, Boswell, and Davies (2016) are used this metric to conduct comparative analysis of different inspection strategies over a certain planning time horizon.

Refer to Table 5, total pipeline in PLO scope is 6,889 km, which means that PetroTama has to inspect minimum 1,722 km pipeline per year under the budget constraint (maximum 4.5 million USD) to comply with regulation. This target may be expressed through the following unit cost metric:

$$Cost\ to\ Length\ Ratio = \frac{Annual\ Ins.Cost}{Annual\ Ins.Length} = \frac{USD\ 4.5\ million}{1{,}722{,}415\ m} = 2.61\ USD/m$$

For the existing inspection program, the ratio is as follows:

$$Cost\ to\ Length\ Ratio = \frac{Annual\ Ins.Cost}{Annual\ Ins.Length} = \frac{USD\ 4.5\ million}{956{,}871\ m} = 4.70\ USD/m$$

The second stage of DMAIC framework is to Measure the problem, which focuses on establishing a quantitative baseline performance for each Critical to Quality (CTQ) parameter. The purpose is to understand existing condition, know how to measure the process, and create a baseline metrics that reflect the existing performance. Summarizing the problem exploration in above Define stage, there are 3 CTQ aspects that can be used to measure the inspection program performance, which are Safety, Compliance, and Cost Efficiency. The metrics and baseline performance for each aspect can be measured quantitatively as follows:

a. Safety

The Safety aspect is limited to preventing pipeline failures that can impact PetroTama's financial and safety performance. PetroTama's has to conduct inspections on the previously uninspected pipeline segments (baseline inspection), as they may contain undetected defects such as corrosion, wall thinning, or structural damage that will increase the probability of failure. The metric to measure this aspect is how fast the inspection program can complete the baseline inspection, with maximum timeframe 10 years as expected by the management.

b. Compliance

To comply with government regulatory, all hydrocarbon pipelines should be inspected and have PLO. The metric to measure this aspect is how the program can increase the number of certified pipeline segments in the future years and ensure that its inspection intervals align with regulatory requirements. Since the validity of PLO is limited up to 4 years, the target should be 100% pipelines in PLO scope has certification in the next 4 years. The other metrics is to evaluate the number of pipelines in PLO scope that comply with maximum 4 years inspection interval, with 100% target.

c. Cost Efficiency

To optimize pipeline inspection cost, the total length of inspected pipelines in a year should be increased. The metric to measure this aspect is how the program can decrease the ratio of inspection cost (USD) divided by total pipeline length (m) per year. The target for this metrics is aligned with the minimum requirements for regulatory compliant described in the Define stage, which is 2.61 USD/m.

Based on the above analysis, the CTQ for this study can be summarized as follows:

Table 6. CTQ Parameter for Pipeline Inspection Program

CTQ Aspect	Metric Definition
Safety	Duration (in years) to complete baseline inspection
Compliance – Certification	% of PLO compliance within 4 years duration
Compliance – Interval	% of inspection interval compliance
Cost Efficiency	Ratio of annual inspection cost (USD) divided by annual pipeline inspection length (m)

Table 6 describes the CTQ parameter for pipeline inspection program, which consist of four CTQ aspects: Safety, Compliance – Certification, Compliance – Interval, and Cost Efficiency. This table also describes the definition of each metric that will later be used to calculate the baseline performance and compare each criterion with the others.

The next step is to measure the existing inspection program performance as the baseline metrics. Performance data is obtained from company data base, then employed to calculate the current performance. Table 7 describes the baseline performance calculation results that are already detailed in the Define stage and their corresponding performance targets.

Table 7. Baseline Performance

CTQ Aspect	Current Performance	Target Performance
Safety	11 years	< 10 years
Compliance – Certification	54%	100%
Compliance – Interval	0%	100%
Cost Efficiency	4.70 USD/m	< 2.61 USD/m

The third stage of DMAIC framework is to conduct root cause analysis. The root causes of the problem are analyzed using the Current Reality Tree (CRT) method. As explained in define and measure stage, there are three main undesirable effects (UDEs) related to the problem:

a) Pipeline failures
b) Non-compliance with government regulations
c) Cost inefficiency

The pipelines failures are caused by the aging condition of pipelines and the large proportion of uninspected segments that have never been inspected. The problems run back to the absence of inspection data and pipeline inspection activities, both of which are constrained by budget and still no improvement on existing inspection program. In the meantime, the absence of a pipeline replacement project worsens the aging facilities, again due to insufficient budget availability.

Non-compliance due to the absence of a valid "persetujuan layak operasi" (PLO) is primarily caused by invalid certificate of inspection (COI) due to the unavailability of inspection data and overdue inspection activities with interval more than four years. This is an indication of non-conformity with the relevant regulation and an inactive inspection program that has not been upgraded to requirements. Pipelines thus operate without compliance with legal and safety requirements.

Cost inefficiency, the third of the significant issues, is a consequence of the use of the improper inspection methods and frequencies. Inefficiency here is primarily due to the absence of a risk-based model of inspection, which would allow the company to schedule according to risk levels rather than predetermined schedules. The company's inability to use this process is again a result of the inability to enhance the overall inspection program.

The CRT identifies two primary root causes: budgetary constraints and no improvement on the inspection program. These root causes contribute to the systemic issues that cause pipeline failures, legal non-compliance, and inefficient utilization of budget. The budget for pipeline inspection activities tends to decrease over the years, where the allocated budget is set at USD 4.5 million, and this is considered as fixed condition that difficult to change. The other root cause is no improvement on the inspection program, meaning that asset integrity team has not yet conducted a comprehensive review on the existing inspection program, resulting several gaps related to inspection coverage, compliance with regulations, and missed the opportunity to apply risk-based inspection methods that help in maximizing cost savings. For the solution, author will be focused on the improvement of inspection program, since the budget availability is considered as a given condition.

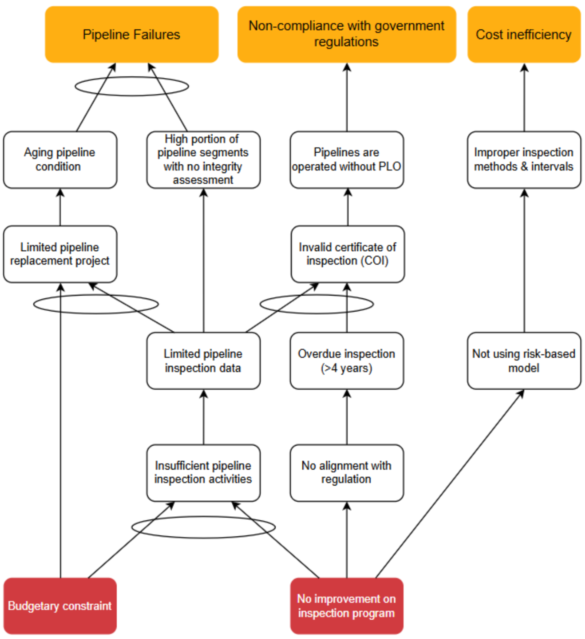

Figure 4. Current Reality Tree

The fourth stage of DMAIC framework is the to develop alternative solutions and conducting decision analysis. The alternative solutions are developed through discussion with several SMEs from asset integrity and inspection team as the main stakeholders for the development process of inspection program. The next step is decision analysis process using the analytical hierarchy process (AHP) approach, that is conducted to select the best solution for the problem.

Development of inspection program process are required several inputs (data and/or references), which are pipeline data, risk ranking, available budget, applicable standards and recommended practices, and regulatory requirements. SIPOC diagram is used to visualize the process, identify the input-process-output, and determine the desired goals to be achieved in order to solve the business issue. This SIPOC diagram is aligned with Conceptual Framework. The goals to be achieved in this improvement initiative are:

a. Accelerating the completion of the baseline inspection program to prevent pipeline failures that could impact safety and financial performance
b. Comply with government regulation, by ensuring that all hydrocarbon pipelines have certificate of inspection (COI) and "*persetujuan layak operasi*" (PLO)
c. Optimize yearly inspection cost, to ensure inspection program can be executed under budget constraint

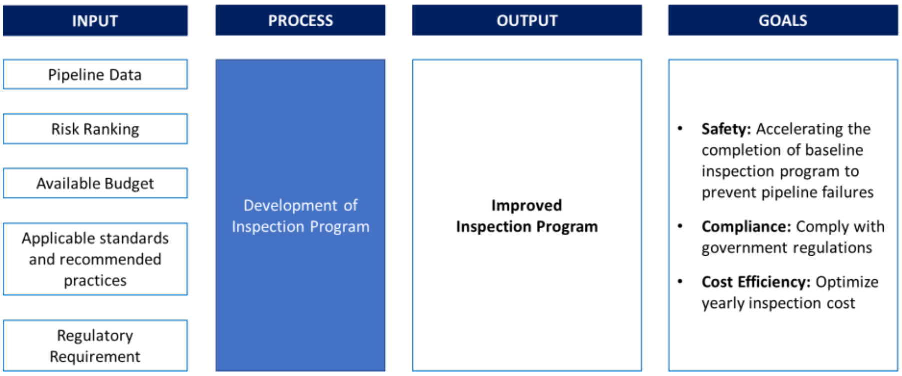

Figure 5. SIPOC Diagram

Figure 5shows the SIPOC diagram for this improvement process. The development of inspection program in the process box is conducted using spreadsheet simulation that consist list of pipeline data, including its size and length that will be impacted to inspection cost of each pipeline segment when combined with selected inspection method and interval. According to piping inspection code (API 570), selecting of the inspection method and interval is equally important. Inspection intervals that are too long may increase the risk of failure, while excessive frequency of inspection can lead to unnecessary downtime and cost.

Table 8 describes the comparison summary of each alternatives that are generated through FGD among SMEs as follows:

1. Existing inspection program: as-is inspection program without any improvement. This time-based inspection program refers to American Petroleum Institute 570 (Piping Inspection Code), the international standard that is widely used in oil and gas industry.
2. Enhanced time-based inspection program: apply time-based inspection program to all pipelines, with improvement on intervals for hydrocarbon pipelines from previously 5-years to 4-years. This alternative also refers to American Petroleum Institute 570 (Piping Inspection Code) and Permen ESDM No. 32 Tahun 2021.
3. Full risk-based inspection program: apply risk-based inspection program to all pipelines, where inspection methods and intervals are determined based on risk level. This risk-based inspection approach refers to American Petroleum Institute RP 580 (Risk-Based Inspection), the international standard that is widely used in oil and gas industry.
4. Combined time-based and risk-based inspection program: apply both time-based and risk-based inspection program to all pipelines. Inspection methods are determined based on risk level, whereas inspection intervals are determined by considering the service fluid. Hydrocarbon pipelines use 4 years time-based interval to comply with regulation, while non-hydrocarbon pipelines are determined based on risk (consequence) level. This approach refers to American Petroleum Institute RP 580 (Risk-Based Inspection) and Permen ESDM No. 32 Tahun 2021.

Table 8. Comparison of Alternative Solutions

No	Alternatives	Inspection Method	Inspection Interval
1	Existing inspection program	Based on pipeline category (Trunkline, Production Line, Flowline, Non-Hydrocarbon, etc.)	5 years for in-scope pipelines
2	Enhanced time-based inspection	Based on pipeline category (Trunkline, Production Line, Flowline, Non-Hydrocarbon, etc.)	4 years for hydrocarbon pipelines and 5 years for others
3	Full risk-based inspection	Based on risk level	Intervals based on risk (consequence level)
4	Combined time-based and risk-based inspection	Based on risk level	For hydrocarbon pipelines: 4 years interval, for non-HC pipelines: intervals based on risk (consequence level)

Spreadsheet simulations are then conducted to all the above alternatives to measure the performance as described in the measure stage. Table 9 describes the data that is used in the spreadsheet simulation, which consist of more than 22,000 pipeline segments, with various diameter (3 inch up to 40 inch) and length (from 1m up to 76,000m).

Table 9. Summary of Pipeline Data used in Spreadsheet Simulation

Number of Pipeline Segments	22,741 segments
Types of Service Fluid	Oil, Gas, Produced Fluids, Condensate, Steam, Water, etc.
Variation of Size or Diameter	min: 3 inch; max: 40 inch
Variation of Length	min: 1 meter; max: 76,441 meter
Variation of Year Built	1950 - 2018
Variation of Risk Ranking	High, Moderate-High, Moderate, Moderate-Low, Low
Variation of Inspection Method	ILI, LRUT, LRUT Partial, PECT, PECT Partial, UT, UT Partial, VT

The simulation results are as follows:

a. Safety

The projection of total uninspected pipeline segments in the next 10 years by using each alternative 1 – 4 are shown in the following charts. The charts (Figure 6 – 9) show the average annual inspection length that are divided to re-inspection (blue bars) and baseline inspection (grey bars). The red line illustrates the projection of total inspected pipeline which increases every year, up to the next 10 years. This red line indicates the results of performance metrics for Safety aspect.

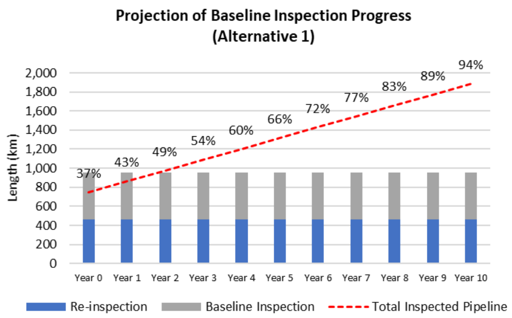

Figure 6. Projection of Baseline Inspection Progress (Alternative 1)

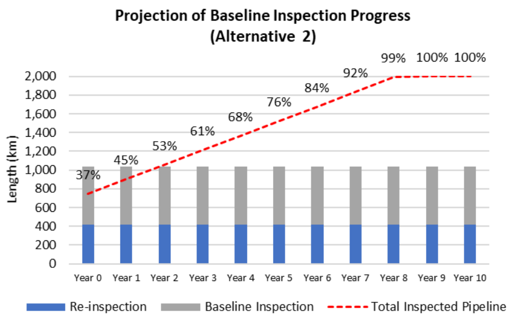

Figure 7. Projection of Baseline Inspection Progress (Alternative 2)

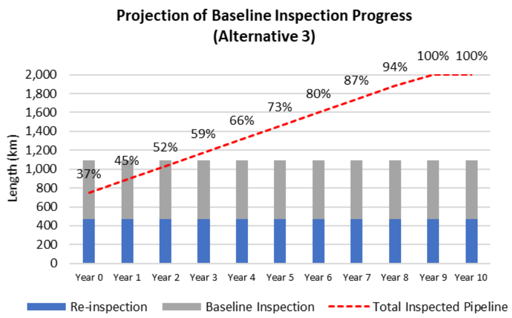

Figure 8. Projection of Baseline Inspection Progress (Alternative 3)

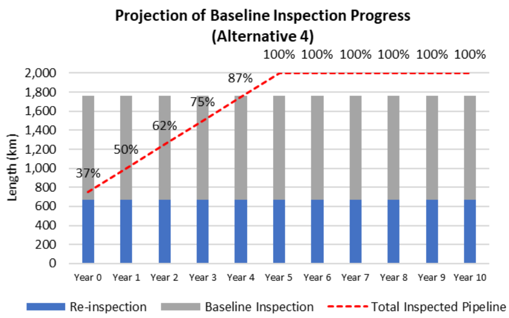

Figure 9. Projection of Baseline Inspection Progress (Alternative 4)

b. Compliance

The following charts (Figure 10 – 13) shows the projection of total certified pipeline segments in the next 4 years and the composition of regulatory-compliant inspection interval by applying each alternative 1 – 4. The left chart illustrates percentage of certified pipelines in the next 4 years and the right chart illustrates percentage of pipelines with regulatory-compliant intervals.

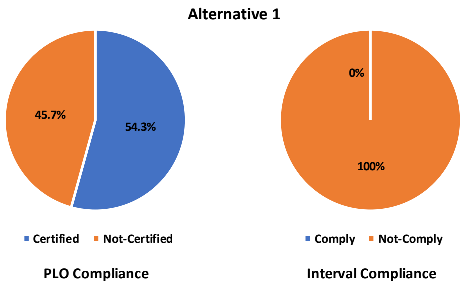

Figure 10. Regulatory Compliant (Alternative 1)

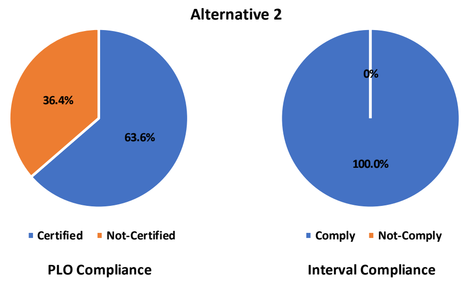

Figure 11. Regulatory Compliant (Alternative 2)

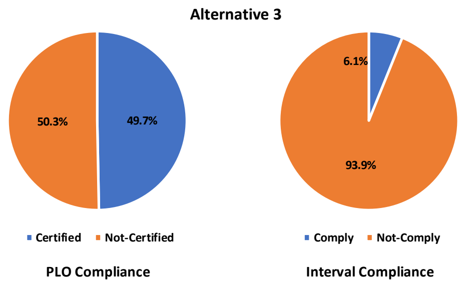

Figure 12. Regulatory Compliant (Alternative 3)

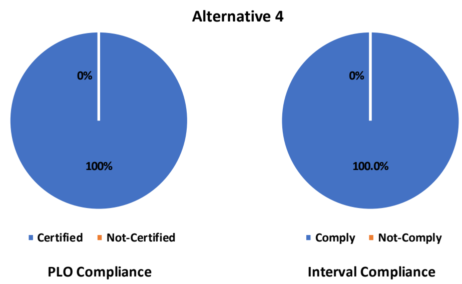

Figure 13. Regulatory Compliant (Alternative 4)

c. Cost Efficiency

The ratio of annual inspection cost (USD) divided by annual pipeline inspection length (km) for each alternative 1 – 4 are shown in the following table:

Table 10. Comparison of Cost to Length Ratio (Alternative 1 – 4)

Formula	Cost to Length Ratio = Annual Inspection Cost / Annual Inspection Length
Alternative 1	Cost to Length Ratio = USD 4,500,000 / 956,871 m = 4.70 USD/m
Alternative 2	Cost to Length Ratio = USD 4,500,000 / 1,096,032 m = 4.11 USD/m
Alternative 3	Cost to Length Ratio = USD 3,539,518 / 1,094,337 m = 3.2 USD/m
Alternative 4	Cost to Length Ratio = USD 4,500,000 / 1,764,878 m = 2.55 USD/m

The performance summary of all alternatives based on spreadsheet simulations can be seen in the following table:

Table 11. Summary of Performance Metrics for All Alternatives

	Alt. 1	Alt. 2	Alt. 3	Alt. 4	CTQ Target
Years to Complete Baseline Inspection	11.0	8.1	8.8	5.0	<10
% PLO Compliance in the Next 4 years	54%	64%	50%	100%	100%
% Interval Compliance	0%	100%	6%	100%	100%
Cost/Length Ratio (USD/m)	4.70	4.11	3.23	2.55	<2.61

The next step is to determine the best possible solution among all alternatives by utilizing AHP. The AHP process includes structuring the hierarchy, conducting pairwise comparison, checking for consistency, and synthesizing priorities.

a. Structuring the Hierarchy

The decision goal of this AHP process is to select the best alternative for optimizing the pipeline inspection program. The hierarchical model of the decision goal, criteria, and alternatives is shown in Figure 14.

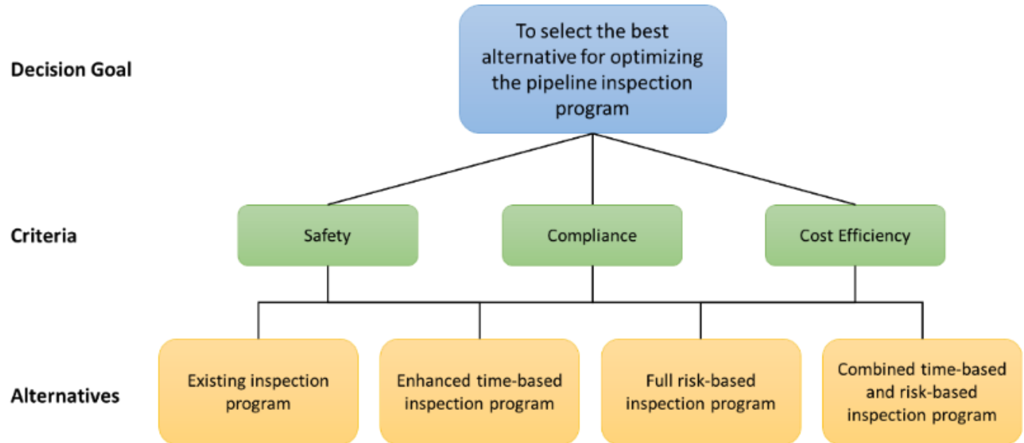

Figure 14. Structure of Decision Hierarchy

b. Conducting Pairwise Comparison

The criteria in conducting pairwise comparison are aligned with what have been defined in the measure stage, which are safety, compliance, and cost efficiency. It includes comparing the importance of each criterion relative to each other and comparing the importance of each alternative relative to each other according to the criteria.

Pairwise comparisons are conducted by several SMEs with different expertise as shown in Table 12. The author has prepared the matrix form consist of questions and intensity of importance scale from 1 to 9 that represent the relative importance as shown in Figure 15.

Table 12. List of Subject Matter Experts

SME	Position	Expertise	Years of Experience
SME 1	Sr Engineer Maintenance & Reliability	Asset Integrity & Reliability Management System	22
SME 2	Engineer Piping & Pipelines	Pipeline Inspection Planning & Budgeting	15
SME 3	Engineer Piping & Pipelines	Pipeline Inspection Execution	19
SME 4	Sr Engineer Piping & Pipelines	Pipeline Integrity Management	19
SME 5	Engineer Piping & Pipelines	Risk-Based Inspection	15

Pairwise Comparison Matrix Form

Initial :
Position :
Expertise :

Questions	Paramater	Intensity of Importance									Paramater
		9	7	5	3	1	3	5	7	9	
	Criteria										
How important is "safety" compared to "compliance"?	Safety										Compliance
How important is "safety" compared to "cost efficiency"?	Safety										Cost Efficiency
How important is "compliance" compared to "cost efficiency"?	Compliance										Cost Efficiency
	Alternatives										
Considering "safety", how important does alternative 1/2/3/4 compared to each other?	Alt 1										Alt 2
	Alt 1										Alt 3
	Alt 1										Alt 4
	Alt 2										Alt 3
	Alt 2										Alt 4
	Alt 3										Alt 4
Considering "compliance", how important does alternative 1/2/3/4 compared to each other?	Alt 1										Alt 2
	Alt 1										Alt 3
	Alt 1										Alt 4
	Alt 2										Alt 3
	Alt 2										Alt 4
	Alt 3										Alt 4
Considering "cost efficiency", how important does alternative 1/2/3/4 compared to each other?	Alt 1										Alt 2
	Alt 1										Alt 3
	Alt 1										Alt 4
	Alt 2										Alt 3
	Alt 2										Alt 4
	Alt 3										Alt 4

Intensity of Importance:
1 - Equal importance
3 - Moderate importance
5 - Strong importance
7 - Very strong importance
9 - Extreme importance

Figure 15. Pairwise Comparison Matrix Form

The collected data from all SMEs are then compiled (shown in Appendix C) to get the consensus value. The results of pairwise comparison matrix filled out by each SME may differ, therefore the data will be aggregated using the geometric mean as shown in the Table 13.

Table 13. Aggregated Result of Pairwise Comparisons by SMEs

Parameter 1	SME 1	SME 2	SME 3	SME 4	SME 5	Geometric mean value	Parameter 2
Criteria							
Safety	3.00	3.00	3.00	5.00	5.00	3.68	Compliance
Safety	5.00	7.00	7.00	9.00	7.00	6.88	Cost Efficiency
Compliance	3.00	5.00	3.00	5.00	5.00	4.08	Cost Efficiency
Alternatives							
Alt 1	0.20	1.00	0.33	0.20	0.14	0.29	Alt 2
Alt 1	0.14	0.33	0.20	0.14	0.20	0.19	Alt 3
Alt 1	0.11	0.20	0.14	0.11	0.14	0.14	Alt 4
Alt 2	0.20	0.33	0.33	0.20	1.00	0.34	Alt 3
Alt 2	0.11	0.20	0.20	0.14	0.14	0.16	Alt 4
Alt 3	0.20	0.33	0.33	0.20	0.20	0.25	Alt 4
Alt 1	0.20	1.00	0.33	0.14	0.14	0.27	Alt 2
Alt 1	0.20	3.00	0.20	0.11	3.00	0.53	Alt 3
Alt 1	0.11	0.33	0.14	0.14	0.11	0.15	Alt 4
Alt 2	0.20	3.00	0.33	1.00	5.00	1.00	Alt 3
Alt 2	0.11	1.00	0.20	0.33	1.00	0.37	Alt 4
Alt 3	0.11	0.14	0.33	0.20	0.14	0.17	Alt 4
Alt 1	0.20	1.00	0.33	0.33	1.00	0.47	Alt 2
Alt 1	0.14	0.33	0.20	0.14	0.14	0.18	Alt 3

Parameter 1	SME 1	SME 2	SME 3	SME 4	SME 5	Geometric mean value	Parameter 2
Alt 1	0.11	0.14	0.14	0.11	0.11	0.12	Alt 4
Alt 2	0.20	0.33	0.33	0.20	0.14	0.23	Alt 3
Alt 2	0.11	0.20	0.20	0.14	0.14	0.16	Alt 4
Alt 3	0.20	0.33	0.33	0.20	1.00	0.34	Alt 4

Based on above geometric mean data, the pairwise comparison matrix for criteria and alternatives are shown in the following tables:

Table 14. Pairwise Comparison Matrix for Criteria

Criteria	Safety	Compliance	Cost Efficiency
Safety	1.00	3.68	6.88
Compliance	0.27	1.00	4.08
Cost Efficiency	0.15	0.25	1.00

Table 15. Pairwise Comparison Matrix for Alternatives by Considering Safety Criteria

Alternative - Safety	Alt 1	Alt 2	Alt 3	Alt 4
Alt 1	1.00	0.29	0.19	0.14
Alt 2	3.50	1.00	0.34	0.16
Alt 3	5.16	2.95	1.00	0.25
Alt 4	7.24	6.43	4.08	1.00

Table 16. Pairwise Comparison Matrix for Alternatives by Considering Compliance Criteria

Alternative - Compliance	Alt 1	Alt 2	Alt 3	Alt 4
Alt 1	1.00	0.27	0.53	0.15
Alt 2	3.74	1.00	1.00	0.37
Alt 3	1.90	1.00	1.00	0.17
Alt 4	6.53	2.67	5.81	1.00

Table 17. Pairwise Comparison Matrix for Alternatives by Considering Cost Efficiency Criteria

Alternative - Cost Efficiency	Alt 1	Alt 2	Alt 3	Alt 4
Alt 1	1.00	0.47	0.18	0.12
Alt 2	2.14	1.00	0.23	0.16
Alt 3	5.52	4.36	1.00	0.34
Alt 4	8.14	6.43	2.95	1.00

Tables 14 – 17 are the matrix that show the results of pairwise comparison for criteria and all alternatives. Each element in the matrix represents the importance level of each criterion or alternative relative to another, with respect to SMEs judgment using Saaty's 1 – 9 scale (Saaty & Vargas, 2012). For example, Safety is considered moderately more important than Compliance, and strongly more important than Cost Efficiency. The alternatives are also compared to each other by considering all criteria.

c. Synthesizing Priorities

At this stage, the pairwise comparison matrices for criteria and all alternatives are normalized to get the priority vector as shown in the following tables:

Table 18. Priority Vector for Criteria

Criteria	Priority Vector
Safety	0.68
Compliance	0.25
Cost Efficiency	0.08

Table 19. Priority Vector for Alternatives by Considering Safety Criteria

Alternative - Safety	Priority Vector
Alt 1	0.05
Alt 2	0.12
Alt 3	0.23
Alt 4	0.60

Table 20. Priority Vector for Alternatives by Considering Compliance Criteria

Alternative - Compliance	Priority Vector
Alt 1	0.07
Alt 2	0.21
Alt 3	0.14
Alt 4	0.58

Table 21. Priority Vector for Alternatives by Considering Cost Efficiency Criteria

Alternative - Cost Efficiency	Priority Vector
Alt 1	0.05
Alt 2	0.09
Alt 3	0.28
Alt 4	0.58

Tables 18 – 21 show the calculation results of priority vector for criteria and all alternatives. Higher priority vector indicates that a criterion or alternative is more important or more prioritized in the decision-making process compared to others. The overall priority of alternatives is calculated by multiplying the priority vector of each alternative with the priority vector of each criteria and summing the result as follows:

$$\begin{bmatrix} 0.05 & 0.07 & 0.05 \\ 0.12 & 0.21 & 0.09 \\ 0.23 & 0.14 & 0.28 \\ 0.60 & 0.58 & 0.58 \end{bmatrix} \times \begin{bmatrix} 0.68 \\ 0.25 \\ 0.08 \end{bmatrix} = \begin{bmatrix} 0.06 \\ 0.14 \\ 0.21 \\ 0.59 \end{bmatrix}$$

Based on above calculation, the priority ranking can be determined as shown in the following Table 22:

Table 22. Overall Priority Ranking

Rank	Alternative
1	Alternative 4 – Combined time-based and risk-based
2	Alternative 3 – Full risk-based inspection program
3	Alternative 2 – Enhanced time-based inspection program
4	Alternative 1 – Existing inspection program

d. Checking for Consistency

The final step of AHP process is calculating the consistency ratio (CR), by dividing consistency index (CI) with random index (RI). The calculations are detailed in Appendix D. The consistency ratio for criteria and all alternatives are shown in the following Tables 23 – 26:

Table 23. Consistency Checking for Criteria Comparison

CI	RI	CR	
0.03	0.58	0.06	acceptable

Table 24. Consistency Checking for Alternatives Comparison Considering Safety Criteria

CI	RI	CR	
0.07	0.90	0.08	acceptable

Table 25. Consistency Checking for Alternatives Comparison Considering Compliance Criteria

CI	RI	CR	
0.03	0.90	0.04	acceptable

Table 26. Consistency Checking for Alternatives Comparison Considering Cost Efficiency Criteria

CI	RI	CR	
0.03	0.90	0.04	acceptable

Since all of the consistency ratio (CR) value are below 0.1, the pairwise comparisons are considered consistent and acceptable to be used in decision making process. Based on the above analytical hierarchy process, the best alternative for optimizing pipeline inspection program by considering all criteria is by implementing "combined time-based and risk-based inspection program" which get the biggest overall weigh as shown in following Decision Hierarchy Result:

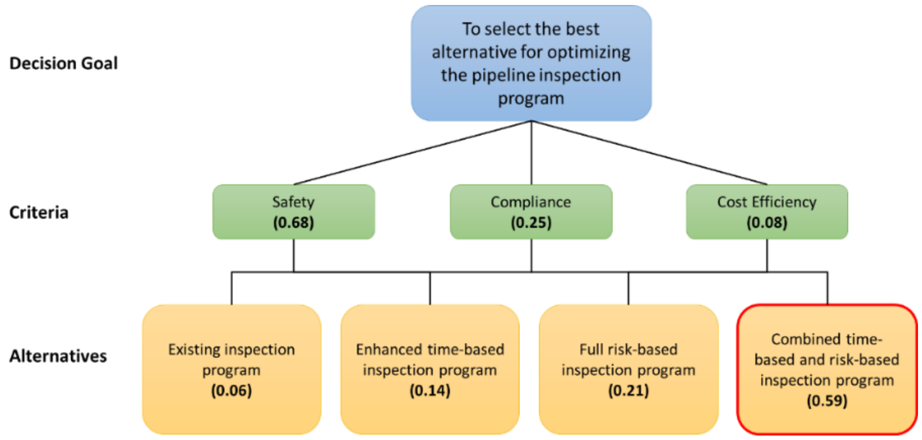

Figure 16. AHP Decision Hierarchy Result

Figure 16 shows the result of Analytical Hierarchy Process. The most important criteria are Safety which get the highest priority vector (0.68), followed by Compliance and Cost Efficiency. The best alternative is by implementing "combined time-based and risk-based inspection program" which get the biggest overall weigh (0.59).

By implementing this alternative, PetroTama can significantly increase the total number of inspected pipeline segments within 5 years timeframe. By having inspection data, PetroTama will be able to proactively identifies potential integrity threats such as corrosion, defects, mechanical damage, and others, that will reduce pipeline failures and its impact to loss of production with financial value up to USD 6 million per year. The other strategic benefit to the organization is that PetroTama can improve its compliance status from non-compliant or partially compliant to fully compliant with the regulation related to pipeline certification by ensuring all of pipeline segments in scope have "persetujuan layak operasi" (PLO). Introducing RBI into the program can also improve the cost efficiency, where by using the same budget allocation, PetroTama can increase the inspection coverage from previously 957 km up to 1,765 km per year.

CONCLUSION

This study evaluates the optimization of PetroTama's pipeline inspection program using the DMAIC methodology, identifying significant gaps in the current program, including the inspection of only 37% of the pipeline network, leaving 5,480 km uninspected. This condition exposes PetroTama to serious risks in safety, compliance, and cost efficiency. The main causes of the issues, including pipeline failures and non-compliance, are traced to budgetary constraints and the lack of regular program improvements. After analyzing various alternatives using the Analytical Hierarchy Process (AHP) and Spreadsheet Simulation, the study concludes that the most effective solution is the implementation of a combined time-based and risk-based inspection program. This approach would significantly increase the number of inspected pipeline segments, reduce the risk of pipeline failures, improve compliance, and enhance cost efficiency by inspecting more pipeline with the same budget. The findings suggest that by optimizing the inspection program, PetroTama could save up to USD 6 million per year in production loss. Future research could explore additional factors influencing the effectiveness of pipeline inspection programs, including advanced technologies or regulatory impacts, and further refine the cost-benefit analysis of implementing risk-based inspections across different industries.

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