Hydrocarbon Pipeline Third Party Damage Risk Assessment using Multi Criteria Decision Making

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Abstract: Many research studies recognized Third Party Damage (TPD) as one of the significant contributors to pipeline failure. Maintenance of hydrocarbon pipelines and its right of way (ROW) as protection from TPD is a significant challenge because massive encroachment and fast-growing third-party activities near pipelines. Therefore, an organization needs to use risk-based analysis for resource allocation prioritization carefully. Analytical Hierarchy Process (AHP) and Simple Multi-Attribute Rating Technique (SMART) are popular Multi-Criteria Decision Making (MCDM) technique that allows multivariable factors to be considered in the decision-making process. Pipeline risk is a function of a multi-variable risk factor. Therefore, the combination of AHP and SMART can be used for pipeline risk assessment. Limitation of the presented decision support system: 1) it still has subjectivity involved, which would introduce uncertainties to the result, 2) the risk result is a relative risk, which makes the result only can be used resource allocation. This work is expected can help the organization for improving resource allocation for risk reduction program and maintenance activities. Although the model is applied for pipeline risk assessment, the same principle can be applied for other risk assessment exercise.

1 INTRODUCTION

The pipeline is the most common hydrocarbon transportation over long distances; it is because pipelines are the safest, reliable, and economical. The pipelines are designed and operated/maintained for a purpose, which is to transfer hazardous material from one location (source or production facility) to another location. Hydrocarbon pipeline has risk associated with its operation because it contains pressurized hazardous material with flammable and toxicity characteristics. The unintentional release of containment could be harmful to public and personnel safety and impair the environment.

Pipelines are subject to various failure mechanisms (e.g., corrosion, third-party damage, incorrect operation, material defect, etc.) with various degrees of impact, from minor to catastrophe and disastrous consequence, in safety, asset loss, and environmental aspect.

Third-party damage (TPD) refers to any accidental damage done to the pipe because of activities of personnel not associated with the pipeline (non-operator). The incident is not as frequent as another damage mechanism (e.g., corrosion), but the consequence was usually more severe. TPD is the leading cause of oil and gas pipeline failure (Jackson, 2018).

US Department of Transportation (DOT) pipeline accident statistics show that third-party damage was often the initiating event of pipeline failure. Ironically, the potential for third-party damage is often overlooked aspects of pipeline hazard assessment. In most cases, initial pipeline design and construction have considered the potential of third-party damage. However, local community encroachments and infrastructure development activities are threatening many pipelines. Most Pipeline Operators had challenges to protect the pipelines right of way (ROW) to minimize the risk of third-party encroachment, especially in developing countries.

Maintenance of hydrocarbon pipelines and ROW is a major challenge. Two major factors that drive the challenge are the need to minimize the cost of operation and, at the same time, shall not compromising on risk. The reality is no organization that has an infinite resource to manage the risk. Therefore, an organization needs to use risk-based analysis for resource allocation prioritization

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carefully. There is a compelling need to have a more accurate risk picture for various pipeline segments from third-party damage hazard.

Risk is defined as the probability of an event that causes a loss with absolute magnitude. In short, the risk is a function of probability and consequences (Muhlbauer, 2015). With this definition, the risk is increased when the probability of failure increases, or the magnitude of the loss or consequence increases. Risk is not constant; it can change over time. Risk is not constant; it can change with time. Risk assessment is taking a snapshot of the risk profile at the moment in time. The results of the risk assessment are then used for risk reduction program to achieve risk as low as reasonably practicable (ALARP).

2 PIPELINE THIRD PARTY DAMAGE RISK

Risk is a combination of multivariable influencing factors, which in general can be grouped into exposure and mitigation. For TPD risk, Muhlbauer (2015) breakdown the factor as follows.

Exposure is defined as an event that, in the absence of any mitigation or safeguard, can result in the incident if insufficient resistance exists. Exposure of third-party damage consists of:

i. Excavation

Excavation exposure often occurs at new construction from heavy equipment activities. Excavation exposure is only applicable to buried pipelines.

ii. Vehicles

Exposure for vehicles hit the pipeline is a function of the type of vehicle, traffic frequency, speed, and distance to facilities. Vehicles hit only applicable to above-ground pipelines

iii. Falling object

Exposure for the falling object could from tools drop, cranes, falling trees. Falling object exposure only applied to above-ground pipelines.

Mitigation is defined as the type and effectiveness of every preventive and mitigative measure designed to block or reduce exposure. Mitigation of third-party damage consists of:

i. Cover of depth
   Cover depth is the amount of protection over the buried pipeline that protects it from third-party activities and impacts. In general, a more in-depth and stronger cover provides better protection.
ii. Impact barrier
   The impact barrier protects above ground pipelines from exposure to mechanical damage, falling object, and vehicle collision.
iii. Line locating
   Line locating involves pipeline marking, line locating devices and procedures, marking practices
iv. Speed control
   Speed control is mainly used to reduce vehicles hit.
v. Sign, Markers, ROW condition
   The more recognizable the pipeline sign, markers, and a ROW can reduce the likelihood of inadvertent damage.
vi. Patrol
   Pipeline patrol is the best practice of reducing third-party intrusions. It is also intended to detect an abnormal condition such as evidence of a leak from pipelines. The patrol also should detect potential third-party threats to the pipeline. Such as when there is excavating equipment operating nearby. The frequency and competency of the patrol are affecting the patrol effectiveness to prevent the incident.
vii. Public education programs
   Programs to educate the public about the hazard of critical activities such as excavation near pipelines. This is important because third-party damage is unintentional or due to ignorance.

3 ANALYSIS OF BUSINESS SITUATION

Root Cause Analysis (RCA) with Why Tree method was conducted. RCA result recommends to lookback the effectiveness of existing pipeline risk assessment and management. There should be a stronger risk assessment process to ensure the resource is allocated at the right level of prioritization. External factors such as increased level of activity around the Company's pipeline is a consequence of growing development and hence cannot be avoided. Increased rate of vandalism and oil theft are complex issues which require the involvement of central government and law enforcer. This research focuses on recognizing and managing things within the Company's influence and controllability. Therefore, the oil theft sabotage issue is taken out of scope.

The quality of the existing pipeline risk assessment process is being questioned. At present, hazard identification and assessment are done on a regular basis every five years cycle. The current risk-based inspection result has recognized the hazard of TPD. However, it failed to be translated into an actionable risk reduction program that fit for the specific hazard.

Another thing to be considered is fast-paced external condition changes due to the development of public infrastructures and increased population around the Company's asset. It signals the need for a risk assessment process that is simple and robust enough to allow dynamic input data changes so that the Company could have an immediate risk reduction response.

4 METHODS

4.1 Risk Assessment Selection

In general, there are three alternatives of pipeline risk assessment method: 1) Simple Decision Support (e.g., use risk matrix), 2) Hybrid (e.g., risk scoring), 3) Probabilistic Assessment (e.g., Quantitative Risk Assessment)

Based on discussion with subject matter expert, Probabilistic Risk Analysis (e.g., QRA) does not meet the criteria for simple and user-friendly. Therefore, QRA is dropped from the option. As discussed to response uptrend of third-party damage risk and a huge number of pipeline segments to be evaluated, simple risk assessment is expected. The remaining option is the Matrix and Risk Scoring Method. Despite its simplicity, the matrix method has an inherent weakness for the consistency aspect. The risk assessment result is highly subjective, which relies upon the facilitator and the risk assessment team member. An example of an index method that has been applied in the Company is the HAZOP technique. This method is still applicable and useful for generic pipeline risk assessment, which represents the worst case for the entire pipeline length. This method is not valid if we want to differentiate risk assessment for hundreds of segmented pipeline with a different condition.

Muhlbauer (WKM) risk scoring technique is one of the risk assessment methods that famous for pipeline application. The score is assigned to each pipeline segment attribute that contributes to the risk level. The scores are from the suggested procedure from Muhlbauer. The lower the score, meaning the lower the quality of safeguard; hence the probability of failure or risk is higher. The assigned score reflects the importance of each item relative to the others. The weighting factor that is used in WKM method is criticized because different weighting factors could result in the different final risk scores. The weighting should be adjusted to field conditions.

Analytical Hierarchical Procedure (AHP) is a promising method for this application. To make a decision support system for pipeline risk evaluation, AHP alone is not adequate. This is because AHP has limitations in making a pairwise comparison for more than nine criteria or alternatives. Because the number of pipeline segments to be evaluated can reach hundreds or thousands of segments, it is impossible to evaluate each segment risk with conventional AHP method.

A combined AHP and SMART method then is considered. The SMART method is utilized to determine the pipeline rating score for each attribute (subfactor) of risk influencing factors. The risk assessor will rate the attribute (subfactor) of risk influencing factor. The minimum rating will be assigned for poor conditions and a maximum rating for excellent condition. The higher the score meaning, the better the condition or lower risk. These rates are multiplied by the risk factor weight before finally adding all together to obtain the total risk score (0-100 scale).

The risk score is calculated with the below equation:

$$Risk\ Score = \sum w_j a_{ij} \tag{1}$$

wj = Risk influencing factor weight using AHP

aij = Alternative score performance against factor using SMART

4.2 AHP and SMART

The AHP, developed by Saaty (1980), provides an intuitive way to analyze complicated problems. Practitioners have widely used AHP because of its ease of applicability and the structure of AHP, which follows the intuitive way in problem-solving. AHP is a theory of measurement that uses pairwise comparisons along with expert judgments. It is one of the most popular Multi-Criteria Decision Making (MCDM) techniques that allow subjective as well as multiple objective factors to be considered in the decision-making process. The AHP allows the active participation of subject matter experts to reach an agreement and gives them a rational basis for making decisions.

The first step in AHP is problem formulation to determine the goal for the decision analysis. In this case, evaluation TPD probability of failure or risk score of each pipeline segment. After the goal is defined, the next step is the identification of risk influencing factors with its attributes first and second level AHP hierarchy. Once a hierarchy is built, the expert or decision-maker begins a prioritization procedure to determine the relative importance of the attribute in each level of the hierarchy. It uses "pair-wise comparisons," and matrix algebra to weight criteria, and the decision is made by using the derived weights of the decision criteria. The decision-maker does not need to provide a numerical judgment; instead, a relative verbal scale or judgment according to their importance. Table 1 explains the AHP scale. For example, if two factors are judged having the same level of importance, the pairwise score will be 1. If one factor is assumed to be remarkably stronger than the other, a score of 9 is assigned.

$$A = \begin{bmatrix} 1 & a_{12} & a_{1n} \\ a_{21} & \cdots & a_{2n} \\ & a_{ji} = 1/a_{ij} & \\ a_{n1} & & 1 \end{bmatrix}$$

Where a_{ij} is the pairwise comparison between element *i* and *j*

Table 1 AHP Qualitative Judgement Score.

Qualitative Judgement	Explanation	Score
Equally	Two attributes have an equal likelihood of rupture	1
Moderately	The likelihood of rupture due to one attribute is slightly more than the other attribute	3
Strongly	The likelihood of rupture due to one attribute is firmly more than the other attribute	5
Very Strongly	The likelihood of rupture due to one attribute is very strongly more than the other attribute	7
Extremely	The likelihood of rupture due to one attribute is extremely more than the other attribute	9
Intermediate judgment	The intermediate values are used when compromise is needed	2, 4, 6, 8

After comparison Matrices are created, relative weights are derived. The relative weights of the elements of each one level concerning an element in the next upper level are computed as the components of the associated normalized eigenvector. The compound weights are determined by adding the weights through the hierarchy. Stages do this, start from the top of the hierarchy to each alternative in the lowest position level, and multiplying the weights along each segment of the path. The result of this aggregation is a standard vector of the global weights of the options. The mathematical basis for calculating the weights was established by Saaty (1980).

One feature of the AHP method is the Consistency Ratio (CR) parameter. It provides a consistency check of relative importance from the pairwise comparison. The maximum acceptable of CR is 0.1.

$$w = \begin{bmatrix} w_1 \\ w_2 \\ w_n \end{bmatrix}$$

is obtained from the decision matrix [A]

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{1n} \\ a_{21} & a_{22} & a_{2n} \\ a_{n1} & a_{n2} & a_{nn} \end{bmatrix}$$

CR is calculated as follow

i. Determine matrix B by multiplying matrix A and matrix w

$$B = A.w = \begin{bmatrix} b_1 \\ b_2 \\ b_n \end{bmatrix} \quad (2)$$

ii. Divide each element in vector B with element in vector w to get new vector c

$$c = \begin{bmatrix} \frac{b_1}{w_1} \\ \frac{b_2}{w_2} \\ \frac{b_n}{w_n} \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ c_n \end{bmatrix} \quad (3)$$

iii. Calculate λ_max by averaging element in vector c

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{i=n} c_i \quad (4)$$

iv. Calculate consistency index, CI, using below equation

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (5)$$

v. Calculate consistency ratio, CR, using below equation, RI is a random index which refers to Table 2

$$CR = \frac{CI}{RI} \quad (6)$$

Table 2 Random Index Table.

n	RI
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
>9	1.49

Including several expert's opinions can avoid bias that may be present single expert judgment. AHP has a useful feature that enables a group to structure a hierarchy jointly and participate in the discussion to decide the pairwise judgment. The discussion facilitator can lead the discussion to obtain consensus. When the team is unable to reach consensus, a geometric mean of participant judgment can be used. It is possible to resolve such differences by selecting more consistent judgments.

If a consensus is difficult to achieve, the geometric mean of individual evaluations is applied as elements in the pair-wise comparison, and then priorities are calculated.

4.3 Data Collection and Analysis

Literature research and past incident investigation report are utilized as a reference in analyzing the problem. Pipeline integrity conditions and external conditions are gathered from the Company's inspection data.

A combination of the Analytical Hierarchy Process (AHP) and Simple Multi-Attribute Rating Technique (SMART) will be exercised to assess risk score.

Group of six experts is appointed for determining the root cause, risk influencing factor (decision criteria), the relative importance of each risk factor, and development of SMART scale standard definition. The expert is selected based on their level of competency and experience in process safety, risk management, asset integrity, operation, and maintenance.

Pairwise comparison, each risk factor is done by individual experts independently. The pairwise comparison is a facilitated session to ensure the expert uses consistent risk factor definition. The pairwise comparison and weighting priority synthesis are conducted with AHP-OS, an online AHP software tool (Goepel, 2015). The AHP-OS tool also provides a Consistency Ratio (CR) number and group consensus level.

5 RESULTS AND DISCUSSION

The decision hierarchy tree is developed based on the risk influencing factor and subfactor, which discussed previously.

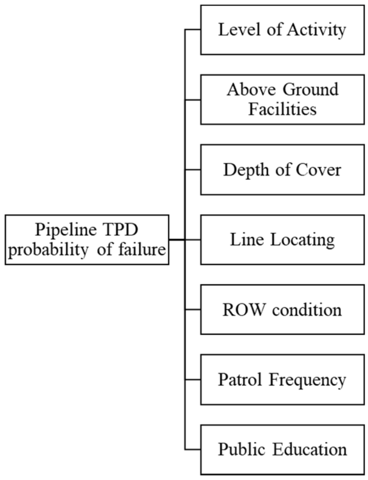

Figure 1 AHP Decision Hierarchy.

The SMART standard definition also defined to explain the scoring 0-100 according to the pipeline attribute.

Table 2 Pipeline Segment Attribute Scale (SMART).

Level Activity	Above ground facilities	Depth of cover	Line Locating
High 0 pts	None 0 pts	Shallow 0 pts	None 0 pts
Medium 40 pts	Weak 25 pts	Average 50 pts	Average 50 pts
Low 75 pts	Average 50 pts	Deep 100 pts	Good 100 pts
None 100 pts	Strong 100 pts		
ROW Condition	Patrol Frequency	Public Education	
Poor 0 pts	None 0 pts	None 0 pts	
Average 40 pts	Monthly 25 pts	Weak 25 pts	
Good 60 pts	Weekly 50 pts	Average 70 pts	
Excellent 100 pts	Daily 100 pts	Strong 100 pts	

AHP procedure result from AHP-OS is shown in Figure 2.

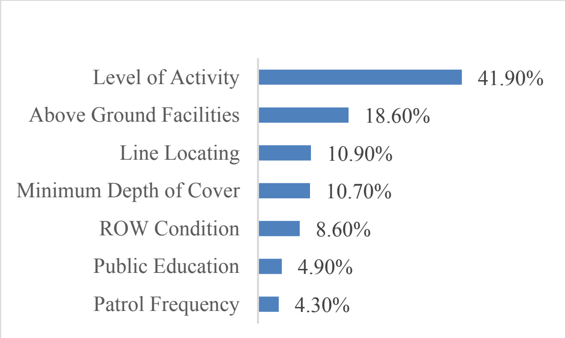

Figure 2 Consolidated Result of Third-Party Damage Risk Factor Weighting.

AHP-OS computed the consistency ratio for individual judgment and consolidated group judgment. The CR for third-party damage POF pairwise comparison is 1.4%. Therefore, weighting can be used for further usage. For group decisions, the AHP-OS software calculates an AHP consensus indicator to quantify the consensus of the group (estimate of the agreement on the outcoming priorities between participants). This indicator ranges from 0% to 100%. Zero percent corresponds to no consensus at all, 100% to full consensus. It is a measure of homogeneity of priorities between the participants and can also be interpreted as a measure of overlap between priorities of the group members (Goepel, 2015). The group consensus for TPD POF pairwise comparison is 79.4% (high).

Based on AHP's expert judgment, the top five risk factor of third-party damage is level of activity (41.9%), above-ground facility (18.6%), and line locating (10.9%), the minimum depth of cover (10.7%), and right of way condition (8.6%). A comparison with the WKM weighting factor is shown in Table 3. The difference in weighting factor is also can affect overall risk score and hence impact to resource allocation quality.

Table 3 Comparison Risk Influencing Factor Weighting.

Factor	WKM	WKM-AHP
Level of Activity	20%	42%
Above Ground Facility	10%	19%
Line Locating	15%	11%
Minimum Depth of Cover	20%	11%
ROW condition	5%	8%
Patrol Frequency	15%	4%
Public Education	15%	5%

The level of activity factor is the most important factor but also the most complicated factor to be resolved because the pipeline operator has relatively little influence to manage the public activity or to prevent illegal encroachment along the pipeline. The only possible option is to re-route the existing pipeline via an alternate location, which still sterile from public activities.

Above ground, the facility is the second most important risk factor because most of the Company's facility was designed and installed above ground. It was designed and constructed a long time before the Government of Indonesia implemented the regulation to mandate the hydrocarbon pipeline to be buried.

The third and fourth factor is directly related with a buried pipeline segment. The expert has agreed that both the pipeline depth of cover and line locating are equally important. The buried pipeline will not be effective in preventing incidents until it has effective program for line locating. This is consistent with key learning points from the past incident investigation that those incidents due to excavation can be prevented if the third-party notify the pipeline operator prior conducted the work.

The fifth important factor, right of way condition, are relatively equal weighting with line locating and depth of cover. The expert opined that maintaining the right of way conditions can ensure the pipeline is visible and improve leak detection. Public education is considered a weak component of risk factors because of learning from experience. The expert opined that the best way to prevent encroachment is by installing a mechanical barrier along the pipeline. Pipeline patrol is also considered less effective in preventing third-party pipeline damage because of extensive coverage of pipeline surveillance requirements. However, experts agree that the patrol program is a crucial component to provide data for third-party damage risk assessment.

6 CASE STUDY

The proposed Decision Support System is then implemented for risk assessment of the following sample six pipeline segments. This segment is selected to represent a typical pipeline segment operated in the Company.

Table 3 Pipeline Properties.

No	Pipeline	Installation	Service
1	A	Buried	Crude
2	B	Above ground	Crude
3	C	Above ground	Crude
4	D	Above ground	Crude
5	E	Above ground	Crude
6	F	Above ground	Crude

Third-party damage risk score ranking (note: lower score means higher risk)

1. A: 26
2. B: 28
3. C: 31
4. D: 34
5. E: 49
6. F: 86

Based on this result, pipeline segments A and B with the current condition are the top two segments with high risk or most vulnerable. Which, therefore, it should be prioritized for maintenance resource allocation to reduce the risk. Segment A has a higher risk because the segment is located above ground, crossing busy public areas (due to encroachment), adjacent with roadways, and not protected with an adequate barrier to prevent hit incident. While segment B, which buried, has risk exposure to illegal excavation damage. Segment B is located nearby ongoing infrastructure construction (toll road).

Following corrective action are proposed for pipeline A:

1. Install additional impact barrier at an identified location which adjacent to roadways
2. Conduct regular housekeeping to clear pipeline right of way

Following corrective action are proposed for pipeline B:

1. Improve line locating procedure implementation, communicate regularly with a third-party contractor
2. Provide barriers, markers, and warning signs at a location nearby construction activities.

When the two corrective actions completed, the risk score will change from 26 to 50 for Pipeline A and Pipeline B will change score from 28 to 49, which makes them at safer state.

The proposed decision support system still has subjectivity involved, which would introduce uncertainties to the result. Dawotola (2012) uses combined Hooke's Classical Model structured expert judgment process and AHP to reduce the subjectivity. The risk result with the proposed model is a relative risk and not absolute risk, which makes the result cannot be used to conclude whether the risk is tolerable or not.

Full deployment of new decision support will require further alignment with the existing program in the Company. The high level of the proposed workflow is shown in Figure 3.

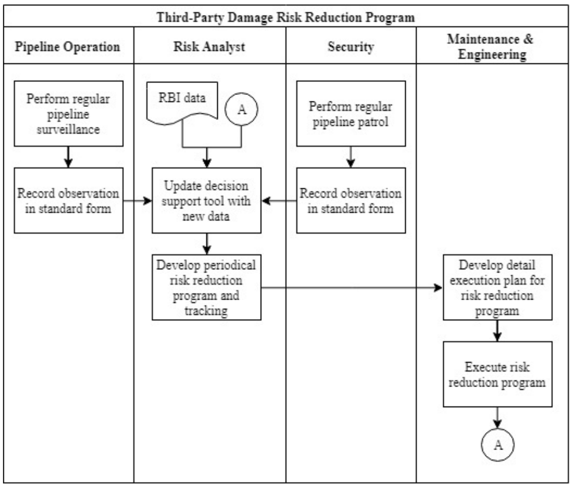

Figure 3 Proposed New Workflow for Third-Party Damage Risk Management.

7 CONCLUSION

Decision Support System (DSS) for third-party damage risk reduction program is presented. The decision support model uses the Muhlbauer (WKM) model, which modified with the Analytical Hierarchy Process (AHP) to improve the prediction probability of failure (POF) from third-party damage.

The level of activity near pipelines contribute to 41.9% of the probability of failure from third-party damage, which means pipeline location plays a crucial role in the overall risk picture. Other factors contribution: above ground facility 18.6%, line locating 10.9%, a minimum depth of cover 10.7% right of way condition 8.6%, public education 4.9%, and patrol frequency 4.3%.

The study also reveals that pipeline hit incident: vehicle hit for above-ground pipeline and excavation hit for the buried pipeline are top two of third-party damage mechanism. Above ground pipeline, risk reduction factor is dominantly affected by above-ground facilities (18.6%), and buried pipeline reduction factor is dominantly affected by the minimum depth of cover and line locating (combined weight 21.6%).

This work is expected can help the organization for improving resource allocation for risk reduction program and maintenance activities. Although the model is applied for pipeline risk assessment, the same principle can be applied for other risk assessment exercise.

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