Bad Actors Criticality Assessment for Pipeline system

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Abstract. Failure of a pipeline system could bring huge economic loss. In order to mitigate such catastrophic loss, it is required to evaluate and rank the impact of each bad actor of the pipeline system. In this study, bad actors are known as the root causes or any potential factor leading to the system downtime. Fault Tree Analysis (FTA) is used to analyze the probability of occurrence for each bad actor. Birnbaum’s Importance and criticality measure (BICM) is also employed to rank the impact of each bad actor on the pipeline system failure. The results demonstrate that internal corrosion; external corrosion and construction damage are critical and highly contribute to the pipeline system failure with 48.0%, 12.4% and 6.0% respectively. Thus, a minor improvement in internal corrosion; external corrosion and construction damage would bring significant changes in the pipeline system performance and reliability. These results could also be useful to develop efficient maintenance strategy by identifying the critical bad actors.

1. Introduction
Over the past few decades, the pipeline has been widely used in the oil and gas industry to transport unrefined fossil fuels from upstream to downstream for further refinement process prior to the delivery of purified fuels to consumer [1]. It is coherent that the majority of the existing pipelines in the world are aged which subjected to several external and internal factors. One of the major causes of pipeline failures is due to internal and external corrosion. These can also be caused by the extreme weather conditions, mechanical failures, manufacturing defects, external forces as well as operational errors. According Mustaffa [2], corrosion contributes approximately 49% to the cause of pipeline failures in USA while failures due to other hazards, maritime activities and natural forces are about 25%, 14% and 12% respectively. The failure of a pipeline may cause damage to the society, environment as well as economic impacts due to financial losses [3]. For instance, the explosion of pipeline in North Sea oil production platform resulted in a total loss of approximately £1.7 billion. Further, the explosion of gas pipeline located somewhere in between Lawas and Long Sukang in the northernmost district of Sarawak resulted in an estimated loss of RM4 billion due to temporary shutdown. This incident also causes for the evacuation of nearby villagers with some houses and vehicles reportedly destroyed [4].

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The failure and downtime of pipeline system will greatly reduce the financial benefit of the plant in terms of downtime cost, maintenance cost and production loss. Therefore, in order to reduce pipeline failure, it is also crucial to understand which bad actors contribute more to the overall system performance and reliability. In reliability terms, Bad Actors generally represent for plant equipment tags or process systems which experience huge loss, such as repair cost and production loss of repetitive failures [5]. In other words, bad actors are also known as the root cause or any potential factor leading to the system downtime. Several researches have been conducted to evaluate the failure of pipeline systems. Sun, et al, [6] predicts the reliability of pipeline with different preventive maintenance strategies by using a split system approach. However, this paper discusses only for a general reliability prediction model without considering possible bad actors. Ossai [7] used Monte Carlo Simulation and degradation models to predict corrosion rates and reliability of oil and gas pipelines. Despite achieving high accuracy in predicting the corrosion rate of pipelines, this combined methodology does not analyze for other factors of pipeline failure. This is also observed in other study proposed by Lee and Kim [8] where only failure prediction of pipeline due to corrosion is addressed through Finite Element Analysis (FEA). To efficiently mitigate the failure of pipeline, it is essential to address all possible bad actors instead of just focusing on corrosion. One of the decent way to understand which failure modes contribute more to the overall system performance and reliability is by incorporating Fault Tree Analysis (FTA). FTA was extensively used as a failure analysis tool by reliability experts in system safety, reliability engineering and in all major fields of engineering such as Nuclear Power industry, Chemical industry, Robotics industry and Software industry [9]. However, it has limited application in the oil and gas industry.

In this paper, FTA is used to evaluate the pipeline system failure. FTA is able to generate quantified evidence from historical database with the aids of mathematical computation. Further, the obtained results are able to rank the failure cause according to the likelihood of occurrence which will lead to application of the decent maintenance procedure, thus reduced downtime and smoother commissioning. Thus, in this study, FTA and BICM were used to evaluate the probability of occurrence and rank the impact for each bad actor in the pipeline system.

2. Methodology

2.1. Fault Tree Analysis (FTA)

This study used FTA to analyze the probability of each bad actor. FTA is a graphical approach which describes the interaction of failures and other events in a system. Figure 1 shows the structure of FTA. Basic events are usually depicted at the bottom of the FTA and are connected to the top events through logic symbols, known as gates. Common events and gates are shown in Table 1. The top event denotes the detected hazards or system bad actors.
Figure 1: Fault Tree Approach

Table 1: Common symbols and logic gates used in FTA
(Adapted from [10])

| Symbol Name        | Symbol | Descriptions                                      |
|--------------------|--------|---------------------------------------------------|
| Basic Event        | ●      | A basic initiating fault (A, B, C, D…..)          |
| Undeveloped Event  | ✢      | A basic event without further developed            |
| Top Event          | ▗      | An event that is depending on the logic of input events |
| OR Gate            | □      | The output occurs if at least one of the event occurs |
| AND Gate           | ◆      | The output occurs only if all the input events occur |

According to Nouri Gharahasanlou, et al. [5], it is essential to estimate the probability of occurrence for the logic gate output fault events in order to estimate the probability of failure for the top event. The corresponding equations to estimate the probability of occurrence of “OR” and “AND” logic gates output fault events are presented in Equation (1) and (2) respectively.

\[
Q_o(t) = 1 - \prod_{i=1}^{n}(1 - q_i(t)) \quad (1)
\]

\[
Q_a(t) = \prod_{i=1}^{n}(q_i(t)) \quad (2)
\]

where \( Q_o(t) \) is the probability of occurrence of output fault or top event, \( q_i(t) \) is the probability of occurrence for each bad actor with a function of time, for \( i = 1, 2, 3, …,n \).

2.2. Birnbaum’s Importance and Criticality Measure (BICM)

Importance measure is used to evaluate and rank the impact of individual bad actors within a system. These importance measures provide a numerical rank to determine which bad actors are more important or critical to system failure. BIM is a partial derivative of system reliability with respect to individual failure mode probability [11]. The index gives an indication of how the pipeline failure probability will change with changes in each failure mode probability. Analytically, this is defined by Equation (3).
$$I_k^p(t) = \frac{\partial Q_k(t)}{\partial q_k(t)}$$  \hspace{1cm} (3)$$

$I_k^p(t)$ is reliability importance of the $k^{th}$ failure mode.

Whereas the Birnbaum importance provided the probability that a given failure mode would be responsible for the failure at time $t$, another measure, “criticality importance” is used to determine the probability that the given failure was responsible for system failure before time $t$. This measure is given by Equation (4).

$$I_k^c(t) = I_k^p(t) \frac{\partial q_k(t)}{\partial Q_k(t)}$$  \hspace{1cm} (4)$$

$I_k^c(t)$ is criticality of the $k^{th}$ failure mode.

3. Results and discussion

3.1. Case study

In this study, the Liquids Pipeline Delivery Network is considered. Table 2 presents the pipeline failure data in Alberta from year of 1990 to 2012 [12]. There are a total of 13 causes of pipeline failure being analyzed such as the internal corrosion, external corrosion, failures due to weld, construction damage, overpressure, pipe, joint, earth movement, valve and fitting, operator error, miscellaneous, damage by others and some undetectable causes. By using failure incidents data for 23 years, Mean Time Between Failure ($MTBF$) can be calculated using Equation (5).

$$MTBF = \frac{\text{Total Operating time}}{\text{Number of failure Incident}}$$  \hspace{1cm} (5)$$

Based on $MTBF$, the two parameters Weibull distribution was used to estimate the shape ($\beta$) and scale ($\eta$) parameters. Weibull distribution is the most efficient distribution in life data analysis and in reliability calculations which involve time related failures is employed to model the wear out or fatigue failure of pipeline system. The $\beta$ and $\eta$ can be estimated by using Maximum likelihood estimation method [13]. The likelihood function is given by:

$$L = \prod_{i=1}^{n} \frac{\beta}{\eta} t_i^{\beta-1} \exp \left[ -\frac{t_i}{\eta} \right]$$  \hspace{1cm} (6)$$

where $\beta$, beta is the shape parameter & $\eta$, eta is the scale parameter or characteristic life.

Differentiating Equation (6) with respect to $\beta$ and $\eta$, and equating to zero can yield Equation (7) and Equation (8).

$$\frac{\partial L}{\partial \beta} = \frac{n}{\beta} - \sum_{i=1}^{n} \ln t_i - \frac{1}{\eta} \sum_{i=1}^{n} t_i^\beta \ln t_i = 0$$  \hspace{1cm} (7)$$

$$\frac{\partial L}{\partial \eta} = -\frac{n}{\eta} + \frac{1}{\eta^2} \sum_{i=1}^{n} t_i^\beta = 0$$  \hspace{1cm} (8)$$

where $t_i$ is the time between failures & $n$ is the sample size.

The estimated value of $\beta$ and $\eta$ were presented in Table 2. As can be seen from Table 2, the value of $\beta$ is less than one which means most of the failures occur in the early stage or the first few kilometers of the pipeline.
Table 2: Parameter estimation for each Bad actors

| Causes of Failure      | Total Time, T (years) | Number of Incident, N | $MTBF$ | $\beta$  | $\eta$  |
|------------------------|-----------------------|-----------------------|--------|----------|----------|
| Internal Corrosion     | 23                    | 9024                  | 2.548×10^{-3} | 0.857682 | 0.002695 |
| External corrosion     | 23                    | 2098                  | 0.01096    | 0.869435 | 0.011639 |
| Third Party Damage     | 23                    | 745                   | 0.03087    | 0.877282 | 0.032817 |
| Weld                   | 23                    | 489                   | 0.04703    | 0.874761 | 0.050022 |
| Construction Damage    | 23                    | 888                   | 0.02590    | 0.874461 | 0.02759  |
| Overpressure           | 23                    | 281                   | 0.08185    | 0.875936 | 0.086991 |
| Pipe                   | 23                    | 509                   | 0.04519    | 0.874257 | 0.048019 |
| Joint                  | 23                    | 614                   | 0.03746    | 0.87746  | 0.039833 |
| Earth Movement         | 23                    | 281                   | 0.08185    | 0.875936 | 0.086991 |
| Valve/Fitting          | 23                    | 558                   | 0.04122    | 0.873781 | 0.043826 |
| Operator Error         | 23                    | 271                   | 0.08487    | 0.875316 | 0.09025  |
| Miscellaneous          | 23                    | 353                   | 0.06516    | 0.875066 | 0.069225 |
| Unknown                | 23                    | 378                   | 0.06085    | 0.875711 | 0.06467  |

3.2. Development of FTA

Figure 2 shows a fault tree diagram constructed based on the failure causes stated in Table 2. The failures of the pipeline are classified into five categories, mainly due to the external interference, mechanical failure, corrosion, incorrect operation and also other type of failure. These components are further divided into circular blocks known as basic events. External Interference is broken up into earth movement, construction damage and third party damage. Examples of earth movement are landslides, earthquakes, or any natural disaster that could lead to pipeline failure, whereas third party damages are generally caused by other parties such as third party excavation and interference. Construction damage are losses suffered during the construction process due to improper techniques applied, faulty alignment or inappropriate backfilling. Mechanical Failures are separated into pipe, joint, weld, valve and fitting. Pipe failure could be hydrogen induced cracking (HIC), fatigue, whereas joint failure are such as gasket failure, O-ring failure, internal joint coupling failure and mechanical coupling failure. Examples of weld defects are girth weld failure or seam rupture whereas valve and fitting failure are such as seal blowouts, pig trap failures and packing leaks. Corrosion could be of internal corrosion or external corrosion that occurs on the internal or external surface of the pipe, respectively, while failure due to incorrect operation are divided into operator error and overpressure failure. Lastly, in the category of others, pipeline failure can be caused by miscellaneous reasons such as failure of pump or compressors and some unknown causes are undetectable. For simplicity of analysis, only OR gate is applied in the development of fault tree model for this study, therefore, the pipeline will fail if any of these basic events occurred.
Figure 2: Fault Tree Model for Pipeline Failure

Once the fault tree is developed, various analytical plots can be produced for analysis. Figure 3 shows the system unreliability through time. As can be observed from Figure 3, the failure probability of the overall system increases as the time increases. At the beginning of operation, the unreliability of the system remains at zero and gradually increases. This indicates that the pipeline may experience higher probability of failure when the operation time is getting longer. In other word, as operation time increases, the pipeline system may expose to high failure risks due to internal corrosion, external corrosion, external interference, manufacturing defects, mechanical failure, incorrect operation and also some other causes.

Figure 3: Probability of Failure for pipeline system

The pipeline can be failed due to several factors as presented in Figure 2 and Table 2. However, it is very important to identify which causes contribute more to the system reliability. Thus, in this study, the reliability importance analysis was conducted. In general, reliability importance can be defined as a measure of the relative importance of each component in a system with respect to the overall reliability of the system. Figure 4 shows the static reliability importance of twelve bad actors in the
pipeline system at operation time of 50 hours. The result indicates that internal corrosion has a higher reliability importance of the blocks in the system at the constant time. It is then followed by external corrosion and construction damage being ranked as secondly and thirdly important. The remaining bad actors or components constitute almost the similar ranking of reliability importance as presented in the graph. Similarly, internal corrosion which is shown in red represents lowest reliability, blocks with yellow and green denote medium reliability and highest reliability. This explains that a small improvement in the internal and external corrosion could bring high system reliability compared to other factors. Therefore, it is very important to adopt an effective maintenance strategy to mitigate the internal and external corrosion in order to have high performance and reliability of pipeline systems.

Figure 4: Static Reliability Importance for bad actors

Figure 5 shows the failure probability through time for each failure cause. At the beginning of the system operation, the failure probability of the system due to each bad actor remains at zero and gradually increases as time increases. As observed from Figure 5, internal corrosion, external corrosion and construction damage are three failure cases with the highest unreliability over time compared to other factors. It is then followed by third party damage, joint failure, valve, fitting, pipe, weld, unknown failures, miscellaneous while earth movement and operator error are the first two failure causes which achieve unreliability of one. This means that internal corrosion and external corrosion are the two most critical failure causes which have the lowest reliability over time among all the factors being analyzed and therefore should be prioritized in risk mitigation processes.
The results indicate that internal corrosion and external corrosion are the most frequent causes of failure with percentage of 48.4% and 12.7% respectively. It is then followed by construction damage by 6.5%, whereas the remaining failure causes contribute only for negligible effects to the system overall failure. Therefore, failure causes which fall under higher failure occurrence ranking must be treated with extra caution and immediate corrective actions must be taken in order to reduce the risks to as low as reasonably practicable. Despite a failure ranking for other causes, any possible control measure such as periodic maintenance and inspection of the pipeline system are encouraged in order to mitigate risk or maintain the risk at acceptable levels.

Table 3: Failure criticality index for each Bad Actor

| Failure Mode         | Failure Criticality Index % | Expected Probability of Failure | Failure Occurrence Ranking |
|----------------------|----------------------------|--------------------------------|-----------------------------|
| External Interference| Earth Movement             | 2.90                           | 0.029                       | 10                          |
|                      | Construction Damage        | 6.50                           | 0.065                       | 3                           |
|                      | Third Party Damage         | 4.20                           | 0.042                       | 6                           |
| Mechanical Failure   | Pipe                       | 4.30                           | 0.043                       | 5                           |
|                      | Joint                      | 3.30                           | 0.033                       | 8                           |
|                      | Weld                       | 4.70                           | 0.047                       | 4                           |
|                      | Valve Fitting              | 3.50                           | 0.035                       | 7                           |
| Corrosion            | Internal Corrosion         | 48.40                          | 0.484                       | 1                           |
|                      | External Corrosion         | 12.70                          | 0.127                       | 2                           |
| Incorrect Operation  | Operator Error             | 1.90                           | 0.019                       | 12                          |
|                      | Over Pressure              | 1.90                           | 0.019                       | 12                          |
| Others               | Miscellaneous             | 2.70                           | 0.027                       | 11                          |
|                      | Unknown                    | 3.00                           | 0.030                       | 9                           |
4. Conclusion

In this paper, the impact and probability of occurrence for bad actors were elevated using FTA and BICM. The findings show that internal and external corossions are highly contributed to unavailability of the pipeline system. The result of the study could also suggest which bad actor to be treated immediately to mitigate the overall risk using the Failure Criticality Index as indicated in Table 3. These results could also help to develop efficient maintenance strategy to increase the reliability and performance of the pipeline system.

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