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ANALYSIS OF FACTORS CONTRIBUTING TO THIRD-PARTY DAMAGE OF NATURAL GAS DISTRIBUTION PIPELINE

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ABSTRACT

Failure of the natural gas pipeline can have severe consequences to individuals, economy, environment and the public in term of consequential damage and property losses. There are various causes of natural gas pipeline failures among which third-party damage offers a high contribution. To minimize third-party damage of NGP contributing factors should be studied to establish viable solutions for risk mitigation. In this paper, factors contributing to third-party damage of NPG in Dar es Salaam region have been studied. A fault tree was constructed and by utilizing fuzzy logic and expert elicitation, the failure probabilities of the basic event were established. The prioritization of factors was performed by criticality measures. The results showed that lack of regulations awareness, unplanned settlements, encroachment and lack of HSE knowledge are among the high contributors of Third-party damage. Therefore, addressing these factors will help to mitigate NGP failures by third party damage.

Keywords: Natura gas pipeline, Failure of the natural gas pipeline, Fuzzy fault tree, Third party damage

NOMENCLATURE

Abbreviations

FTA	Fault tree analysis
FFTA	Fuzzy fault tree analysis
HSE	Health, safety, and environment
MCS	Minimal cut sets
NGP	Natural gas pipeline
TPD	Third party damage

1. INTRODUCTION

Natural gas consumption increases worldwide and is among the preferred source of energy due to its environmentally friendly properties and high calorific value. Worldwide many NGP are constructed for various application in industrial and domestic purposes [1, 2]. However, NGP can offer high risk to properties and individuals once damaged and lead to unintentional gas release to the surroundings. Most NGP are pressurized and due to natural gas physical and chemical characteristics (high dispersion, flammable and explosion), the consequences of pipeline failures are disastrous and have an effect to the society, economic and environment [3, 4]. There are various cases of gas pipeline incidents and their effects on human life are detrimental [4-8]. The causes natural gas incident are TPD or external interference which have the highest percentage of causing NGP failures followed by corrosion. Other factors are material or weld defects, natural forces, equipment, and incorrect operation [9-11].

In Tanzania, natural gas came into operation in 2004 where the 16-in pipeline from Songosongo to Dar es Salaam region was commissioned and in 2015 another 36-in pipeline was commissioned from Mnazi Bay and Songosongo to Dar es Salaam. Since the first operation of the pipeline network, several incidents have occurred and Table 1 summarizes the causes and resulted effects of incidents occurred in Dar es Salaam gas distribution pipeline. The 9th January 2018 incident led to fire conflagration and damage of properties as shown in Figure 1. This has raised a concern about the NGP inherent risks and safety of pipeline passing through or near people's settlements has become a discussion in relation to TPD. Currently, the Tanzanian Government promotes the use of natural gas for domestic purposes in Dar as Salaam region, plans and advertisement on NGP investment are on progress since 2016 [12].

In Literature, many methods which include qualitative and quantitative methods have been applied by researchers for risk assessment [4]. FTA is one among

Table 1: Incidents on Dar es Salaam- Tanzania natural gas pipeline

S/N	Year	Street	Mode of accident	Cause	Effects
1	April 17, 2014	Kurasini	Pipeline puncture and gas leakage	Excavator by third party contractor.	Damage of pipeline infrastructure, shutdown of gas supply to 2 industries, Loss of gas.
2	May 1, 2014	Kurasini	Pipeline puncture and gas leakage	Excavator by third party contractor.	Damage of pipeline infrastructure, shutdown of gas supply to 2 industries, Loss of gas.
3	March 5, 2015	Kurasini	Pipeline puncture and gas leakage	Excavator by third party contractor.	Damage of pipeline infrastructure, shutdown of gas supply to 2 industries, Loss of gas.
4	August 22, 2015	Vingunguti	Pipeline puncture and gas leakage	Excavator by third party contractor.	Damage of pipeline infrastructure, shutdown of gas supply to 1 industry, Loss of gas.
5	January 26, 2017	Chang'ombe	Pipeline puncture and gas leakage	Trench excavation using pit axe.	Minor damage of pipeline infrastructure, shutdown of gas supply to 1 industry.
6	January 9, 2018	Buguruni	Gas pipeline rupture and fire conflagration	Excavator during water pipeline excavation.	Damage of surrounding residential buildings, electrical infrastructure and 3 injuries, damage of pipeline infrastructure, shutdown of gas supply to many industries.

the most widely used method in system reliability, maintainability and safety analysis. The method is applied in many fields such as nuclear reactor, aerospace, petrochemical industry, chemical process, oil and gas transmission, electric power and so on [13-15].

The FTA can be used based on the conventional approach where failure probabilities of basic events or components are considered as exact values. However, in real practice estimating precise failure probability of the components is often difficult due to insufficient data or vague characteristic of the events [16, 17]. To overcome this limitation rough estimation of probabilities can be performed by treating the failure probabilities as random variables with known probability distributions. Fuzzy sets theory has been used by many researchers in estimating failure probability based on fuzzy numbers [18-20].

The disadvantage of FTA is it's non-generic or inexact in nature since it differs depending on the developer, it is enormous and can take a lot of time to a complete in a complex system. Data of all the events in the fault tree are usually unknown or not accurately known. Though, the limitation of unknown data can be overcome by employing techniques such as fuzzy logic and expert elicitation. Reliant on judgment and insight that is based on subjective opinions, estimate or perception of reality, increases risk of inaccurate information which can compromise the accuracy of the results [21-24].

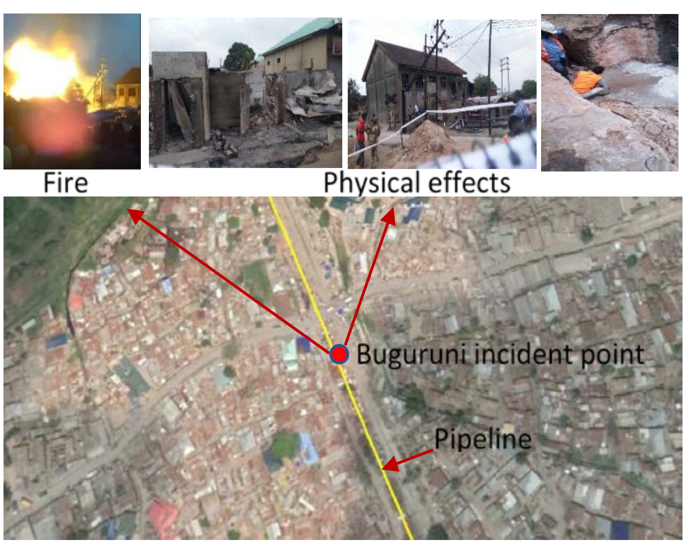

Figure 1: Gas pipeline incident at Buguruni in Dar es Salaam

However, FTA helps as a decision support tool and it can be used with both a large and a small number of participants. FTA technique can solicit input and insight from a wide number of experts [23] and as the main advantage, FTA has the ability to identify the root cause of an event from a top event selected, as well as the combinations of failures that must occur based on the undesired even [21]. The FFTA method which can overcome the limitation of conventional FTA method is generally considered to be effective and efficient on solving problems where there are no sharp boundaries and precise values or when little quantitative information is available on parameters fluctuations [13, 25].

In this paper, The FFTA in conjunction with the expert judgment was adapted for importance analysis of factors leading to TPD of NGP in the Dar es Salaam region. The paper organization includes the construction of the FTA in section 2.1, formulation of MCS and Important analysis in section 2.2, computation of failure probability in section 2.3, results and discussion in section 2.4 and conclusions at the final Section.

2. FTA IN NATURAL GAS PIPELINE

2.1 FTA Construction

FTA can be explained as a logic symbolic model generated in the failure domain through tracing of the failure path [26]. The FTA can be conducted in qualitative or in a subjective way by generating the "…fault tree, entering failure probabilities for each fault tree initiator, propagating failure probabilities to determining the TOP event failure probability, and determining cut sets and path sets…" [26]. A TOP event is an event which is not expected to occur such as failure of the system and Logical signs, such as 'AND' and 'OR' gates are used to represent relationships among various events [14]. For NGP, various researchers have utilized FTA analysis in natural gas pipelines [14, 20, 27-29].

In this paper, the fault tree was constructed as shown in Figure 2. The pipeline failure by TPD was defined as the top event of the fault tree. Three categories of damage agents namely occupancy, incidental and safety activeness was considered as sub-top events. This fault tree comprised of 47 basic events as shown in Table 2.

2.2 FTA Analysis

FTA involves qualitative and quantitative analysis. Qualitative analysis of FTA includes (a) the minimal cut sets (MCS) of the fault tree, (b) qualitative component importance and (c) minimal cut sets potentially susceptible to common cause (common mode) failures [30]. Various techniques can be applied for searching and reducing the minimum cut sets of a fault tree, most of these techniques are reviewed in the literature [30, 31]. Methods for Important Measurement of MCS include risk achievement worth, risk reduction worth (r), Fussell-Vesely, Birnbaum, and criticality measures [32-35]. In this paper criticality important measure which gives the probability that an event i has occurred and is critical to system failure was used. Given the probability of a top event as $p(T_E)=Q(p_1,p_2,...p_n), n\in N^+$ critical or relative importance probability of the basic event E_i is expressed as [36].

$$I^{CR}(E_i)=\frac{\partial Q(p_1,....p_n)}{\partial p_i}.\frac{p_i}{Q(p_1,...p_n)} \qquad (1)$$

Where, $I^{CR}(E_i)$ is the probability importance coefficient of basic events i, $Q(p_1,...p_n)$ is the probability of the top event and p_i is the probability of basic event. Denoting the MCS of Top event as K_i which are obtained based on the logic combination of basic

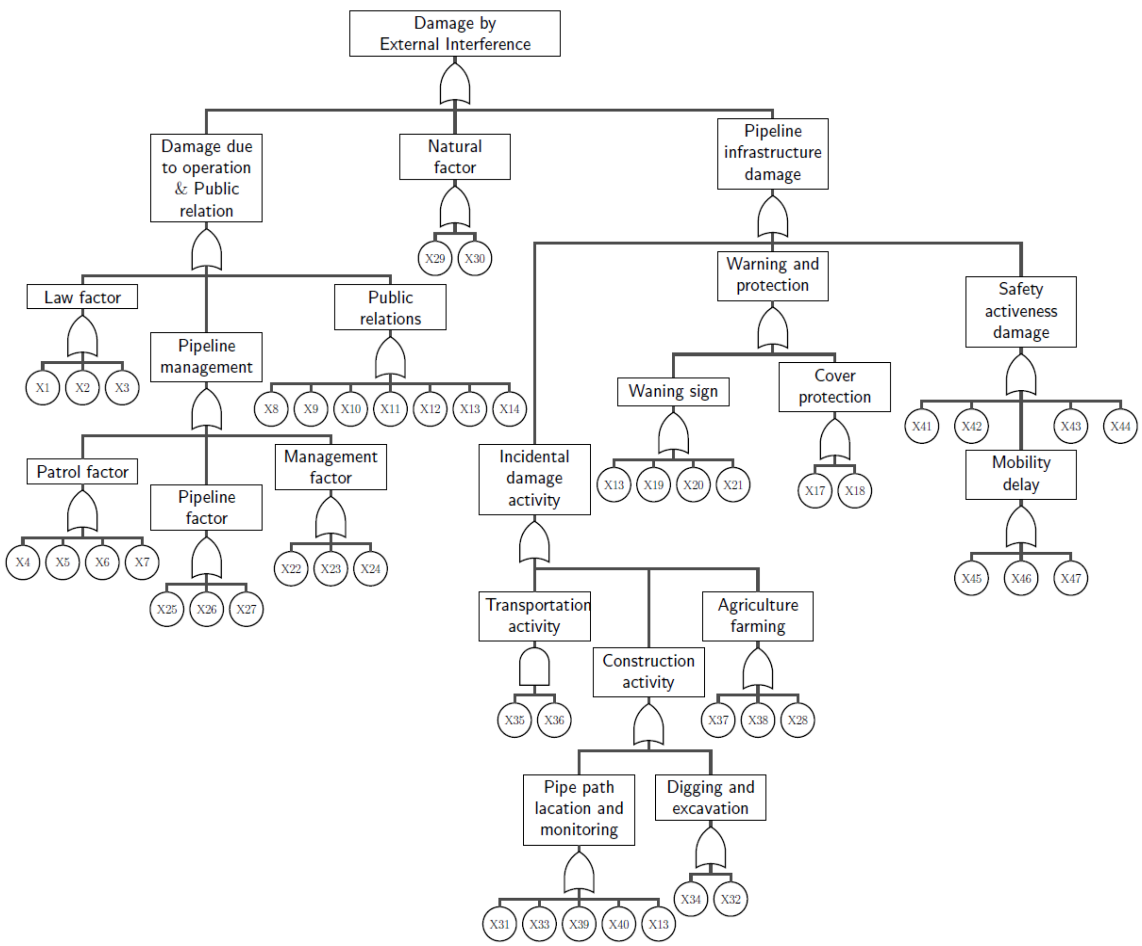

Figure 2: Fault tree of pipeline failures by third-party damage

events X_i as shown in Figure 2, the probability of the top event was established from a general equation expressed as;

$$p(T_E)=\sum_{i=1}^{n}p(K_i)-\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}p(K_i).p(K_j)...$$
$$+\sum_{i=1}^{n-2}\sum_{j=i+1}^{n-1}\sum_{k=j+1}^{n}p(K_i).p(K_j).p(K_k)... \quad (2)$$
$$+(-1)^n p(K_1.K_2...K_n)$$

Where, K_i are the i^{th} minimal cut sets. The first part of Equation (2) can be used to estimate the probability of the top event in practical engineering due to the low occurrence frequency of the basic events [14]. If only the first part is considered Equation (2) can be reduced as

$$p(K_i)=\prod_{i\in E_i}p(X_i) \quad (3)$$

2.3 Probability of Basic Events

Evolution of top event failure probabilities was accomplished based on the following procedures

a) **Expert selection and weighting:** Expert in different fields involved in the oil and gas sector such as operation, maintenance, regulation authorities, and academic institutions were considered to provide a judgment of pipeline failure by TPD. Weighting method as presented by [14] was used for ranking experts and the Delphi method of expert elicitation was used for gathering experts opinion [37]. An email was sent to experts with detailed information that could enable experts to access the level of each basic event to lead a pipeline failure in a specific environment, experts were guided to provide answers in five linguistic terms namely very low, low, medium, high and very high.

b) **Fuzzy numbers and converting fuzzy data into crisp scores:** To convert linguistic terms into corresponding fuzzy numbers, the third scale of Cheng and Hwang was used Chen and Hwang [38]. Fuzzy data were converted into crisp scores to obtain a fuzzy possibility score (FPS) which represents the most possibility that an expert believes the occurrence of a basic event [14]. Modified Jain's and Chen's fuzzy ranking approaches were used in obtaining the FPS [38].

c) **Aggregating experts' opinion:** The weighted linear (arithmetic) combination approach also known as linear opinion pool was used due to its simplicity and appealing in both understanding and computation [14, 39].

d) **Determining fuzzy failure probability (FFP):** FPS is fuzzy scores and should be transformed into FFP to ensure compatibility with real numbers. An approach presented in Yuhua and Datao [14] was used to determine the FFP of basic events.

2.4 Results and Discussion

Failure probability of basic events from Figure 2 was determined and presented in Table 2. Importance analysis of each basic event was calculated from the failure probability based on Equation (1) through Equation (3). The results of importance analysis are presented in Figure 3, which shows the second MCS which correspond to basic events X2 (Residents around pipeline lack awareness of regulations) and MCS 33 corresponding to X33 (Lack of HSE knowledge of third party workers/operator along pipeline) have high influence to NGP incidents, MCS 14 and 46 corresponding to X14 (Encroachment on NGP facility) and X47 (Unplanned settlements) respectively are next events that experts opinion perceives have high contribution to NGP incidents. MCS 12, 32 and 38 corresponding to basic events X12 (The public lack of awareness of NGP risks), X32 (Excavation using excavator equipment) and X39 (Massive individual construction and poor settlement planning) are third next category with a high probability of causing NGP failure. MCS 35 corresponding to basic event X35 (Vehicle collision) and X36 (Ground facilities above pipeline) shows least contribution since the two factors are grouped with AND gate in the fault tree (Figure 2). Also, the dependent of these factors in term of occurrence makes these two basic events to have low contribution and specifically not applicable for sections with the buried pipeline.

Observations from Figure 3 indicates there is low awareness of regulations to resident around NGP (X2) and low awareness of pipeline risks to residents around

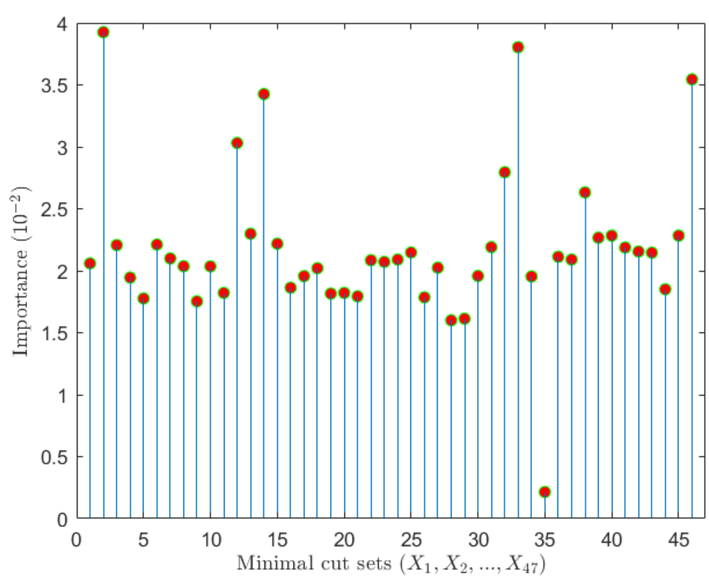

Figure 3: Failure importance of Minimal cut sets

pipeline (X12). These two factors (X2 and X12) can be solved by planning propaganda on NGP risks i.e. through advertisements, mass media, and local government. In turn, HSE training or supervision to operators (X33) will lower the pipeline damage. Encroachment on pipeline pathways (X14) was also revealed as a factor that increases the risk of NGP directly or indirectly since in some areas economic activities such as food burning continue near a pipeline or top of the pipeline, this can easier fire outbreak upon the occurrence of unintentional natural gas release. Unplanned settlement (X47) makes the pipeline to pass near people's facilities

Table 2: Basic events for third-party damage of natural gas pipeline

S/N	Event Factors	Failure probability
X1	Relevant laws and regulations not perfect	0.134
X2	Residents around pipeline lack awareness of regulations	0.256
X3	Lack of laws or regulations enforcement of different parties over pipeline safety	0.144
X4	Infrequency of patrolling along pipeline	0.127
X5	Patrolmen lacks responsibility	0.116
X6	Failure to monitor risk activities	0.144
X7	Failure to attend argent call on time (delay of attending events)	0.137
X8	Disharmony in the relationship among residents around pipeline	0.133
X9	Propaganda of pipeline safety are lacking	0.114
X10	There is low moral consciousness of public property	0.133
X11	Communication with the local government not well established	0.119
X12	The public lack of awareness of natural gas pipeline risks	0.198
X13	Signage negligence committed by third party	0.150
X14	Encroachment on natural gas pipeline facility	0.223
X15	Vandalism damage behavior	0.145
X16	Gas stolen by drilling holes	0.121
X17	Unqualified ground protection facilities	0.128
X18	Shallow Depth of cover (depth the pipeline is buried)	0.132
X19	No warning sign above pipeline	0.118
X20	Insufficient ground warning sign	0.119
X21	Poor signage visibility	0.117
X22	Imperfect pipeline management	0.136
X23	Low level of pipeline management	0.135
X24	Poor maintenance/service plan	0.136
X25	Unacceptable pipeline quality	0.140
X26	Pipeline service time is extended (skipping normal service period)	0.116
X27	Bad pipeline corrosion resistance	0.132
X28	Damaged by wildlife and livestock	0.104
X29	Stress on pipeline from growing plants	0.105
X30	Natural disaster	0.128
X31	Route sharing/interaction of other public buried facilities around pipeline	0.143
X32	Excavation using excavator equipment	0.182
X33	Lack of HSE knowledge of third part workers/operator along pipeline	0.248
X34	Local construction and digging using chisels and holes	0.127
X35	Vehicle collision &	0.106
X36	Ground facilities above pipeline.	0.132
X37	Manual digging for farming/incaution burning of vegetation	0.138
X38	Automatic digging for farming	0.136
X39	Massive individual construction and poor settlement planning	0.172
X40	Lack of guideline to individual households' construction over natural gas pipeline	0.148
X41	Presence of perfect alarming system	0.149
X42	Active response to alarming	0.143
X43	Well organized communication over incidents	0.140
X44	Inadequate mapping of pipeline and integration with parties	0.140
X45	High level of car congestion	0.121
X46	Poor street roads from main roads	0.149
X47	Unplanned settlements	0.231

and have an impact on mobility and safety activeness upon immediate action. Also, the unplanned settlement makes difficult to path NGP due to lack of well-defined and enough roads to path pipeline.

2.5 Conclusions

Coverage of Dar es Salaam NGP is expected to expand with time and Government emphasis of using natural gas for domestic purposes will increase the number of NGP customers in Dar es Salaam. This study has established the highest contributing factors of TPD in Dar es Salaam region as lack awareness of regulations awareness of individuals around NPG , encroachment on NGP facility, lack of the public awareness of NGP risks, unplanned settlement, massive individual construction and poor settlement planning, Lack of HSE knowledge of third party workers/operator along NGP and excavation using excavator equipment. As the planning of NGP expansion is underway in Tanzania, it is important for the Government and Regulatory Authorities to take measures on factors which have been identified as the highest contributor of pipeline failures by TPD. Establishing solutions on the highest contributing factors will help to mitigate the risks that can be resulted by NGP failures due to TPD and also will easier expansion of NGP to more customers especially in uncongested areas where settlement planning can be achieved.

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