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Third party damages of offshore pipeline
海底管道的第三方损伤

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Abstract - **Risk assessment is established to assist authorities in determining the priority of maintenance using risk which integrates both safety and failure. An efficient pipeline risk assessment should be able to characterize and calculate the risk associated with the pipeline. Unfortunately, the calculation of risk requires knowledge about the probability of failure and the consequence of failure. Both of which are difficult to estimate and in practical, the system under analysis cannot be characterized exactly. Numerical or objective data are often inadequate, highly uncertain and sometimes not available to perform calculations. To deal with this kind of situation effectively and consistently, a rigorous method of quantifying uncertainty using provided data is needed as well as to update existing information when new knowledge and data become available.**

In this paper, a probability analysis model of offshore pipeline failure due to third party damages is presented. The interaction between ship anchors, dropped objects and fishing gears are discussed. Bayesian networks model is proposed to determine the probability of third party damages to subsea pipelines. To generate the probabilities of different kind of nodes in a Bayesian network, a systematic probability approach is proposed with an emphasis on eliciting the conditional probability tables with multi-parents. The UK PARLOC database and DNV reports were used for the work. The paper concluded that Bayesian Network is a superior technique for risk analysis of pipeline failure. It is envisaged that the proposed approach could serve as a basis for decision making of pipeline maintenance.

Keywords – **Bayesian Network, Third party damage, Pipeline failure, Risk assessment**

I. INTRODUCTION

Oil and gas transmission pipelines are demonstrably safe and reliable means of transporting hydrocarbons. This is due to the combination of good design, materials and operating practices. The material used to design a pipeline is basically for them to operate under severe stress condition. However, diverse unavoidable factor may lead to pipeline failure as the limiting stress condition is achieved [1].

Review of historical subsea pipeline incident data and the literature summarizing pipeline failures suggest that failure causes can be grouped into four categories [2, 3]. Fig. 1 shows the distribution of offshore pipeline failure causes. It is illustrated by the historical data that the external interference (38%) is a significant contributor to potential pipelines failures followed by corrosion (36%). Most common factors of outside force or third party damage are from impact and offshore anchoring activities. The consequences of any pipeline failure may cause a serious impact to the life safety, environment and economy. In order to mitigate the severity of pipeline consequences, regular inspection and maintenance are crucial. However, maintenance activities can represent a significant cost as pipeline may cover large distances, often located in inaccessible areas and aging pipeline system incurred more maintenance frequency. Thus, risk assessment is established to assist authorities in determining the priority of maintenance using risk which integrates both safety and failure. There are several researches were conducted in developing framework to analyze risks connected to pipelines [4-7]. Nevertheless, the most significant drawback of existing frameworks for pipeline risk assessment is that they have not been performed from a causal perspective as a proper risk assessment requires a holistic outlook that embraces a causal view of interconnected event.

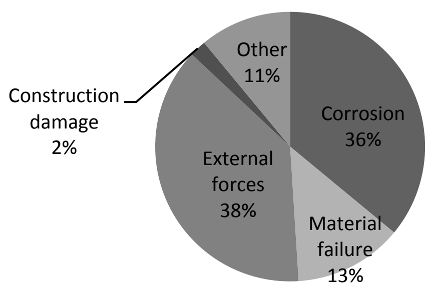

Fig.1, Offshore pipeline failure causes.

In spite that, engineering problems are subjected to significant uncertainty which is an inseparable part of real world systems. It is necessary to be able to represent, treat and manage the uncertainty in a consistent manner. Furthermore, in the decision making process, the uncertainty related to system assumptions is of tremendous importance. It is as important to be well accounted for in the calculation of risks as the degree of uncertainties and their dependencies might influence the assessed risks [8]. Several approaches being developed to represent and express uncertainties in risk assessment for pipeline failure such as fuzzy logic [9] and Bayesian statistics [1]. Yet, in practical risk assessment, the most common approach to treat the uncertainty is by probabilistic approach, in their Bayesian formulation for the treatment of rare events and poorly known process typical of high-consequence technologies [10].

II. Bayesian Network

Bayesian Networks (BN) is a probabilistic graphical model for a set of variables A={A_1,...,A_n}, which consist of qualitative and quantitative components. Qualitatively, a BN is formed from the variables together with the directed edges or arcs. In the model, each node represents a variable (discrete or continuous) that can be in one of a finite state. Meanwhile, the arc linking two variables designate causal or influential relationships between them. The structure of the BN is explicitly represents the dependence and independence relationship among the set of variables.

As the structure is defined, the strength of relationships among the variables can be achieved from the joint probability distribution of all the variables numerically which represents a BN. The probability of independencies among the model can be described efficiently by this distribution. Each variable in the graph has an associated probability distribution (PD) conditional on its direct predecessors (parents) also known as conditional probability table (CPT).

Conditional independence implies due to absence of an arc between two nodes. However, by taking into account the distribution of its parents, the conditional probability of a node can be determined. By implementing the concept, it is thus possible to specify the joint probability of the entire network structure. The relationship can be calculated by applying the chain rule for Bayesian networks. A unique joint probability distribution of the entire network over all the variables is given by the product of conditional distributions attached to each node as in Eq. (1):

$$P(A_1, \dots, A_n) = \prod_{i=1}^{n} P(A_i | parents(A_i)) \tag{1}$$

The probability statement of model parameters is made up from some initial or prior belief (probability) about an event. Once new information on evidence/event is observed, the state of knowledge of the prior probability can be updated by calculating revised probabilities which also known as posterior probabilities. In general, this rule is a repeating process about an event A given information about event B every time new or additional evidence/information becomes available. The Eq. (2) is given as:

$$P(A \mid B) = \frac{P(B \mid A)P(A)}{P(B)} \tag{2}$$

The term P(A) is called prior or marginal probability of A. It is prior in the sense that it predicts any information about B and this is what causes all the arguments. P(A|B) is called the posterior probability of A given B as it is derived from the specified value of B. Whereas, P(B|A) is the conditional probability of B given A. P(B) is called prior or total probability of B and it is the one that provides evidence of interest for the probability update of A.

Bayesian networks can as well be transformed to a valuable decision model called influence diagrams which are highly intuitive in the decision making process [11]. It consists of belief networks with two additional node types, namely decision nodes and utility nodes. Decision nodes correspond to controllable decisions that have an effect on the system. Utility nodes on the other hands represent criteria for making choices and are used to assign values to particular outcomes.

Influence diagrams can be built and manipulated using program package such as *Hugin Expert*. The outcome of an influence diagram includes the marginal probability distribution of all variables in the domain and the expected utilities for the decision. If evidence is observed and propagated, expected utilities for the decision variable will be computed and updated. Thus, an influence diagram provides a dynamic decision tool presenting the optimal strategy, possibly conditional on a set of knowledge [12].

III. Risk Assessment using BN Model

A risk based ranking of pipeline segment is valuable to assist authorities in determining the priority of inspection and maintenance of pipeline. The common method reported from the literature to quantify the risk is by applying the risk formula of;

Risk = probability of failure x *probability of consequences*

This method however, decomposing the risk into two components and so as the uncertainties. Moreover, the value can only be obtained with detailed analysis of the variables involved.

In this paper, the suggested risk assessment is by quantifying the risk in causal analysis. This approach treats a risk as an event that can be characterized by a causal chain involving (at least)[13] :

- The event
- At least one consequences event that characterises the impact
- One or more initiating event
- One or more control events which may stop the initiating event from causing the risk event
- One or more mitigating events which may help avoid the consequence event

With the causal perspectives approach suggested, a risk is not treated as a single event but by a set of event.

IV. Third Party Damage

"Third-party damage" is known as damages due directly to acts of man and includes all activities not directly related to the pipeline of study. Three possible hazardous scenarios that may

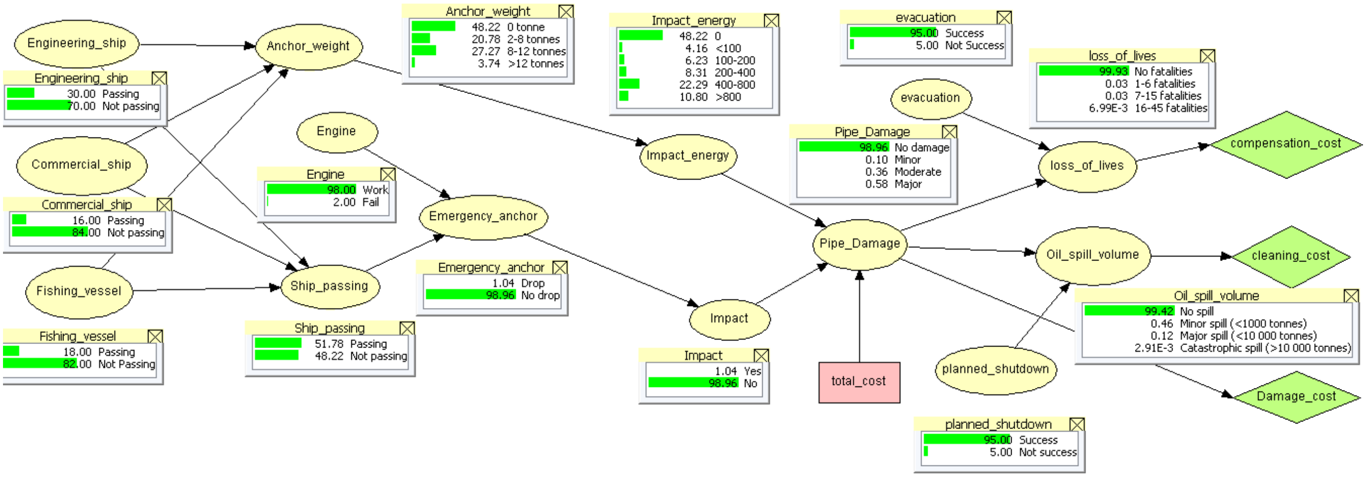

Fig 2, Proposed Bayesian network model for section 1.

threaten the pipeline are dropped object, anchoring and fishing activities.

Dropped object is the event where an object can be lost from vessels. The most frequent incident in the open sea is the lost of container from commercial ships crossing the pipeline route. However, only a small fraction of containers sunk due to heavy load or to a lack of water tightness while others will stay floated [14]. Thus the risk of this dropped object can be neglected.

Fishing activities on the other hand, threaten the pipeline which mainly due to bottom trawling. Load from the trawl gear is associated with prompt impact, subsequent overdraw or hook up. Yet, experience with numerous offshore pipelines in the North Sea show that fishery and offshore pipelines can co-exist safely as protected pipeline can withstand trawl gear interaction [15].

Despite that, historical data shows that 22/96 leaked incidents were caused by anchor impact [16]. Thus, only anchoring activities are considered in this study. The major cause leading to drop of anchor is unplanned or emergency anchoring as planned anchoring is made in authorized areas of pipeline absent.

The possible damage induced by an external impact is based on deformation level of the pipeline at the end of interaction process [14]. This deformation occurs depend on the impact energy towards the pipeline. Throughout this study, impact energy was used to define damage of pipeline as each pipeline has its own characteristics.

V. Anchor-Pipeline Interactions Scenario

There are three types of ships possibility will pass through the pipeline in open sea which are commercial ships, engineering ships and fishing vessel. The weight of anchor is depending on the type of ships and it then affects the probability of impact energy. Impact on pipeline happens when ship's engine crossing through a pipeline is not working. Subsequently, anchor is dropped under emergency condition. Damage to a subsea pipeline is integrated by impact energy and impact on the pipeline. The potential consequences due to pipeline damages are loss of lives, oil spillage, production loss and repair. The amount of oil spill also depends on the success of production shut-down operations; meanwhile, loss of lives depends on the success of operations to evacuate victims during the event.

The network is then expanded into an influence diagram by introducing decision node and utility functions which gather information for the potential benefits and enabling the 'oil estimation of expected total cost. Given the outcome state of spill', a value node of 'environmental cleaning cost' is created, given the outcome state 'loss of lives' a value node of 'compensation and loss of reputation' is introduced and given the outcome of 'pipe damage' a value node of 'damage cost' referring to production and cost to repair damage is created. All the value nodes are introduced to estimate the total expected cost as a function of the decision denoted as 'total cost'. The scenario is then transformed into BN model as in Fig. 2.

VI. Application Example: Nord Stream Pipeline

In this section, the utilization of developed BN model framework is discussed based on example of Nord Stream pipeline interaction with ships along the Baltic Sea involving five countries; Russia, Sweden, Germany, Finland and Denmark [17]. The properties of the pipeline sections with high density ship traffic were defined as in Table 1.

TABLE 1, Total expected cost for each section

Pipeline section	Section length (km)	No of ship passing (per year)		
		Fishing ship	Commercial ship	Engineering ship
1	10	400	805	775
2	15	1000	1960	860
3	10	790	2180	920

The proposed model shown in Fig. 2 is used and the methods for CPTs elicitations are discussed. For two states events, conversion of Boolean operations (disjunction, v and conjunction, ʌ) into CPTs is applied. Disjunction is applied for node ship passing and type of ships (*ship passing = fishing vessel v engineering ship v transport ship*) as in Fig. 3 indicating 1 is ship passing and 0 is ship not passing. Meanwhile, conjunction is applied for node ship passing, engine and emergency anchor (emergency anchor = ship passing ʌ engine) as shown in Fig. 4 with 1 is anchor drop and 0 for no drop.

Edit Functions View

Ship_passing

Engineering...	Passing				Not passing			
Fishing_vessel	Passing		Not Passing		Passing		Not Passing	
Commercial...	Passing	Not passing	Passing	Not passing	Passing	Not passing	Passing	Not passing
Passing	1	1	1	1	1	1	1	0
Not passing	0	0	0	0	0	0	0	1

Fig.3, Disjunction CPTs of fishing vessel, engineering ship and transport ship.

Edit Functions View

Emergency_anchor

Ship_passing	Passing		Not passing	
Engine	Work	Fail	Work	Fail
Drop	0	1	0	0
No drop	1	0	1	1

Fig.4, Conjunction CPTs for emergency anchor.

The CPTs for impact energy and pipe damage are elicited according to historical data from recommended practice for pipeline protection, DNV-RP-F107 presented by [18]. Fig. 5 shows the probability of impact energy given anchor weight based on the historical data proposed for a pipeline with normal protection requirement. The damages to the pipeline are classified and defined according to [18] report as follows:

i. No damage.
ii. Minor damage: no repair required and no hydrocarbons release.
iii. Moderate damage: repair required but not leads to hydrocarbons release.
iv. Major damage: damage leading to release of hydrocarbons. Immediate stop of pipeline operation and to be repaired if the pipe in ruptured. Damage section need to removed and replaced.

Edit Functions View

Impact_energy

Anchor_weight	0 tonne	2-8 tonnes	8-12 tonnes	>12 tonnes
0 kJ	1	0	0	0
<100 kJ	0	0.2	0	0
100-200 kJ	0	0.3	0	0
200-400 kJ	0	0.4	0	0
400-800 kJ	0	0.1	0.7	0.3
>800 kJ	0	0	0.3	0.7

Fig.5, Probability of impact energy given anchor weight.

From the state of pipeline, consequences due to the failure are assessed. In pipeline mid-line zone, releases of hydrocarbon may endanger third party personnel. In this case, only major release scenarios (rupture) may threat the personnel. The personnel here is refers to the crew and passengers of vessels operating in the vicinity of a pipeline. Ignition will only occur if the gas above the sea surface is flammable concentration and possible ignition sources are present within this cloud. The outcome of the event is often difficult to predict accurately. It may be assumed in major release events, 1-10% of these events the gas release will ignite [18].

The number of fatalities is estimated based on quantification of societal risk resulted from the consequences analysis of the third party activities (dropped object, dropped anchor, dragged anchor and fishing) reported for subsea gas pipeline [15]. The societal risk result was plotted on F-N curves and it is used to develop the CPT for node 'loss of lives'. It is demonstrated from the report that the level of risk is broadly acceptable when compared with agreed risk tolerability criteria.

In determining the cost valuation of human life, several approaches have been proposed. These include Willingness to pay (WTP), Value of statistical life (VSL), the CSX-value and Human capital approach [19]. For this example, the valuation of loss of life is estimated from work done by [20]. They suggested that for developed countries, the average value of a statistical life according to Life Quality Index and macro-economic valuation is in between £ 0.8 M – £3.3 M. The quantitative inputs for compensation cost utility node is £11.2 Million, £27.9 Million and £83.7 Million for 1-6 fatalities, 7-15 fatalities and 16-45 fatalities respectively.

To simplify the model, damage to environment is measured only in terms of oil spill volumes. Both minor and major release scenarios may give an impact to the environment. The pollution from the spillage affects the eco-system in the water, shoreline environment, sea birds and fishes. The environmental consequences are usually expressed as clean – up efficiency or estimated time for achievement of full recovery of the affected area. The estimation of cleanup costs for oil spill is according to average cleanup cost per tonne spilled based on analysis of oil spill cost data from the OSIR International Oil Spill data [21]. From the report, the average cleanup cost is £ 5281.38 per tonne for Europe region. The cleanup-cost is £41.2 Million for minor spill, £47.5 Million for major spillage and £80 Million in case of catastrophic spill.

Lastly, the damage cost which is the summation of production loss and pipeline repair cost is evaluated. The assumption value is found from the evaluation done by [22]. Both costs have been assumed to be linearly related to time taken for repair. In this assumption, material cost for repairs have been neglected. The estimated costs are as follows:

- Loss of production £ 2 M per day
- Repair cost of £ 0.1 M per day

It is assumed to repair a moderate damage is up to 16 days (clamp repair) and for large damage (newspool piece installed using mechanical connectors) 30 days is required. Addition of 3 days vessel mobilization has been assumed for every case. The damage cost for moderate and major event is £39.9 Million and £69.3 Million, respectively.

The BN model is analyzed and the total cost incurred for each section is shown in Table 2. From the data used in this example, the major contributor to the expected cost of failure is product losses and repair cost with 90%, 86% and 85% for pipe section 1, 2 and 3 respectively. The contribution of other cost to the total of expected failure cost is relatively low. Result from Table 2 is utilized in order to compare and rank the risk of different pipeline section. Section 3 has the highest cost incurred thus this section has the highest priority for maintenance operations followed by Section 2 and Section 1.

In addition, a number of entered evidence situation for this model can be investigated and the total expected cost will be recalculated. As an example, in worst case scenario where pipeline is 100% in major damage, the total expected cost incurred is £83.78 provided the planned shutdown is 95% success. From the analysis, the main contributors for the major damage event to occur are ‘engine fail’ and ‘engineering ship passes’.

TABLE 2, TOTAL EXPECTED COST FOR EACH SECTION

Pipe Section	Total cost incurred (£ Million)
1	0.63
2	0.86
3	0.90

VII. CONCLUSION

This paper has demonstrated the application of Bayesian network modelling for risk assessment of subsea pipeline due to anchor interaction. Firstly, BN model is developed for pipeline-anchor interaction. The network then is expanded into an influence diagram by introducing decision node which is the ‘total cost’ and utility functions (‘compensation cost’, ‘cleaning cost’ and ‘damage cost’) which gather information for the potential benefits and enabling the estimation of expected total cost. This is then followed by the elicitation of CPTs. Generally, there are many ways to establish the CPTs. To evaluate the proposed model, a case study from Nord Stream is adopted and most of the CPTs are elicited from statistical and historical data. Probability prediction and evidence propagation were conducted to analyze damage probability and to highlight problematic area respectively. The proposed model illustrate that risk analyst are able to figure out the causes of pipeline damage and the consequences such as loss of live, oil spill volume and repair cost and production loss. In addition, the developed influence diagram offer a tool to support risk ranking and risk reduction measures based on expected failure cost incurred for a given segment of a pipeline.

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