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Quantitative risk analysis of offshore drilling operations: A Bayesian approach

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ABSTRACT

Blowouts are among the most undesired and feared accidents during drilling operations. The dynamic nature of blowout accidents, resulting from both rapidly changing physical parameters and time-dependent failure of barriers, necessitates techniques capable of considering time dependencies and changes during the lifetime of a well. The present work is aimed at demonstrating the application of bow-tie and Bayesian network methods in conducting quantitative risk analysis of drilling operations. Considering the former method, fault trees and an event tree are developed for potential accident scenarios, and then combined to build a bow-tie model. In the latter method, first, individual Bayesian networks are developed for the accident scenarios and finally, an object-oriented Bayesian network is constructed by connecting these individual networks. The Bayesian network method provides greater value than the bow-tie model since it can consider common cause failures and conditional dependencies along with performing probability updating and sequential learning using accident precursors.

1. Introduction

Risk analysis is an important tool to develop strategies to prevent accident and devise mitigative measures. It is of great relevance and applicability in offshore drilling operations due to challenges in safety measures arising from the harsh environment and remoteness. Further, typically known as compact areas enclosing a high density of equipment and personnel, offshore drilling rigs are complex systems having the potential for unexpectedly severe consequences during an accident. Blowouts, though rare, are the most feared and violent accidents significantly threatening human lives, environment and assets (Holand, 1997).

A blowout is an uncontrolled flow of hydrocarbons (e.g., gas and condensate) or even saltwater from a well to the surrounding environment as the ultimate consequence of a kick. This environment can be the atmosphere (surface blowout) or other underground formations (underground blowout). A kick is an unwanted influx of formation fluids into the wellbore as a result of loss of well control (LWC), in which the pressure of formation fluids, i.e. pore pressure (P_P), exceeds the pressure exerted by the column of drilling fluid on the bottom of the wellbore, i.e. bottom hole pressure (*BHP*) (Andersen, 1998). A kick can result in a blowout if it is not detected in a timely manner and properly prevented. Well control operation, comprising technical, managerial and organizational measures, is aimed at maintaining the well integrity and reducing the risk of LWC through kick prevention, kick detection, blowout prevention and kill operations (Fig. 1).

Fig. 1 shows the sequential steps followed to maintain well integrity. The first three steps are related to the *loss of well control* while the last one is related to the *regain of well control* and is performed only if a blowout can be prevented. Recently, a complex series of human errors and mechanical failures resulted in a LWC in the Macondo Well on April 20, 2010, which finally led to a blowout, leaving deaths, injuries and a significant amount of hydrocarbon spill (BP, 2010). The fire and explosions that followed the blowout finally caused the Deepwater Horizon drilling rig to sink. According to the report provided by the BP incident investigation team (BP, 2010), a chain of events was to blame for the LWC. Of these events, poor cementing caused a kick to occur (i.e., failure of step 1 in Fig. 1) while failure to notice the kick indications such as changes in the flow rate and the wellbore pressure resulted in the kick not being detected until it flowed up into the riser (i.e., failure of step 2 in Fig. 1). The failure of the blowout preventer (BOP) to close in the well escalated the kick into a blowout (i.e., failure of step 3 in Fig. 1). Since the kill lines as well as the choke lines of the BOP were damaged, it was also impossible to perform a kill procedure to re-establish well control (i.e., failure of step 4 in Fig. 1).

The risk of blowout cannot be eliminated, but can be reduced through preventive and mitigative measures. Since risk is defined as the product of probability and consequence, preventive safety measures are aimed at reducing the probability whereas mitigative measures are applied to alleviate consequences. Priority is usually given to the former, i.e., preventive measures (Holand, 1997). Safety measures are normally contemplated and allocated to the

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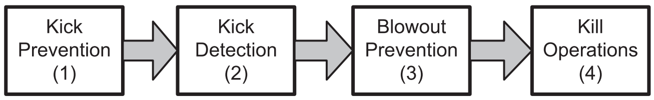

Fig. 1. Schematic of well control operation.

system of interest through risk analysis. Risk analysis not only determines if the risk is acceptable, but also identifies major risk contributing factors for which reducing measures should be applied. To conduct drilling operation risk analysis, blowout probability estimation is the first task usually carried out using statistical methods and past historical data.

Due to limited data and large uncertainty arising from data source variability, blowout probability estimations using statistical data are often questioned (Holand, 1997). Data uncertainty is due to wide ranges of data which differ in terms of the place of blowouts (e.g., North Sea or Canadian arctic waters), type of wells (e.g., exploratory or development), depth of drilling (e.g., shallow or deep water), and time of blowout (e.g., during drilling or tripping). From the location point of view, factors such as weather conditions, formation temperature, pressure, permeability and porosity differ from place to place (Andersen, 1998; Holand, 1997; Nilsen et al., 2001). Therefore, data sources of blowout frequency estimation require extreme caution in their use. For example, the ERCB database (http://www.ercb.ca) covers onshore blowouts while WOAD (1994) contains offshore blowouts as well as other offshore accidents. SINTEF Offshore Blowout Database (1995) covers both exploratory and development blowouts from the North Sea and the U.S. GoM OCS (Gulf of Mexico Outer Continental Shelf).

Even with reliable and up-to-date historical blowout data, these generic data do not identify the series of events that finally resulted in a blowout. Thus, not only well-specific data such as pore pressure (P_P), bottom hole pressure (BHP), fracturing pressure (F_P) and the type of barriers are not taken into account, but also the causes of the blowout whether human errors or mechanical failure are not considered in the frequency estimation.

To overcome the aforementioned drawback of statistical methods, there have been attempts to localize generic data to the case of interest using adjustment factors. These adjustment factors reflect well-specific data (e.g., pore pressure) as well as company-specific data (e.g., kick management policies), the applications of which result in site-specific blowout frequencies. As an example of such statistical-based adjusting methods, BlowFAM (Dervo and Blom-Jensen, 2004) is based on the SINTEF database and examines different elements such as drilling activities, reservoir characteristics and management parameters to identify a total adjustment factor.

On the other hand, many researchers have studied the blowout phenomenon through its components. Thus, causal relationships among blowout components along with well-specific and company-specific parameters can be analyzed in a systematic manner. Bercha (1978) used a fault tree (FT) model to estimate the blowout probability of both exploratory and development wells in Canadian arctic waters. The application of event trees (ET) was briefly discussed to represent a blowout as a potential consequence of a kick. The whole accident, starting from the causes of the kick and ending with the blowout however is modeled using FT in their work (Bercha, 1978). Andersen (1998) proposed a stochastic model based on the physical mechanism of the kick as the initiating event of the blowout. The FT method was then applied to estimate the probability of the kick within each drilling sub-operation. Grouping of the well drilling operation into sub-operations such as drilling, tripping and casing was considered due to different primary causes and safety barriers involved in each sub-operation.

Although static FT have been extensively used in risk analysis of kicks and blowouts (Andersen, 1998; Arild et al., 2008, 2009; Bercha, 1978, 2010; Bercha et al., 2008; BP, 2010; Nilsen et al., 2001; Worth et al., 2008), it is not the most appropriate technique for large systems. Static FT fails to capture dependent failures and common cause failures (Bobbio et al., 2001; Khakzad et al., 2011, 2013a,b). Further, aside from static parameters such as formation porosity and permeability, there are dynamic parameters such as formation temperature and pressure which vary over time as the well goes deeper. Also, drilling parameters such as the weight and volume of drilling mud are always prone to unexpected changes because of unexpected gas pockets, losses in formation and improper wellbore fill-up in case of tripping (Holand, 1997). More importantly, safety barriers change as the well proceeds from one phase (e.g., drilling) to another (e.g., production); this needs to be taken into account when conducting risk analysis of drilling operations.

Bayesian network (BN) is a probabilistic inference technique for reasoning under uncertainty. It has been used in the field of risk analysis and safety assessment over the last decade. BNs apply d-separation and the chain rule to represent causal relationships among a set of random variables considering local dependencies (Jensen and Nielsen, 2007). Many authors have shown the parallels between FT and BN (Bobbio et al., 2001; Boudali and Dugan, 2005; Khakzad et al., 2011; Torres-Toledano and Sucar, 1998) and discussed how the limitations of the former technique are to a large extent addressed by the latter. The main advantage of BN making it a superior technique for risk analysis of dynamic systems such as well control is the ability to perform probability updating. Applying Bayes' theorem, BN updates the initial beliefs as new information about the system becomes available over time. Therefore, the risk analysis can be used as a decision-making tool to decide between various scenarios at the design stage of well operation. It can also be applied during the well lifecycle to identify risk factors and allocate proper safety measures as changes take place in the well system. The merit of BN models in risk analysis of well control becomes accentuated as frequent accident precursors such as kicks can be used to update the likelihood of blowouts (Skogdalen et al., 2011).

The present work is aimed at demonstrating the application of BNs in risk analysis of drilling operations and making a comparison with the bow-tie (BT) method. The scope of the work is limited to the first three steps of well control as shown in Fig. 1: investigating the probability of a kick and its propagation into a blowout. In other words, well control regain is not covered in this study. The current study has used the concept and blowout logic discussed by Andersen (1998) and Bercha (1978).

Well control events including the physical mechanism of kick, kick detection and the escalation of kick into blowout and the relevant barriers are discussed in Section 2. A brief description of risk analysis methods, BT and BN, is given in Section 3. Section 4 is devoted to the application of BT and BN to well control risk analysis while the conclusion is presented in Section 5.

2. Well control

2.1. Kick mechanism

A kick is defined as an uncontrolled and unwanted influx of formation fluids into the wellbore. It is the initial event that can potentially escalate into a blowout. Even if a kick is controlled, it takes some time to circulate out the influx and re-establish the wellbore pressure balance. Extra costs are inevitable due to recovery works and several days of delay in resuming the drilling procedure (Nilsen et al., 2001). In some cases, the kick-induced damage is so severe that the well is plugged and abandoned.