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Dynamic Bayesian networks based performance evaluation of subsea blowout preventers in presence of imperfect repair

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ABSTRACT

This paper presents a quantitative reliability and availability evaluation method for subsea blowout preventer (BOP) system by translating fault tree (FT) into dynamic Bayesian networks (DBN) directly, taking account of imperfect repair. The FTs of series system and parallel system are translated into Bayesian networks, and extended to DBN subsequently. The multi-state degraded system is used to model the imperfect repair in the DBN. Using the proposed method, the DBN of subsea BOP system is established. The reliability and availability with respect to perfect repair and imperfect repair are evaluated. The mutual information is researched in order to assess the important degree of basic events. The effects of degradation probability on the performances are studied. The results show that the perfect and imperfect repairs can improve the performances of series, parallel and subsea BOP systems significantly, whereas the imperfect repair cannot degrade the performances significantly in comparison with the perfect repair. To improve the performances of subsea BOP system, eight basic events, involving LWHCO, LLPR, LCC, LLICV, SLPSV, LRPIL, PIHF and SVLPLE should given more attention, and the degradation probability of basic events, especially the ones with high sensitive to system failure, should be reduced as much as possible.

1. Introduction

A subsea blowout preventer (BOP) system plays an extremely important role in providing safe working conditions for drilling activities in 10,000 ft ultra-deepwater regions. Subsea BOP failures could cause catastrophic accidents such as the explosion of the deep-sea petroleum drilling rig *Deepwater Horizon* and the oil spill off the coast of Louisiana on April 20, 2010. It was concluded that the failure of the BOP to shear the drill pipe and seal the wellbore was caused directly by the physical location of the drill pipe near the inside wall of the wellbore, which was outside the blind shear ram cutting surface during activation (BOEMRE, 2011; Harlow, Brantley, & Harlow, 2011). In the wake of recent disasters in oil and gas exploration and production, the performance evaluation of subsea BOP systems is becoming recognized.

A few literatures involving the performance evaluation of subsea BOP systems were reported. Traditional analysis technique, such as fault tree, failure modes and effects analysis and Markov chain, were used for the purpose of reliability assessment. Shanks, Dykes, Quilici, and Pruitt (2003) studied the reliability of deepwater BOP control system and described a statistical process for determining the reliability and failure rate necessary to accomplish the maintenance goal. Holand and Rausand (1987) and Holand (1996) collected reliability data regarding subsea BOP failures and malfunctions, and calculated the failure rates of subsea BOP components and rig downtime. The availability of the subsea BOP systems was estimated using the fault tree analysis method. Fowler and Roche (1994) studied the system safety of well control equipment including BOPs and hydraulic control systems using failure modes and effects analysis and fault tree methods. The results showed that despite human errors, the ram BOP and its associated controls constituted a highly reliable system. Cai et al. (2012) assessed the performance of subsea BOP systems with respect to common-cause failures by merging the independent Markov models with the Kronecker product approach.

Recently, driven by the fact that Bayesian Networks (BN) and dynamic Bayesian networks (DBN) can perform forward or predictive analysis as well as backward or diagnostic analysis, BN and DBN techniques receive considerably increasing attention in the field of reliability analysis. In predictive analysis, the probability of occurrence of any node is calculated on the basis of the prior probabilities of the root nodes and the conditional dependence of each node. In diagnostic analysis, the posterior probability of any given set of variables is calculated given some observation (the evidence), represented as instantiation of some of the variables to one of their admissible values. Nordgard and Sand (2010) described a methodology for application of BN for risk analysis in

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electricity distribution system maintenance management. Khakzad, Khan, and Amyotte (2011) demonstrated the application of BN in safety analysis of process systems, and compared the approaches of fault tree and BN. Jones, Jenkinson, Yang, and Wangn (2010) applied BN modeling to a maintenance and inspection department, and established and modeled various parameters responsible for the failure rate of a carbon black producing system, in order to apply it to a delay-time analysis study. Mahadevan, Zhang, and Smith (2001) developed a methodology for the application of the BN to structural system reliability assessment.

BN models for reliability evaluation can be achieved by converting the traditional reliability models. Torres-Toledano and Sucar (1998) presented a general methodology for transforming a reliability structure represented as a reliability block diagram to a BN representation, and with this, the reliability of the system can be obtained using probability propagation techniques. Bobbio, Portinale, Minichino, and Ciancamerla (2001) presented an algorithm to convert a fault tree (FT) or a dynamic fault tree into a BN or DBN. A software tool named RADYBAN was also developed for automatic translation (Montani, Portinale, Bobbio, & Codetta-Raiteri, 2008). Webera and Jouffeb (2006) presented a methodology that help developing dynamic object oriented BN to formalize complex dynamic models as equivalent models to the Markov chains. Kim (2011) extended the research, and provided a method of mapping a reliability block diagram with general gates model into an equivalent BN model without losing the one to-one matching characteristic for quantitative analysis. Khakzad, Khan, and Amyotte (2013) presented a methodology to map bow-tie into BN for dynamic safety analysis of process systems.

Till now, BN and DBN are seldom used to evaluate the reliability of subsea BOP systems. The key issue in this thematic field is the integration of repair actions into a BN and DBN model. Flammini, Marrone, Mazzocca, and Vittorini (2009) presented both a failure model for voting architectures based on BN and a maintenance model based on continuous time Markov chains, and proposed to combine them according to a compositional multiformalism modeling approach in order to analyze the impact of imperfect maintenance on the system safety. Neil and Marquez (2012) presented a hybrid BN framework to model the availability of renewable systems. They used an approximate inference algorithm for hybrid BN that involves dynamically discretizing the domain of all continuous variables and used this to obtain accurate approximations for the renewal or repair time distributions for a system. Portinale et al. presented an approach to reliability modeling and analysis based on the automatic conversion of dynamic fault tree or series and parallel modules into BN taking repair into consideration (Codetta-Raiteri, Bobbio, Montani, & Portinale, 2012; Portinale, Raiteri, & Montani, 2010).

The work focuses on the translation from FT into DBN of series and parallel systems, taking account of imperfect repair. The paper is structured as follows: Section 2 presents the DBN modeling of series and parallel systems, and gives the reliability and availability results. Section 3 analyzes a case to demonstrate the application of DBN modeling with imperfect repair. Section 4 summarizes the paper.

2. Dynamic Bayesian networks with imperfect repair

2.1. Overview of BN and DBN

BN is widely used in quantitative risk assessment because the model can perform both of predictive and diagnostic analysis. A BN consists of qualitative and quantitative parts. The qualitative part is a directed acyclic graph in which the nodes represent the system variables and the arcs symbolize the dependencies or the cause–effect relationships among the variables. The quantitative part is the conditional probabilistic table, which gives the relations between each node and its parents.

BN models relationships between variables at a particular point in time or during a specific time interval. Although a causal relationship represented by an arc implies a temporal relationship, BN does not explicitly model temporal relationships between variables. The only way to model the relationship between the current value of a variable, and its past or future value, is by adding another variable with a different name.

DBN is a long-established extension to ordinary BN that allow explicit modeling of changes over time. Each time step is called a time-slice. Two time slices for each variable are considered in order to model the system temporal evolution. The relationships between variables in a time-slice are represented by intra-slice arcs. And the relationships between variables at successive time steps are represented by inter-slice arcs.

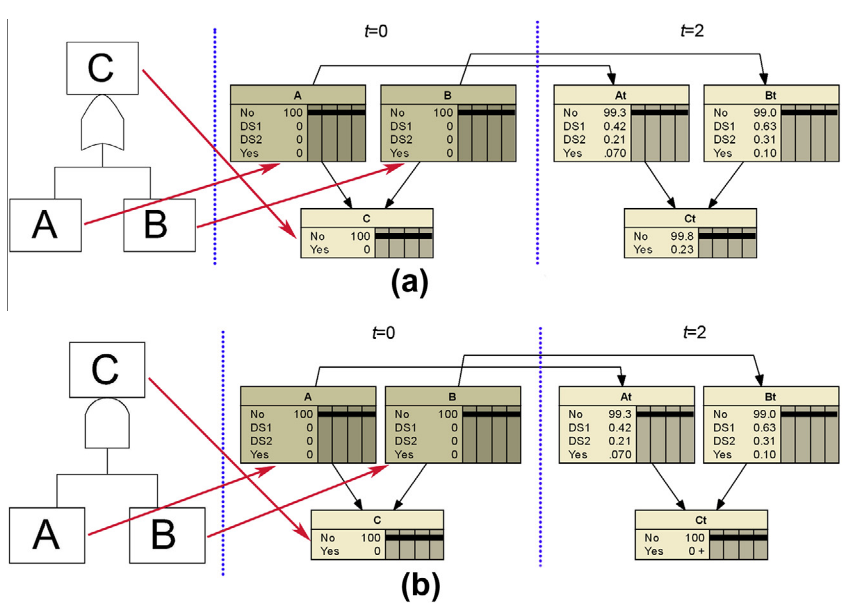

Fig. 1. DBN of (a) series and (b) parallel systems with two components.