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A methodology for updating emergency schemes by combining dynamic Bayesian networks with graphical evaluation and review technique

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The blowout risk in offshore drilling operations is characterized by uncertainty and complexity. Blowout accidents usually result in significant casualties, property losses, and even environmental disasters. To alleviate the consequences of accidents and evaluate the emergency risk, we propose to integrate dynamic Bayesian networks (DBN) and graphical evaluation and review technique (GERT) to develop a risk assessment model. In the proposed methodology, we establish a topological network to describe the failure coupling of nodes in the emergency schemes by DBN. Subsequently, the dynamic failure probability change of different nodes can be obtained through failure probability analysis. To optimize emergency schemes, GERT is integrated into the sensitivity analysis to evaluate the risk of nodes in the emergency schemes. The duration of emergency operations can be optimized by the results. Offshore capping stack, an effective deepwater blowout emergency technique, is used to demonstrate the applicability of the methodology. The results show that the proposed model is beneficial to determine emergency operations in offshore oil and gas activities.

Keywords: Emergency scheme, Dynamic Bayesian network, Graphical evaluation and review technique, Transfer function, Strategy optimization.

1. Introduction

Due to the increasing information stream and the largely uncertain, the operations in the drilling process are complex and dynamic [1]. The characteristic of deepwater activities includes harsh operating environments [2]. Major accidents, such as blowouts, usually stem from multi-factor coupling including human, technical, and organizational errors [3, 4]. Emergency operations are exposed to harsh environments, geological conditions, and long offshore distances. The complexity of the deepwater environment and accident evolution, as well as the severity of well control failure, put forward higher requirements for the updating of emergency schemes. For instance, the explosion of the Deepwater Horizon drilling platform in the Gulf of Mexico led to 11 deaths and 49 million barrels of crude oil spill [5, 6]. A crucial reason is that the blowout preventer (BOP) failed to close the well. To reduce the severity of the accident consequences and improve the emergency response capability, it is necessary to update emergency schemes in a dynamic environment.

As a probabilistic graphical model, a dynamic Bayesian network (DBN) has been widely applied in the field of risk assessment [7]. Owing to the integration of multiple states and the temporal dimension, DBN can be conducted not only by prognostic but also by diagnostic analysis [8]. Some scholars proposed to map traditional methods into Bayesian network (BN) to capture the causal evolution of systems failure. Cai et al. [9] proposed the availability-based engineering resilience metric and DBN-based evaluation methodology. Yodo et al. [10] conducted the predictive resilience analysis of complex systems using dynamic Bayesian networks. The application of DBN in this paper depicts the failure probability in emergency activities. To construct the emergency scenario and evaluate the time risk of the emergency scheme, we apply graphical evaluation and review technique (GERT) to solve above-mentioned questions. Due to the advantages of the probabilistic branching, the looping and the ability to handle any distribution for activity time, GERT had been widely developed in R&D projects [11]. Tao et al. [12] used the GERT method extended by a characteristic function to analysis schedule risk analysis for new product development. Geng et al. [13] constructed a GERT-based resilience assessment framework for complex engineered systems. GERT can quantify the change in variable states, where the transfer function describes the dynamic nodes in emergency schemes.

In this paper, we combine DBN with GERT to optimize the emergency schemes. Firstly, we analyze and construct the emergency system. Secondly, we establish the DBN model to identify the failure probabilities of activities. Thirdly, regarding the failure probabilities, we can evaluate the time risk of the emergency schemes. Finally, we make decisions based on the model results.

The remainder of this paper is structured as follows. Section 2 describes the basics of the integration of DBN and GERT. Section 3 presents a case study and results. Finally, Section 4 concludes the paper.

2. Methodology

We proposed an integrated methodology for updating emergency schemes by combining DBN and GERT. The methodology can be divided into four steps.

In this method, step 1 aims to decompose the system and define the emergency activities of the system. Step 2 intends to construct a DBN model to calculate the failure correlation between key nodes. Step 3 is used to establish the GERT model to evaluate the emergency schemes from the perspective of the time. Based on step 3, the sensitivity analysis also can be developed to make efforts about the decision-making of the emergency schemes in step 4.

2.1. *DBN*

Considering the correlation and complementary of the information at the different time frames, traditional BN cannot meet the inference requirements under dynamic environments with incomplete information [14]. As an extension of BN, DBN allows estimating the joint probabilities with time [15]. The joint probabilities of nodes $X=(X_1,X_2,X_3,\ldots,X_{\mathrm{n}})$ can be calculated based on Equation (1).

$$P(X)=\prod_{i=1}^{n} P(X_i \mid Pa(X_i)) \tag{1}$$

Where $Pa(X_i)$ represents parent nodes of nodes X.

In a DBN model, its parent nodes at the time t, states and parent nodes at the previous time step influence the node at the time t [8]. The joint probabilities of a series of nodes $X=(X_1,X_2,X_3,\ldots,X_{\mathrm{n}})$ can be calculated based on Equation (2).

$$P(X^t)=P(X_1^t,X_2^t,X_3^t,\ldots,X_n^t)= \prod_{i=1}^{n} P(X_i^t \mid X_i^{t-1}, pa(X_i^t), pa(X_i^{t-1}) pa(X_i^{t-2}) \ldots pa(X_i^0)) \tag{2}$$

2.2. *GERT*

GERT was proposed by Pro Prisker in 1968. It has been widely used in reliability engineering, project management and supply chain management [11]. In this paper, we construct the GERT model to describe the network of emergency schemes. To evaluate emergency timeliness, GERT is used to optimize emergency operations.

For random variable X and arbitrary real number S, M_X is the moment generating function of the random variable X. It can be calculated in Equations (3) and (4).

$$E(X)=\sum_{x\in X} xp(x) \tag{3}$$

$$M_X(S)=E[e^{sX}]=\sum_{x\in X} e^{sx}p(x) \tag{4}$$

Where $p(x)$ stands for the activity completion probability.

We define the transfer function of the activity (i, j) as $W_{ij}(s)$.

$$W_{ij}(s) = p_{ij} \cdot M_{ij}(s) \tag{5}$$

To evaluate the time schemes, the indicator $E[X]$ can be calculated in Equation (6).

$$E[X] = \frac{\partial\left[M_{E(s_1)}\right]}{\partial s_1}\Big|_{s_1=0} = \frac{\partial}{\partial s_1}\left[\frac{W_{E(s_1)}}{W_{E(0)}}\right]\Big|_{s_1=0} \tag{6}$$

$V[X]$ can be used to measure the stability level of variables. The calculation process is

$$V[X] = E[X^2] - E[X]^2 = \frac{\partial^2}{\partial s_1^2}\left[\frac{W_{E(s_1)}}{W_{E(0)}}\right]\Big|_{S=0} - \left\{\frac{\partial}{\partial s}\left[\frac{W_{E(s)}}{W_{E(0)}}\right]\Big|_{S=0}\right\}^2 \tag{7}$$

Linear fitting is introduced to predict the outcome of the failure relationship through adjacent independent activities. The linear model with k independent variables $x_1, x_2, \cdots, x_k$ and a dependent variable y can be shown as:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \in \tag{8}$$

where $\in$ represents the residual term (error) of the model, and $\beta_0, \beta_1, \beta_2, \cdots, \beta_k$ are the linear coefficients of the model.

Through implementing the DBN model and the fitting model, we can obtain the dynamic failure relationships between the nodes. The fusion of DBN and GERT is reflected in the measurement of node transmission probability and risk-influencing factors reflecting from DBN.

3. Case study

In this paper, we take a deepwater blowout accident as an example to illustrate the applicability of the proposed methodology. The blowout accidents on the offshore platform generated serious casualties, property losses and environmental pollution. In the blowout emergency process, it is necessary to consider the optimization of the time in emergency activities. Timely emergency response can significantly reduce the loss of accident consequences.

The capping stack is an efficient emergency shut-in technique. Defined as an emergency system, the emergency process of the capping stack can be decomposed to subsystems. The emergency scheme is composed of multiple emergency stages and activities in chronological relationships. In the emergency process, function testing needs to be implemented before running the capping stack. Operators lower the diamond cutting tool to cut the riser above the original lower marine riser package (LMRP). Remotely operated vehicle (ROV) is used to guide operations. The dispersant equipment is applied to prevent hydrate formation.

The DBN model can be established from the perspective of emergency activities in a blowout accident, as shown in Fig. 2. Through the linear regression relationship between the adjacent activities in Table 1, we can gain the completion probabilities to support the GERT model.

Table 1 Linear regression relationship of activities.

Activity No.	Linear regression fitting relationship	R-squared
(A, B)	$y = 0.0036x + 0.8819$	$R^2 = 0.9998$
(A, D)	$y = 0.0004x + 0.9866$	$R^2 = 0.9996$
(B, C)	$y = 0.0001x + 0.9905$	$R^2 = 1$
(D, E)	$y = 0.0007x + 0.9515$	$R^2 = 1$
(C, F)	$y = 0.0003x + 0.9864$	$R^2 = 1$
(E, F)	$y = 0.0003x + 0.9864$	$R^2 = 1$
(F, G)	$y = 0.0053x + 0.7337$	$R^2 = 0.9994$

The GERT model can model the emergency process based on the timing of activities in Fig. 1. Given the completion probabilities, the emergency can be evaluated by the above equations.

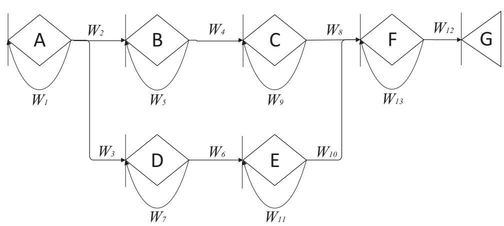

Fig. 1. The emergency scheme in GERT.

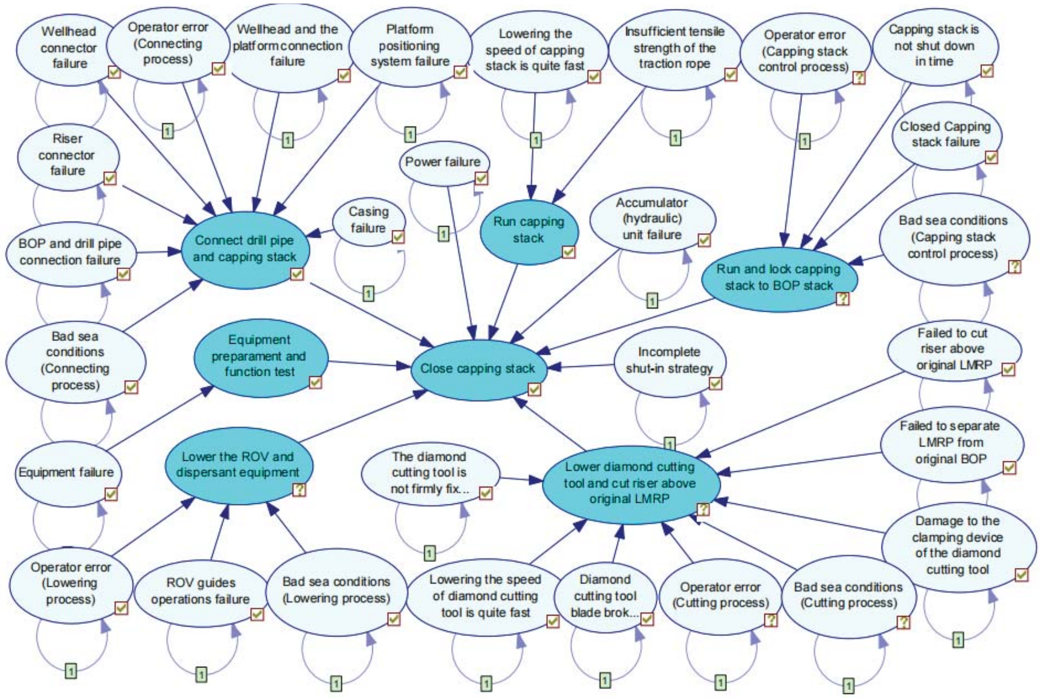

Fig. 2. DBN structure of emergency progress in the blowouts.

The activities in Fig. 1 represent the specific emergency activities in the offshore blowout accident in Table 2.

Table 2 The description of emergency activities.

No.	Description
A	Equipment preparation and test
B	Connect drill pipe and capping stack
C	Lower the ROV and dispersant equipment
D	Run capping stack
E	Cut riser above original LMRP
F	Run and lock capping stack
G	Close capping stack

By calculating the transfer functions in Table 3, we find the success probability $P = W_{E(0)} = W_{(0,0)} = 0.6324$ and the time risk of the emergency scheme are 15.22, which means the completion time at this condition.

To make optimal decisions of the scheme, we set sensitivity analysis about the activity (A, B), (C, F), (D, E), (E, F), (F, G) in Fig. 3. The results of sensitivity analysis optimal scheme can support the optimization of the emergency scheme.

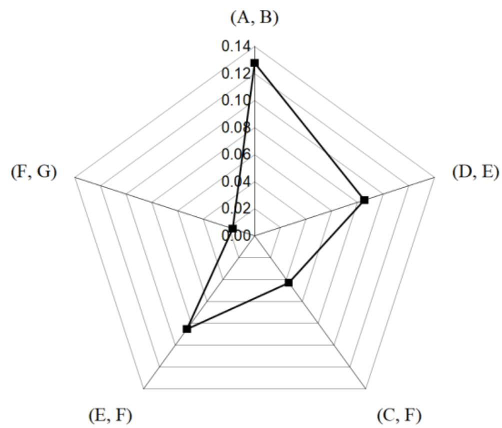

Fig. 3. The sensitivity analysis results.

In Fig. 3, activity (A, B) is more sensitive to time. Although these activities have a difference in the time risk indicator, they are the same in the successful probability. Given the results, emergency schemes should be paid more attention to the sensitive nodes.

Table 3 The transfer function with respect to 13 variables.

Activity No.	Transfer function	Completion probability	Time distribution	Moment generating function	Comprehensive risk transfer function value
(A, A)	W_1	0.0522	N (10,2)	$e^{10s_1+s_2^2}$	$0.0522e^{10s_1+s_2^2}$
(A, B)	W_2	0.8855	15	e^{15s_1}	$0.8855e^{15s_1}$
(A, D)	W_3	0.9906	1	e^{s_1}	$0.9906e^{s_1}$
(B, C)	W_4	0.987	1	e^{s_1}	$0.987e^{s_1}$
(B, B)	W_5	0.0102	N (10,2)	$e^{10s_1+s_2^2}$	$0.0102e^{10s_1+s_2^2}$
(D, E)	W_6	0.9522	10	e^{10s_1}	$0.9522e^{10s_1}$
(D, D)	W_7	0.0058	N (10,2)	$e^{10s_1+s_2^2}$	$0.0058e^{10s_1+s_2^2}$
(C, F)	W_8	0.9867	5	e^{5s_1}	$0.9867e^{5s_1}$
(C, C)	W_9	0.0023	N (10,2)	$e^{10s_1+s_2^2}$	$0.0023e^{10s_1+s_2^2}$
(E, F)	W_{10}	0.9867	10	e^{10s_1}	$0.9867e^{10s_1}$
(E, E)	W_{11}	0.0275	N (10,2)	$e^{10s_1+s_2^2}$	$0.0275e^{10s_1+s_2^2}$
(F, G)	W_{12}	0.739	2	e^{2s_1}	$0.739e^{2s_1}$
(F, F)	W_{13}	0.005	N (10,2)	$e^{10s_1+s_2^2}$	$0.005e^{10s_1+s_2^2}$

4. Conclusion

In this paper, we established a DBN-GERT model to update the emergency schemes. Regarding the time risk with the critical nodes, this model can be used to optimize the emergency schemes. The combination of DBN and GERT supports the completion probability for GERT. DBN can represent the dynamic stochastic process. The failure probabilities in DBN are converted into the activity completion probabilities. Based on sensitivity analysis results, the optimization of emergency schemes can be conducted. The hybrid model enhances the safety of emergency operations and reduce the consequence losses under the accident scenarios. In the future work, we can consider the comprehensive utility analysis to introduce more indicators (risk, cost et al.) to optimize the emergency schemes.

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References

1. Di Maio F., Baraldi P., Eslamian A., Zio E., Jacinto C., (2022) A dynamic event tree for a blowout accident in an oil deep-water well equipped with a managed pressure drilling condition monitoring and operation system. Journal of Loss Prevention in the Process Industries, 79: 104834.
2. Meng, H., Chen G., and Liu X., (2019) A capping technique for emergency response in offshore blowout accidents. Journal of Loss Prevention in the Process Industries, 62: 103925.
3. Meng, X., Li X., Wang W., Song G., Chen G., and Zhu J., (2021) A novel methodology to analyze accident path in deepwater drilling operation considering uncertain information. Reliability Engineering & System Safety, 205: 107255.
4. Li, X., Abbassi R., Chen G., and Wang Q., (2020) Modeling and analysis of flammable gas dispersion and deflagration from offshore platform blowout. Ocean Engineering, 201: 107146.
5. Dadashzadeh, M., Abbassi R., Khan F., and Hawboldt K., (2013) Explosion modeling and analysis of BP Deepwater Horizon accident. Safety Science, 57: 150-160.
6. Rahman, M.S., Colbourne B., and Khan F., (2021) Risk-Based Cost Benefit Analysis of

Offshore Resource Centre to Support Remote Offshore Operations in Harsh Environment. Reliability Engineering & System Safety, 207: 107340.

7. Khakzad, N., (2015) Application of dynamic Bayesian network to risk analysis of domino effects in chemical infrastructures. Reliability Engineering & System Safety, 138: 263-272.
8. Tong, Q., Yang M., and Zinetullina A., (2020) A Dynamic Bayesian Network-based approach to Resilience Assessment of Engineered Systems. Journal of Loss Prevention in the Process Industries, 65: 104152.
9. Cai, B., Xie M., Liu Y., Liu Y., and Feng Q., (2018) Availability-based engineering resilience metric and its corresponding evaluation methodology. Reliability Engineering & System Safety, 172: 216-224.
10. Yodo, N., Wang P., and Zhou Z., (2017) Predictive Resilience Analysis of Complex Systems Using Dynamic Bayesian Networks. IEEE Transactions on Reliability, 66(3): 761-770.
11. Wang, Z., Liu S., and Fang Z., (2020) Research on SoS-GERT Network Model for Equipment System of Systems Contribution Evaluation Based on Joint Operation. IEEE Systems Journal, 14(3): 4188-4196.
12. Tao, L., Wu D., Liu S., and Lambert J., (2017) Schedule risk analysis for new-product development: The GERT method extended by a characteristic function. Reliability Engineering & System Safety, 167: 464-473.
13. Geng, S., Yang M., Mitici, M., Liu, S., A resilience assessment framework for complex engineered systems using graphical evaluation and review technique (GERT). Reliability Engineering & System Safety, 2023. 236.
14. Guo, Y., Jin Y., Hu S., Yang Z., Xi Y., and Han B., (2023) Risk evolution analysis of ship pilotage operation by an integrated model of FRAM and DBN. Reliability Engineering & System Safety, 229: 108850.
15. Zinetullina, A., Yang M., Khakzad N., Golman B., and Li X., (2021) Quantitative resilience assessment of chemical process systems using functional resonance analysis method and Dynamic Bayesian network. Reliability Engineering & System Safety, 205: 117232.