CHEMICAL ENGINEERING TRANSACTIONS

VOL. 77, 2019

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Genserik Reniers, Bruno Fabiano

ISBN 978-88-95608-74-7; **ISSN** 2283-9216

DOI: 10.3303/CET1977123

Developing Data-based Bayesian Network for Human Operation Analysis during Hot Work

Yanchun Wang[a], Yi Liu[b,*], Wei Wang[a], Jian Chen[a], Hanhai Dong[b], Dongfeng Zhao[b],Faisal Khan[c]

[a] College of Mechanical and Electronic Engineering, China University of Petroleum (East China), Qingdao 266580, China
[b] College of Chemical Engineering, China University of Petroleum (East China), Qingdao 266580, China
[c] Centre for Risk, Integrity and Safety Engineering (C-RISE) , Faculty of Engineering and Applied Science, Memorial University, St. John's, NL, A1B 3X5, Canada
liuyi@upc.edu.cn

Hot work has caused numerous accidents during the inspection and maintenance process in recent years in China. This paper collected the hot work accidents in China since 2007 and integrated them into a database. The database contained the information such as the time, site, sequence, source, type, cause and consequence. Through analysing the database, most accidents were relevant to human operations. We classified unsafe and irregular operations caused by human factors during hot work. The causes of hot work accidents involved a series of problems during the approval, supervision and construction. Integrating hot work procedures, we established the main safety evaluation framework containing three factors, i.e., approval, execution environment, and protective measures. The method of Bayesian Network (BN) aiming at solving uncertain problems was utilized to identify unsafe operations quantitatively during hot work. Eventually, eight key proposals were presented to avoid hot work accidents. The proposed framework was developed to assess human operations in chemical plants during hot work. Causes of hot work accidents in chemical plants mainly consisted of failure to handle permits of hot work, production system without isolation, unremoved flammable materials, and failure to install fire prevention measures. The results can provide compelling support for human management and training during hot work.

1. Introduction

In the production process of enterprises, especially the chemical plants determine the characteristics of high temperature and high pressure, flammable, explosive and easy poisoned because of their production characters. The system of production must carry out the necessary maintenance after a certain period of operation, among which the hot work maintenance operations are frequent (Li, 2017). According to the safety regulations for hot work of chemical production units, hot work refers to non-routine operations and can directly or indirectly generate open flames. Hot work is a technical, demanding, risky and special operation. Workers are at risk when doing hot work, including oil and gas, hazardous chemicals production and storage industries (Tang and He, 2015). Due to various reasons, dangerous accidents often occur during hot work. The types of accidents include fire and explosion, burning, mechanical damage, etc., causing huge losses and seriously threatening the lives of employees. Therefore, it is very important to take measures to prevent accidents.

In recent years, many hot work accidents have occurred in China, most of which occurred during the inspection and maintenance process, and the consequences are serious. Hot work has attracted the attention of safety management personnel, but there is no reasonable way to prevent it. In the past research on the hot work accidents, most of them focused on the process and consequences of a single accident, such as the U.S. Chemical Safety and Hazard Investigation Board (CSB) investigated the Partridge Raleigh oil storage

Paper Received: 23 February 2019; Revised: 16 April 2019; Accepted: 14 July 2019

Please cite this article as: Wang Y., Liu Y., Wang W., Chen J., Dong H., Zhao D., Khan F., 2019, Developing Data-based Bayesian Network for Human Operation Analysis during Hot Work, Chemical Engineering Transactions, 77, 733-738 DOI:10.3303/CET1977123

tanks explosion and proposed seven key preventive measures for hot work in the tank fields. No one has conducted statistics on recent hot work accidents. After the accident statistics and analysis, we found that most of the accidents were related to human operations. Therefore, it is important to combine the specific steps of the hot work and gradually find out the common causes of accidents, standardize the operation of relevant operators, strengthen safety management, do a good job of safety precautions, and avoid accidents. Zhang (2005) put forward the steps of hot work: determination of the location of hot work; on-site analysis and implementation of safety measures; on-site risk notification; approval of hot work permits and confirmation of safety measures; on-site monitoring and implementation of operations; completion of inspection and acceptance; cleaning up the site .

Researchers have dedicated effort to understanding how and why accidents occur. Katsakiori et al. (2009) postulated the theory and model of accident causation, including linear models and complex nonlinear models. Mawuli et al. (2017) summarized the models used in recent decades, showed potential tools for accident modeling, and how to implement BN, Fault Tree, FRAM, and other probabilistic modeling methods. After the accomplishment of the hot work accident database statistics, the paper aims to use the BN to form an evaluation framework to identify the key factors causing the hot work accidents. The main framework includes approval, execution environment and protective measures. The method of BN aims at forecasting possible hot work accident scenarios from past accidents data. In this methodology, the probabilities can be updated as new information becomes available. The BN can be used flexibly to consider the interdependence and condition of the factors involved in the hot work process.

2. Bayesian Network and Sensitivity Analysis

Friis-Hansen (2000) compared the outcome of the proposed model using BN and the output from an Event Tree Analysis. The study also applied the Bayesian network to diagnose misfire and leakage in a marine diesel engine and attempted to combine BN with structural reliability methods for requalifying a pipeline in the North Sea. Martin et al. (2014) used Bayesian networks to analyze the factors affecting the performance of tasks that involve a high risk of falls from ladders or other auxiliary equipment. Another application of BN was made by Myles et al. (2015), who applied BN to a model of risk propagation in a supply network. Shubharthi et al. (2016) proposed to develop a dynamic fault tree for a chemical process system/sub-system based on BN and provided the dynamic Bayesian network to demonstrate the dynamic operational risk assessment methodology.

BN is a graphical network based on probabilistic reasoning, which mainly describes the uncertainty of knowledge (Ding et al., 2009). BN was first proposed by Pearl (1988), which is an effective tool for applying probability theory to uncertainty reasoning. BN follows a qualitative part (Directed Acyclic Graph) and a quantitative part (Conditional Probability Table), represented by N=<G, P>. G is represented as a directed acyclic graph of <V, E> having N nodes. $V=\{X_1,...,X_n\}$ represents a set of variables, and the directed edges E represent a probability causality relationship between nodes. P is the quantitative part, which refers to the conditional probability of each variable under the parent node, and is represented by specifying a conditional probability table (CPT) on each node. The basis of BN is the Bayes theory, which is expressed as:

$$\mathrm{P}(A|E) = \frac{P(E|A)P(A)}{P(E)} \tag{1}$$

Pearl (1988), Zhang and Thai (2016), and Pristrom et al. (2016) have explained in detail the principle of BN. Uncertainties exist in the use of BN to model scenarios. It may be in the form of the probabilities used, including those derived from expert opinions by Mawuli et al. (2017). Finding the critical factors from BN is the primary task of modeling. Lliwg (2015) suggested that the most effective way to identify the most important parameters in a BN model is to implement sensitivity analysis. To determine the most important factors in a hot work accident scenario is one of the main goals of this present study.

The basic reasoning of a BN is to calculate the posterior probability distribution of an investigated variables set for a given observations variable set V. BN inference is mainly based on the Bayesian network's expression of the joint probability distribution of variables, and the process of quickly calculating the probability value to be evaluated. Researchers have proposed many effective algorithms for reasoning, including precise and approximation algorithms. These algorithms have been developed into software packages to facilitate the application of BN. The GeNIe software developed by the University of Pittsburgh Decision Systems Laboratory greatly simplifies the calculation process and enables evaluations and diagnostic results to be very intuitive from the diagram. This paper uses GeNIe to model and reason hot work accident scenario.

3. Hot work accident scenario model

3.1 Collection of past hot work accidents

It has been found some literature describing hot work accidents that occurred during facilities life cycle. However, a complete record of accidents, as well as occurrence sequence, its probable causes and consequences still need to be added effectively. The procedure for establishing a database of hot work accidents is similar to that of the database of accidents and incidents at fuel ethanol facilities. There are four main sources of data, including internet, literatures, reports, and newspapers. Due to limited resources, only reported incidents were collected. The information collected mainly contains the time, location, process, causes and consequences of the accident. A total of 67 hot work accidents have occurred since 2007, 58 of which occurred in petroleum and chemical plant areas and caused dangerous consequences of fire and explosion. In addition to this, there are many less serious hot work accidents, no specific place and time, so it is not listed. Figure 1 shows the number of accidents per year from 2007 to 2018. According to the collected hot work database, the causes of accidents are analysed primarily for the unsafe operations of people. The model established has three main frameworks: approval, operating environment and protection measures.

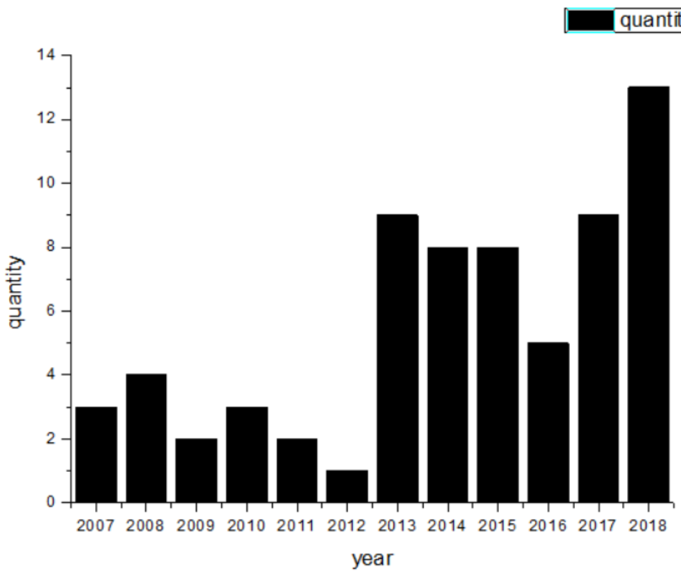

Figure 1: The number of hot work accidents occurring each year

3.2 Classify potential human operational factors and build BN model

This step performs hazard identification in the scene of hot work. To identify the potential factors for each step in conjunction with the operational procedures and the hot work safety precautions required by the National Fire Protection Association (NFPA) standards. Any hot work spot must have a permit. The approval process is the entire procedure of implementing the safety measures, including the certification, isolation of production systems, purging, replacement, removal of combustibles, gas detection and fire-fighting measures, etc. Secondly, the person in charge of the project must provide a safe disclosure to the executors of the hot work.

Establishing a BN model based on potential human operational factors to obtain the probability of an accident scenario. Each node of the network has two states: “yes” or “no”. “Yes” indicates the positive affirmation of cause for a particular variable, while “no” is a negative indication. In this paper, the source of prior probability has three channels involved reports, expert opinions, and statistical accident database. In the reports of fire and explosion fault trees in petrochemical industries such as oil tanks and liquefied petroleum gas, most causes of the accidents originated from combustibles and open flames generated by illegal hot work. In this type of fault tree analysis, illegal hot work appeared as intermediate events rather than specific to every human operation. Therefore, the expert scoring method was adopted. To effectively reduce the prior probability error, the multiple interpolation method is used to refit the prior probability of the expert opinion, reducing the adverse subjective interference in the human evaluation and improving the credibility of the expert opinion. At the same time, combined with the frequency of the hot work accidents in the past ten years, these accidents database can be used as a guide for experts to choose reasonable probability. The essence of this study is not to require quantitative accuracy, but to illustrate the proposed method and have a quantitative way of how to make decision-making opinions when similar incidents occurred.

The BN model for common causes of hot work accidents is shown in Figure 2. The causes are divided into three aspects: approval, execution environment and protective measures. The main causes of approval failure process include the contractor, hot work certificate, and signature work without risk identification. The contractor and the hot work certificate were further broken down. The poor working environment may be due to the presence of flammable and explosive substances, ineffective supervisor and no communication, and the causes of flammable and explosive substances contain four contents. The protective measure's failure can be attributed to no fire-fighting measures, improper labor insurance supplies, improper emergency handling, and the use of non-explosion-proof tools.

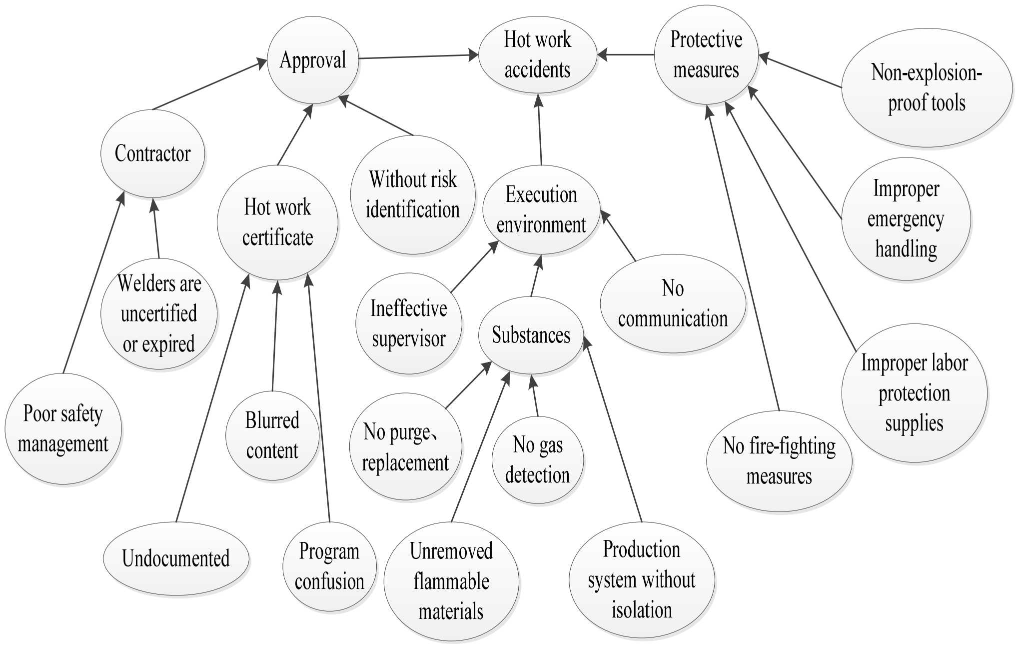

Figure 2: The BN for hot work accident

3.3 Sensitivity analysis

The causes of the accident are composed of multiple factors. Finding the most critical factors require sensitivity analysis, which can provide information about resource allocation for decision making and identify the most critical variables or factors in an accident scenario. In the process of performing sensitivity analysis, the basis for the calculation of the change ratio is Eq. (2). The sensitivity analysis results are shown in Figure 3. The probability of the most sensitive factor is higher than the others. Only the most significant changes are shown in the figure. Sensitivity analysis results are subjective and guided by the probabilities of other variables. It’s highly dependent on decision makers. Therefore, it is crucial to use this methodology as the first step to decision making and choose the variables for prioritization when preventing scene changes. It is also important for reducing the impact of an accident should it occur.

$$\frac{A\ posteriori\ probability\ of\ \ setting\ the\ event\ to\ 1 - Priori\ probability}{Priori\ probability} \tag{2}$$

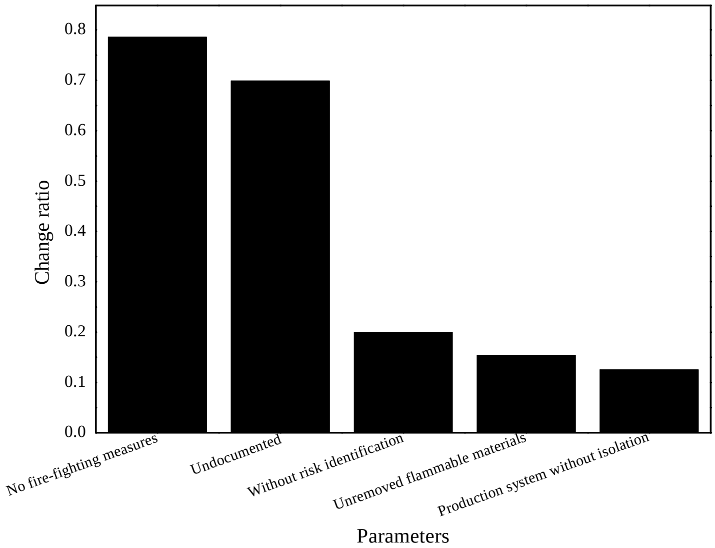

Figure 3: Change ratio of the casual factors of hot work accidents

4. Conclusions and discussion

The application of Bayesian Network methodology for the analysis of causes during hot work has been presented. The use of Bayesian network provides analysts with the opportunity to establish interdependencies between casual factors, which is not possible in conventional methods such as Fault Tree. Sensitivity analysis is performed to define the critical factors leading hot work accidents, it is the best way identify the most contributory factors. The result is key to making a decision on the construction and supervision of resources for accident prevention during hot work.

The result in Figure 3 showed that in the cause of human operations in hot work accidents, variables with significant change mainly include failure to install firefighting measures, failure to handle permits of hot work, without risk identification, unremoved flammable materials and production system without isolation. Among them, the setting of firefighting measures and the approval process of hot work permit are the major reasons. During the operations in the process of construction, the importance of human beings cannot be neglected. The occurrence of fires and explosions was caused by the staff's failure to carry out the above procedures, so education and training managers and operators are particularly important. According to the consequences of sensitivity analysis, eight key measures were proposed to prevent hot work accidents:

1. Written permission— A professional who conducts a hazard identification, reviews and approves all hot work, issues a hot work permit, and clarifies the content of the work.

2. Risk Assessment— Conducting a risk assessment carefully before starting a hot work. Identify potential risks and propose risk control measures based on the job site, operating procedures, and the surrounding environment.

3. Emergency— Preparing emergency plans and setting fire prevention measures. If a fire is triggered, it can be put out in time.

4. Isolation— Adding blind plates to equipment, pipes, etc. to prevent leakage, and parking operations.

5. Elimination—Cleaning up the combustibles, and the flammable materials under and below the hot point must be cleaned up. Cleaning and replacement are required when working in the equipment.

6. Gas Monitoring—Gas monitoring of the working area using a flammable gas detector before and during the hot work.

7. Training—Safety management personnel and operators should receive safety training for hot work, and hold a certificate.

8. Supervising the contractor—Selecting a qualified contractor to inform the operational risk and the safety supervisor was in place.

These recommendations and factors require conducting and monitoring and should be given more attention to prevent hot work accident occurrence. The above recommendations also can apply to other special work, such as confined space operations.

The hot work accidents collected in this article are far from enough. If you want to study the hot work accidents better, you will collect accidents at home and abroad through relevant departments and conduct detailed analysis. The management of people in hot work needs to start with the suggestions, but in actual operation, unexpected situations often occur, including human mental state and physical condition, etc. These factors are not considered in this paper. More precise research needs to consider these aspects.

The BN has the ability to express uncertainty and conduct uncertainty reasoning, and it can flexibly predict and diagnose the system. This paper combined Bayesian Network to effectively assemble expert knowledge and experience to analyse and discuss the causes of hot work accidents. The data used might have errors, and the estimation of top event probability was not accurate. Accurate research needs to collect more data and consider the complexity of the operating scheme. It can be simulated using the Taylor series and Monte Carlo method mentioned by Liwag (2015), and the obtained values will be more accurate.

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