Chemical Engineering Science 142 (2016) 62–78

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Dynamic quantitative operational risk assessment of chemical processes

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HIGHLIGHTS

- Probability of event occurrence is estimated by monitoring multiple key variables.
- Probability is continuously updated considering real-time disturbances in variables.
- Consequences are estimated by dynamic loss functions with multivariate.
- Operational performance is dynamically assessed by quantitative risk value.

ARTICLE INFO

Article history:
Received 5 March 2015
Received in revised form
27 October 2015
Accepted 23 November 2015
Available online 11 December 2015

Keywords:
Dynamical risk assessment
Dynamical loss functions
Probability updating
Multiple variables monitor
Operational performance

ABSTRACT

This paper presents a novel dynamic quantitative risk assessment method to analyze the operational performance of chemical processes. Unlike traditional methods, the proposed method estimates the probability of undesirable event occurrence by monitoring multiple key variables in the process. This probability is continuously updated considering real-time disturbances in the variables. The consequences are estimated using dynamic loss functions developed considering multiple key state variables. As a result, the process' operational performance is assessed dynamically in the form of quantitative risk (dollar) value. The quantitative dynamic risk value helps to make swift operational decisions to maintain the process within the safer operating limits, thus preventing untoward incidents/accidents. To demonstrate the efficacy of the proposed methodology, it is tested on two case studies, a simple tank system and the benchmark Tennessee Eastman process.

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1. Introduction

An important shortcoming of the traditional process safety management (PSM) system is its isolation and lack of integration with the rest of the process operation (García Herrero et al., 2002). Process industries rely heavily on failure data to monitor performance. As a result, required improvements or changes are only identified after an incident has occurred (Khan et al., 2010). The United States Center for Chemical Process Safety (CCPS) suggests that: "Facilities should monitor the real-time performance of management system activities rather than wait for accidents to happen. Such performance monitoring allows problems to be identified and corrective actions to be taken before a serious incident occurs" (CCPS, 2007).

To monitor process safety performance in a timely way, process safety performance indicators are used to monitor and improve the safety of process plants. One of the most important and challenging issues for process safety is the early recognition of deterioration in safety performance caused by operation, maintenance, management, organization and safety culture factors before actual events and/or mishaps occur (Khan et al., 2010).

This paper focuses on dynamic quantitative risk assessment and its integration with operational performance analysis, to assess the safety and quality of the process facility.

In order to achieve the highest levels of safety and quality, with the ultimate goal of fostering a zero-incident and zero-defect culture, the aim should be to eliminate the main sources of the losses, i.e. process deviations. For process facilities the causes of deviations may include process disturbances, feed variability, mechanical and operational integrity degradation, human errors, wrong setting and improper methods (Hashemi et al., 2014b). To analyze the impact of process deviations on safety, Hashemi et al. (Hashemi et al., 2014a) proposed the application of loss functions to safety analysis and compared their properties. The method was further extended by integrating both safety and quality losses associated with process deviations (Hashemi et al., 2014b).

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http://dx.doi.org/10.1016/j.ces.2015.11.034
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The deviations are frequently caused by disturbances or measurement noises. In this paper we propose a dynamic quantitative risk assessment method, in which the probability of loss is updated over time using the measurements of multiple key variables. At the same time, multivariate key state variables from different units in the process are monitored to estimate the potential consequences in terms of loss (dollar value). Using probability and estimated loss, risk is assessed dynamically. The developed risk assessment method is used as a leading indicator of real time process performance, so that it can support real time operational decision-making.

This paper proceeds as follows. The existing methods for risk-based operational performance analysis are reviewed in Section 2. The proposed methodology is described in Section 3 followed by two case studies in Section 4. Finally, the discussions and conclusions are presented.

2. An overview of quantitative risk assessment

2.1. Probability assessment and updating

Combining loss models with the probabilities of process deviations provides a framework to develop a dynamic quantitative risk-based approach to access process performance assessment. As risk includes both the probability of an end process state and its consequences, a risk-based approach reduces the potential for assigning an undue amount of resources to manage lower-risk events, thereby freeing up resources for tasks that address higher-risk events (CCPS, 2007; Khan et al., 2001).

Abnormal events of varying magnitudes result in incipient faults, near-misses, incidents, and accidents in chemical plants. Their detection and diagnosis have been active areas of research (Venkatasubramanian et al., 2003a, 2003b, 2003c). However, estimation of the failure probabilities of safety systems to predict these consequences (end-states), has received little attention in the chemical process industries (Meel and Seider, 2006). Quantitative risk assessment (QRA) is used as an approach to access and manage safety of the process system. However, the conventional QRA methods are unable to update risk on a dynamic basis.

Kalantarnia et al. (Kalantarnia et al., 2009) developed methods that use Bayesian theory to update the likelihood of event occurrence. Using the available accident precursor data, safety system failure likelihood and the event tree, the end-state probabilities were revised dynamically in these techniques. As reviewed by Meel et al. (Meel and Seider, 2008) and Kalantarnia et al. (Kalantarnia et al., 2009), there have been efforts to make risk assessment methods dynamically adaptable with real-time changes occurring in a process. Kalantarnia et al. (Kalantarnia et al., 2010) modeled the BP Texas City refinery accident using the Bayesian failure updating mechanism with consequence assessment. Khakzad et al. (Khakzad et al., 2012) developed a risk analysis method to update the probability of both causes and consequences in a dynamic environment; failure probabilities of primary events and safety barriers were constantly revised over time, and an updated bow–tie was used to estimate the posterior probabilities of the consequences which in turn results in an updated risk profile. Pariyani et al. (Pariyani et al., 2012a, 2012b) proposed a dynamic risk analysis methodology that uses alarm databases to improve process safety and product quality. The methodology consists of tracking abnormal events over an extended period of time. The event-tree and the set-theoretic formulations were used to compact the abnormal-event data, and Bayesian analyses were used to calculate the likelihood of the occurrence of incidents. Millions of abnormal events data were compacted to efficiently calculate probability with large alarm databases in real time. Zadakbar et al. (Zadakbar et al., 2012) proposed a methodology to calculate process risk in combination with a data based fault detection method; the approach is built upon principal component analysis (PCA) combined with a quantitative operational risk assessment model. They later proposed (Zadakbar et al., 2013) the methodology in which the Kalman filter has been combined with a risk assessment procedure to detect an abnormal event. Yu et al. (Yu et al., 2014) developed a self-organizing map based methodology that can deal with abnormal events in processes with nonlinear and non-Gaussian features.

Most of the above methods may be considered dynamic in estimating the probabilities of potential events; however, there are two issues that need to be addressed. (1) It is assumed that a univariate key process characteristic can be assigned to a system; (2) the probabilities are calculated mainly based on deviations of monitored state variable values or data of previously occurring abnormal events. In practice, typically there is more than one key variable associated with an abnormal end state. Regarding the second problem, the probability calculation based on measured data considers a single target state of the key variable. However, there may be multiple steady states (Wang et al., 2010a, 2010b, 2010c). Due to strong nonlinear characteristics in chemical processes measurement with disturbances there might be unstable conditions, bifurcations (Wang et al., 2008, 2012a, 2012b, 2011), even oscillatory phenomena (Wang et al., 2013, 2014b) near the singularity operating point (Wang et al., 2009, 2014a, 2012c) in processes.

In this paper, the probability and consequences are estimated considering multiple key variables. At the same time, the disturbances of manipulated variables are monitored dynamically to update the loss occurrence and its probability. The effects of process deviations on both losses and the probability of occurrence are considered to estimate the dynamic quantitative risk assessment (DQRA) for process performance analysis.

2.2. Consequence assessment

Quality management and the safety management system are related; they are two sides of the same coin (Krause, 1993). Deviations are unavoidable during process operations. The propagation of these deviations may result in lower quality as well as losses. In a processing facility, the ability to manage process safety, and at the same time to maintain product quality is the main concern for its daily operation.

The benefits of integrating safety and quality management systems have been discussed in the literature (Dumas, 1987; García Herrero et al., 2002). While quality management methods aim to minimize the variability inherent in product quality, safety management procedures aim to minimize the chances of occurrence of incidents and accidents and their severity (Adams, 1995; Krause, 1993).

One of the most common methods to integrate safety and quality is to quantify the two elements. Loss functions are commonly used to quantify losses associated with deviations of process variables. Traditionally, losses are quantified either as squared error loss functions or weighted loss functions. Recent developments consider the use of inverted probability distribution for quantify losses.

Spiring (Spiring, 1993) used an inverted normal probability density loss function (INLF) to provide a more reasonable assessment of losses. Sun et al. (Sun et al., 1996) developed a modified INLF that provided a more moderate loss representation, and provided a method for fitting the modified INLF to reflect the user's actual loss. The result was a nonlinear least squares method for estimating the shape parameter of their modified INLF. And later, Leung et al. (Leung and Spiring, 2002, 2004) continued to

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