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Development of a risk-based maintenance strategy using FMEA for a continuous catalytic reforming plant

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ABSTRACT

Petrochemical facilities and plants require essential ongoing maintenance to ensure high levels of reliability and safety. A risk-based maintenance (RBM) strategy is a useful tool to design a cost-effective maintenance schedule; its objective is to reduce overall risk in the operating facility. In risk assessment of a failure scenario, consequences often have three key features: personnel safety effect, environmental threat and economic loss. In this paper, to quantify the severity of personnel injury and environmental pollution, a failure modes and effects analysis (FMEA) method is developed using subjective information derived from domain experts. On the basis of failure probability and consequence analysis, the risk is calculated and compared against the known acceptable risk criteria. To facilitate the comparison, a risk index is introduced, and weight factors are determined by an analytic hierarchy process. Finally, the appropriate maintenance tasks are scheduled under the risk constraints. A case study of a continuous catalytic reforming plant is used to illustrate the proposed approach. The results indicate that FMEA is helpful to identify critical facilities; the RBM strategy can increase the reliability of high-risk facilities, and corrective maintenance is the preferred approach for low-risk facilities to reduce maintenance expenditure.

1. Introduction

Petrochemical industries and refineries involve a wide range of flammable, explosive and toxic materials that are usually handled at elevated temperatures and/or pressures. Faults or failures within the facilities may lead to serious consequences because of the existence of these hazardous chemicals. Thus, a high level of reliability and safety is a critical issue for the success of petrochemical plants and refineries.

High safety and reliability levels rely heavily on proper maintenance activities that will reduce the incidence of unexpected breakdowns and unscheduled downtimes (Alsyouf, 2007). To ensure the smooth running of a plant, it is essential that maintenance activities consume a large amount of manpower and material resources. As the requirements of safety and reliability increase, the resources required in maintenance have also grown. It is not uncommon in refineries for the maintenance department to be the largest department, often comprising approximately 30% of the total manpower and with a significant operational budget second only to energy costs (Dekker, 1996). Tan and Kramer (1997) stated that maintenance costs comprise 20%–30% of the operating budget in the chemical industry. With regard to the problem of how to use available resources in the most effective way, cost-effective maintenance strategies are both vital and necessary.

Over the past few decades, maintenance strategies have been through a major metamorphosis from primitive break down maintenance to the more sophisticated strategies like condition-based maintenance and reliability-centered maintenance (Patton, 1983; Rao, 1996; Rausand, 1998). The risk-based maintenance (RBM) strategy, which emerged in the 1990s, provides a new vision for asset integrity management (Backlund & Hannu, 2002; Farquharson, & Choquette, 2002; Harnly, 1998; Kjellen, Motet, & Hale, 2009; Kumar, 1998; Montgomery, & Berratella, 2002). The RBM strategy uses the risk level as a criterion to plan maintenance tasks and has received increasing attention from researchers in recent years.

Apeland and Aven (2000) presented a Bayesian method for RBM optimization as an alternative to the probabilistic framework. Jovanovic (2003) reviewed practices and trends in the area of risk-based inspection and maintenance in power and process plants by comparing European and US studies. Arunraj and Maiti (2007) reviewed research on RBM and risk assessment technologies. A risk-based inspection and maintenance procedure was developed and applied to an oil refinery by Bertolini, Bevilacqua, Ciarapica,

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and Giacchetta (2009). Khan's team has made significant contributions to the development of the RBM strategy. Khan and Haddara (2003) proposed a complete framework for the RBM strategy, in which the probability of the unexpected event was determined using fault tree analysis and the consequences involved the estimation of system performance loss, financial loss, human health loss and environmental and/or ecological loss. On the basis of comparison results between the calculated risk and acceptable risk criteria, intervals of preventive maintenance for key equipment were obtained. To illustrate its applications in detail, the RBM strategy has also been applied to a number of situations including offshore oil and gas processing facilities, an ethylene oxide production plant, and a power plant (Khan & Haddara, 2004a; Khan & Haddara, 2004b; Krishnasamy, Khan, & Haddara, 2005). Arunraj and Maiti (2010) used risk as a criterion to select the appropriate maintenance policy and the results showed that condition-based maintenance was suitable for high-risk equipment and corrective maintenance for low-risk equipment. To achieve the minimum risk for the expected life of a liquefied natural gas plant, a risk-based shutdown management strategy was considered (Keshavarz, Thodi, & Khan, 2012).

In an RBM strategy, the risk of a particular failure scenario is defined as the product of likelihood and consequences. These consequences have three key features: personnel safety effect, environmental threat and economic loss. Although economic loss can be directly measured in terms of money, it is a rather sensitive matter to assign financial cost to personnel injury and environmental pollution. Failure modes and effects analysis (FMEA) is a widely used, effective tool to identify and assess how potential failures can affect the performance of a process. In the present paper, to judge the severity of the personnel safety effect and environmental threat, a semi-quantitative method of FMEA is developed based on subjective information derived from experts.

The failure probability of a facility can be calculated using a Weibull distribution model; then the risk can be calculated by multiplying failure probability with consequences. In risk evaluation, the concept of a risk index is introduced to facilitate the comparison between the calculated risk and the known acceptable risk criterion; thus three risk indexes can be obtained. To integrate the three risk indexes into a single index, weight factors that represent the relative importance of the three consequence features are determined using an analytic hierarchy process (AHP). Finally, proper maintenance tasks are scheduled under the risk constraints. The remainder of this paper is organized as follows: Section 2 proposes the framework of the improved RBM strategy; a case study of a continuous catalytic reforming (CCR) plant is presented in Section 3 to demonstrate the detailed procedures of the methodology; and finally, conclusions are presented in Section 4.

2. Risk-based maintenance (RBM) strategy

The RBM strategy is a quantitative approach integrating reliability analysis and risk assessment to develop a cost-effective maintenance policy. Generally the RBM strategy consists of the following four modules: identification of a system scope, risk assessment, risk evaluation and maintenance planning.

2.1. Identification of a system scope

Refineries and petrochemical plants usually contain large quantities of pressure vessels, compressors, pumps, pipelines and other various instruments. Considering the whole plant as a system, it can be generally divided into several subsystems according to its operational characteristics. The subsystems are usually connected in three different ways, namely by series, parallel and standby structures. This applies for a subsystem as well, which consists of several facilities. The facility is regarded as the basic element of risk assessment and evaluation.

2.2. Risk assessment

Risk can be seen as a natural consequence of refinery and petrochemical production activities. It is impossible to eliminate all risks, so risks are reduced to an acceptable level. Risk assessment requires the application of the appropriate techniques to analyze the risk of an unexpected failure scenario, which involves the estimation of the likelihood (failure probability) and consequences (severity of the undesired failure scenario).

2.2.1. Estimation of failure probability

A failure scenario occurs when the plant fails to meet the production requirements, including break down, reduction of output, inferior quality of output and even the occurrence of accidents such as fire and explosion. The failure scenario can be identified according to the process features, operational conditions and the safety management status of the plant. Considering a failure scenario as a top event, a fault tree is constructed to delineate the ways in which the top event can occur. Logic signs including "AND" and "OR" gates are employed to graphically represent the relations among the top event, intermediate events and basic events.

The failure probability of each basic event can be determined by statistics regarding adequate data associated with faults and accidents, which are mainly collected from the operation, accident and maintenance records of industrial plants (Hoyland & Rausand, 1995). When the failure probability of each basic event is known, the failure probability of the top event can be calculated using an AND/OR gate.

$$P_{(\mathrm{AND})} = \prod_{i=1}^{n} P_i \quad (1)$$

$$P_{(\mathrm{OR})} = 1 - \prod_{i=1}^{n} (1 - P_i) \quad (2)$$

where P is the failure probability of the top event, P_i denotes the failure probability of the basic event i, and n is the number of basic events associated with the AND/OR gate.

2.2.2. Consequence analysis

The objective of this procedure is to quantify the potential consequences of the failure scenario. When a failure scenario occurs, the consequences often have three key features: personnel safety effect (C_1), environmental threat (C_2) and economic loss (C_3). Economic loss can be evaluated directly in terms of money; however, it is a sensitive issue how to assign financial costs to health or loss of life and environmental pollution. It should be noted that a facility is prone to several failure modes, and each failure mode may lead to different consequences. Therefore, FMEA is an appropriate method to analyze different modes and their consequences of failures.

The FMEA methodology is one of the risk analysis techniques recommended by international standards such as Society of Automotive Engineers, US Military of Defense, and Automotive Industry Action Group. FMEA is organized around failure modes, which link the cause and effect of failures. FMEA takes three parameters into consideration which are usually evaluated through easily interpreted linguistic expressions, each correlated to a score rage (minimum of 1 to a maximum of 10): Severity (S), Occurrence (O), and Detection (D). The Severity measures the seriousness of the