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Accident modelling and analysis in process industries

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A R T I C L E I N F O

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A B S T R A C T

Accident modelling is a methodology used to relate the causes and effects of events that lead to accidents. This modelling effectively seeks to answer two main questions: (i) Why does an accident occur, and (ii) How does it occur. This paper presents a review of accident models that have been developed for the chemical process industry with in-depth analyses of a class of models known as dynamic sequential accident models (DSAMs). DSAMs are sequential models with a systematic procedure to utilise precursor data to estimate the posterior risk profile quantitatively. DSAM also offers updates on the failure probabilities of accident barriers and the prediction of future end states. Following a close scrutiny of these methodologies, several limitations are noted and discussed, and based on these insights, future work is suggested to enhance and improve this category of models further.

1. Introduction

The chemical process industry (CPI) is a highly complex system with diverse equipment, control schemes and operating procedures. It is also common for plants in this industry to utilise a variety of hazardous materials as raw materials and/or products. The interactions among these components, human factors, and management and organisational (M&O) issues make CPI susceptible to process deviations, which, in turn, may lead to failures if not properly managed (Khan and Abbasi, 1998c, Papazoglou et al., 1992). As illustrated by Fig. 1, when process failures occur, some may be recovered from, while others escalate into minor or major accidents and losses. To maintain the plant economy at desired levels, process plants are often equipped with a comprehensive process control system to ensure smoothness of operation and to prevent accidents. The system provides protection through varying degrees of automation, facilitated by human intervention and shielded by additional layers of protection as mitigating measures should the system fail. Nevertheless, despite all these measures, accidents still continue to happen. Examples of recent accidents in the CPI, along with some key information, are shown in Table 1.

An efficient means of combating accidents is to formulate suitable preventive measures targeting the right plant components. However, this is difficult to realise unless accidents can be anticipated and are thoroughly understood, such that the failed component can be identified prior to the occurrence of an accident. Such efforts fall within the realm of accident modelling, which relates the causes and effects of events that lead to accidents. Effectively, accident modelling seeks to answer two main questions: (i) why does an accident occur, and (ii) how does it occur. The development of these methodologies can be traced back to 1941, when Heinrich introduced the domino theory (Qureshi, 2007).

Accident models can be classified in many ways. Qureshi (2007) has proposed a reasonably comprehensive classification by dividing the models into two broad categories, i.e., traditional and modern: the traditional approach is further categorised into sequential (SAMs) and epidemiological (EAMs), while the modern approach includes systematic (SyAMs) and formal (FAMs). This classification can be further extended by introducing a third category within the modern approach, called the dynamic sequential accident model (DSAM) (see Fig. 2). DSAM is a precursor-based technique that includes two modelling schemes: (i) process hazard prevention accident models (Kujath et al., 2010; Rathnayaka et al., 2011a); and (ii) dynamic risk assessment (DRA) models. Some of the most common accident models based on this categorisation are shown in Fig. 2.

The accuracy, capability, and limitation of accident models vary significantly, depending on their purpose and focus (Rathnayaka et al., 2011a). Brief descriptions of these AMs (except the DSAMs because they will be extensively reviewed in this article), as well as their limitations regarding their use in the CPI, are summarised in Table 2. One major problem with these models is that they are

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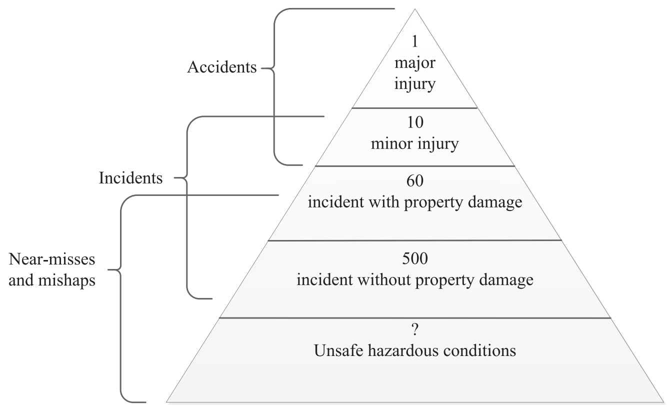

Fig. 1. Safety Pyramid (adopted from Phimister et al. (2003)).

generally case-specific, with outcomes that are mostly descriptive and qualitative. Those that have quantitative components suffer from data scarcity and uncertainty limitations. As such, they have a limited ability to provide general solutions that are capable of representing a wider class of problems and representing non-linear interactions, uncertainties and data scarcity.

In contrast, DSAMs have the advantage of simplicity due to their sequential structure and can represent non-linearity and interactions through the use of different model sequences within one framework. DSAMs use real-time precursor data (e.g., near-miss, mishap, incident, and accident) to estimate the likelihood of all possible end-states. Furthermore, they provide updated risk profiles that facilitate better decision-making. Such uses of precursor data are particularly useful in cases involving a high likelihood of occurrence or severe losses commonly found in the CPI, as well as in the nuclear, aerospace, and aviation industries. Thus, precursor programs have been developed for compulsory safety requirements such as site-specific and company-specific near-miss programs in the CPI. Similarly, the nuclear industry has also introduced the Accident Sequence Precursor (ASP) and the Institute for Nuclear Power Operation's Significant Event Evaluation and Information Network programs (van der Schaaf et al., 1991).

This paper analyses the development and application of dynamic sequential accident models as a part of precursor-based accident modelling. Section 2 extensively reviews the DSAMs and their developmental steps, and highlights recent developments within each step. Section 3 covers the application of DSAMs. This is followed by the future research needed in AMs and risk-assessment-based precursor data in section 4, and the conclusions of this analysis are presented in section 5.

2. Dynamic sequential accident model (DSAM)

DSAM is a part of precursor-based dynamic risk analysis that uses common sequential models such as Fault Tree (FT) and Event Tree (ET) to represent accident scenarios and is often combined with other approaches to accommodate non-linear and complex interactions, as well as dynamic updating features, in one framework. To overcome uncertainty issues associated with failure data, an updating scheme based on precursor data was proposed as early as 1982 (Minarick and Kukielka, 1982). This study, which was carried out to estimate core damage failure probability in the nuclear industry, was echoed in many other efforts, leading to the development of methodologies that integrate the use of precursor data into reliability analysis. Some of these works include Modarres and Amico (1984); Lois (1985); Hoertner and Kafka (1986); Hoertner et al. (1985); Ballard (1985); Cooke et al. (1987); Bier and Mosleh (1990); Oliver and Yang (1990); Cooke and Goossens (1990); Bier (1993); Abramson (1994); Bier and Yi (1995); Yi and Bier (1998); Meel and Seider (2006); Meel (2007); Kalantarnia et al. (2009a); Rathnayaka et al. (2011a, 2011b); Pariyani et al. (2012a, 2012b), the most significant of which is the systematic dynamic methodology proposed by Oliver and Yang (1990). Their method uses a Bayesian approach to update the failure probabilities of safety systems in an Event Tree through the use of precursor data. In addition to overcoming uncertainty and the scarcity of reliable data, this dynamic feature also provides posterior information that supports risk-based decision-making for safer plants.

As illustrated in Fig. 2, the DSAMs can be conveniently categorised into two modelling schemes: process hazard prevention accident models (PHPAMs) and dynamic risk assessment (DRA) models. These will be elaborated in subsequent sections.

2.1. *Process hazards prevention accident model (PHPAM)*

This family of accident models was recently introduced by Khan and co-workers, targeting applications in the CPI. To date, two models have been proposed, i.e., an off-shore oil and gas process industry accident model, and a system hazard identification, prevention and prediction (SHIPP) methodology. The off-shore oil and gas process industry accident model developed by Kujath et al. (2010) is founded on the assumption that accidents in off-shore oil and gas facilities are initiated by hydrocarbon release, which then propagates into accidents. As a safety measure, five prevention barriers are installed along the accident propagation path to prevent and/or mitigate the impact of the release, as shown in Fig. 3. Within this modelling paradigm, the worst-case scenario occurs when all barriers fail, resulting in major or catastrophic accidents. Failures of prevention barriers are modelled using FT, while the resulting consequences are modelled using ET. Precursor data of end-state events in the ET are used to update the failure probabilities of the safety barriers using Bayesian theory. The model was successfully applied to the Piper Alpha (1988) and BP Texas City refinery (2005) accidents. However, the model has some limitations, including the following: (i) it only considers operational and technical failures as causes of accidents, and other contributing factors such as human and organisational errors are not reflected (Rathnayaka et al., 2011a); and (ii) it does not consider other initiating events that could lead to accidents, such as explosions or other forms of energy releases.

To overcome the weaknesses of the off-shore model, an extension was introduced by Rathnayaka et al. (2011a) by incorporating the neglected factors into a new framework to model CPI accidents. This extended model is called the System Hazard Identification, Prediction and Prevention (SHIPP) methodology. Within the SHIPP framework, all accident causations related to operational and technical, human, management and organisational aspects are included and formulated into seven prevention barriers as shown in Fig. 4. Among these, three barriers, i.e., release prevention (RPB), ignition prevention (IPB) and escalation prevention (EPB) are the same as in the off-shore model. Three barriers are new, i.e., dispersion prevention (DPB), human factor prevention (HPB), and management and organisational prevention (M&OPB). The last barrier, i.e., damage control and emergency management prevention (DC&EMB), is a combination of the harm and loss barriers in the off-shore model with some modifications.

Based on a release of material, six consequences are considered depending on the success or failure of the barriers. These consequences are safe, near-miss, mishap, incident, accident, and serious