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Analysis of the safety barrier function: Accidents caused by the failure of safety barriers and quantitative evaluation of their performance

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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

An evaluation of the safety barrier system currently in place in the modern workplace is required to prevent major accidents and present new recommendations regarding safety levels. Safety barriers were classified and their components were described to evaluate their performance. We established a new evaluating method that included three indicators, namely the degree of confidence, the effectiveness and the economic impact. A calculation method is developed to assess each indicator using fuzzy mathematic theory. We described the progression of an accident considering the failure of safety barriers and used the observations to devise proper barriers to stop the propagation of unexpected events. The proposed method is applied to simulate a catastrophe involving the explosion of an oil storage facility which constitutes our case study. The obtained results are practical and applicable and show a high degree of quality and flexibility.

1. Introduction

Any industrial activity involves unexpected events that are tied to the behavior of workers, the organization of work and the facility design. We can locate multiple preventive or protective barriers in actual work environments (Sunindijo, 2015). These barriers contain components to protect, mitigate and prevent hazardous sequences of events. We can build adequate safety barriers by analyzing their functions and thus reduce risks. Explaining how the safety barrier system fails and the causes of their failure will help reduce the potential accidents and their consequences.

A growing attention is given to the performance of existing safety barriers and their adequacy. It is worth carrying out the performance evaluation. The evaluation of safety barriers performance originated in the former European Project Accidental Risk Assessment Methodology for Industries System (ARAMIS). The project involved several existing methodologies such as the Layer of Protection Analysis (LOPA) and Bow-Tie diagrams. With the development of theories on systematic safety, the performance evaluation of safety barriers became a tool to prevent, control and mitigate accidents. Ramzali et al. (2015) employed the Event Tree Analysis (ETA), Fault Tree Analysis (FTA) and Reliability Block Diagram (RBD) methods to build a safety barrier system for offshore drilling wells. Xue et al. (2013) proposed a new model involving a barrier to avoid blowout accidents during drilling wells. Their model employed a three-level well control and primary and secondary well control barriers depending on the Swiss Cheese Model (SCM). A physical safety barrier for protecting vehicles from roadside hazards was designed and tested by Soltani et al. (2013)to achieve optimum performance. Hayes (2012) developed a procedure, similar to job safety or a work permit, determining how best to proceed based on safety barrier performance.

The performance evaluation of safety barriers greatly relies on hazard scenarios, risk propagations, and operation procedures. Several new lines of research investigate the evolution of accidents. Valerio et al. (2009) presented a model assessing the domino potential hazard including of the repercussions of applying inherent and passive protection measures. Based on the relationships between the internal hazardous factors, Sharif et al. (2002) developed a model describing the cumulative effect of risk factors which is expected to prevent accidents through analyzing all hazards at their early stages. Underwood and Waterson (2014) proposed a comparative method considering whether SCM can provides a viable option for analyzing accidents through systematic thinking. Accidents were simulated involving different types of fracture on a leg to verify the progression in the severity of the injury. Severe accident prevention and mitigation measures were developed to provide strategies and guidelines for the occurrence of similar

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types of accidents (Hu et al., 2015).

Current industrial practices do not take into account the performance evaluation of safety barriers for preventing major accidents. Qualitative and graphical descriptions are insufficient to implement practical preventive strategies. Some existing research identifies all potential fatality sources for a given individual and determines the contribution of each source in predicting the overall risk. The primary risk sources for oil, gas and petrochemical workers are: (1) occupational, e.g. slips, falls and drowning, (2) transportation, e.g. road traffic and air transport accidents and, (3) hydrocarbon-related, e.g. loss of containment leading to the release of toxic material, fires or explosions.

To optimize the performance of safety barriers one can develop its core competence by studying the evolution mechanism of interconnected risk factors. The evolution occurs when a primary unwanted event in an accident is propagated ("temporally") within a system and/or ("spatially") to nearby systems in sequence or concurrently. The event transforms into or trigger one or more secondary unwanted events, which in turn trigger further (higher order) events, and so on. The final consequences are often more severe than those of the primary event (Cozzani and Reniers, 2013). Another important action is the establishment of a quantitative evaluation model. Although qualitative evaluation methods are simple and easy for application, it is not recommended or high risk system especially when the risk factors show complex relationships with each other.

The remainder of the paper is organized as follows. Section 2 presents an introduction to the proposed research. Section 3 categorizes in more detail the safety barriers. The evolution of accidents related to the failure of safety barriers and the domino effect are investigated in Section 4. Section 5 presents a mathematical model that includes three evaluation indexes followed by a comprehensive evaluation model of the performance of safety barriers employing fuzzy mathematic theory. Section 7 presents the testing method illustrated by the explosion of an oil storage facility which constitutes our case study.

2. Description of the proposed approach

Our approach aims to support industrial and other decision makers in evaluating the performance of existing safety barriers in their work environment and in installing necessary safety barriers to prevent accidents. The classification of safety barriers considers the industrial risk and the operation safety. We developed a comprehensive and systematic classification of safety barriers and their safety performance through a mathematical model setting evaluation indexes representing the barrier quality. Where quantitative data are not available, we use our expert judgment and a scoring method. We analyzed various stages of an accident through the failures of safety barriers. We can determine the evolution mechanism of an accident and explain how a series of unexpected events can eventually result in a major accident. The evolution of an accident can take different paths and each possible path can be blocked by proper barriers.

A schematic structure of the proposed approach is shown in Fig. 1. The schema is a step by step guide to evaluate and enhance the safety of existing barriers. Different technological processes, equipment production and operating environments among typical industries will necessitate the installation of different safety barriers. Our case study is an oil storage tank farm. However, since the proposed approach uses the accident evolution and the barrier system concurrently, the proposed approach is applicable to various industrial projects.

3. Category of safety barriers

The safety barrier model was introduced by James Reason in 1990 (Hickey and Qi, 2013). However, the concept of "safety barrier" is not universally accepted (Dianous and Fiévez, 2006). For example, Sklet (2006) had taken several dimensions and attributes into consideration to describe the safety barrier performance. Neogy et al. (1996) divided the safety barriers into three types: physical barriers, management and process barriers and personnel barriers, but their description and usefulness lack details. In our simulated accident scenario involving an oil storage tank farm, we did classify the safety barriers into three broad categories and further added subdivisions based on the hazard identification and risk index presented in Table 1.

3.1. Personnel barriers

The purpose of personnel barriers is to apply human knowledge and control to prevent improper behaviors in a safety system to reduce accidents.

3.2. Organizational barriers

Organizational barriers can be installed through a sound management program. The organizational barriers apply to, but are not limited to, management institutions, regulatory agencies and fund guarantee.

3.3. Technological barriers

Technological barriers depend on technological measures to prevent accidents and mitigate their consequences. Technological barriers are subdivided into:

- ✧ ***Passive barriers***: These have the capability of preventing risks during an entire system life cycle, with no need of human interactions or energy and information sources. Passive barriers may constitute physical barriers (such as a retention wall) or permanent barriers (such as corrosion prevention systems) or intrinsic safety design.
- ✧ ***Positive barriers***: These barriers must be automated or manually activated to operate or are mechanical and need to be activated by hardware/software to function. These included emergency shutoff valves, automatic interlocking devices and automatic sprinkler systems.
- ✧ ***Detection barriers***: The barriers detect and monitor potential risk events and send information to trigger other barriers. Detection barriers cannot prevent and protect against accidents. An example would be a flammable gas detector.

4. Performance evaluation of safety barriers

4.1. Establishing an evaluation index system

The selection and allocation of safety barriers will focus on a deeper knowledge of dangerous phenomena. We propose three evaluating indicators that include the degree of confidence, effectiveness and cost.

- ***Degree of confidence***: The concept is provided by the definition of the safety integrity level found in the IEC61511-technical content. The concepts are extended to various types of safety barriers.
- ***Effectiveness***: Effectiveness means whether a safety barrier prevents accidents. That implies the barrier system will