Multi-Perspective Process Safety Analysis for Process Utility Systems under Industry 4.0

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Abstract

Safety related factors can be measured, observed, or quantified in process safety management, but safety improvement is not easily validated. This paper initially presents a critical review of process safety analysis applied to process intensification, which is classified as an inherently safer design approach. The review revealed a lack of consensus on safety performance metrics for intensified processes, making it difficult to draw consistent conclusions on safety performance improvements.

Existing safety analysis approaches often focus on the design phase from a process lifecycle perspective. This work therefore also proposes a multi-perspective approach to safety analysis. The approach combines the hierarchy of controls perspective with the automation pyramid, and the digital twin concepts. This approach is applied and discussed in a case study of a retrofitted heat recovery system in an ammonia refrigeration plant.

**Keywords**: Process Safety, Safety Analysis, Digital Twins

* 1. Introduction

Over the past several decades, new process safety management concepts have been developed following investigations of major process safety incidents. Different process safety management (PSM) tasks are then performed throughout the life cycle of production facilities. In general, inherently safer designs are selected early in the process life cycle. Based on the hierarchy of controls, inherently-safer-design-decisions are the most effective in improving process safety. Process Intensification (PI) is the first of the four inherent safer design principles. A much-debated question is whether safety is improved in these PI processes compared to their conventional counterparts.

Current industry practice encourages the implementation of risk-based activities, i.e. risk-based safety management, risk-based inspection, and maintenance. A key activity in PSM is Hazard Identification & Risk Assessment (HIRA). A typical PSM activity is carried out by a multi-disciplinary team with different areas of expertise working together. As computer-aided tools become more available and used for PSM, it is important to have a smooth and safe transition from expert opinion-based approaches to more automated PSM and risk assessment processes.

In this work, we used the concept of hierarchy of controls to discuss the limitations of the computer-aided tools in the safety assessment of intensified processes. We also discussed the importance of considering multiple phases of the process lifecycle in the modelling for safety analysis the light of Industry 4.0 (I4.0). A multi-perspective safety analysis approach is proposed and discussed with a case study of a heat utility system.

* 1. Computer-Aided Process Safety Tools

In the past, quantitative risk assessment (QRA) has been the focus of computer-aided tools. In QRA, risk is composed of failure frequencies and consequences. Quantitative analysis uses empirical data for failure frequencies and different matrices are used for consequences. Risk-based analysis expresses risk in terms of consequence indices only. The Fire and Explosion Damage Index (FEDI) is commonly used, which deals with the consequences related to toxicity, flammability, and explosiveness. Another commonly used index is the Individual Risk (IR) indicator, which is a function of the distance between the epicentre of the accident and the location of the potential harm to personnel. FEDI and IR can be used in the selection of design alternatives in the inherently safer design approaches (Park *et al*., 2019). The calculation of these safety indices can be automated in the safety analysis at the process design stage (Janošovský *et al*., 2022). Traditional probabilistic risk assessment (PRA) at the design stage is static and only considers the risks at a snapshot in time. Unlike such PRA, the operational phase uses computer-aided tools to account for time-varying effects, i.e. disturbances, in risk estimation. Such a transition to dynamic risk analysis requires more sophisticated probabilistic models or data-driven approaches.

Digital visualisation is also used in PSM as a computer-aided tool. The tools range from graphical flowsheet interfaces to high-fidelity 3D plant models with virtual reality (VR) capabilities. There are also computational fluid dynamics (CFD) or finite element (FE) models for behavioural failure simulation. Such tools allow safety training to be conducted remotely in simulation environments and are ideal for improving operational procedures. With the advent of generative artificial intelligence (AI), intuitive human-machine interfaces (HMI) are expected to become increasingly available. Pioneering work has been done to make ChatGPT a participant in the HAZOP process, which was based on Large Language Modelling (LLM) (Xuan and Daniel, 2023). In the future, natural language processing (NLP) and generative AI may be used to translate the process-safety-relevant written work into more intuitive formats for human interaction, i.e., using AI to translate the written operational procedures, guidelines, best practices, and regulations into animated visual content with audio interfaces. Augmented Reality (AR) and Mixed Reality (MR) could also enable new interfaces for safety training and for promoting a good safety culture in engineering enterprises.

* 1. Safety Analysis Used in Process Intensification

Process Intensification (PI) is one of the inherently safer design principles. However, the results of process safety analysis of process intensified processes are conflicting. In this work, a literature review of process safety analysis applied to process intensification was conducted. This review involved entering the search terms “process intensification” AND “safety” into the Scopus (The University of Auckland) search engine on the 7th of November 2022. The search returned 234 peer-reviewed articles. After removing duplicates, 219 articles remained. These 219 articles come from 113 different sources. Chemical Engineering and Processing - Process Intensification is the most popular source, and 23 of the 219 articles came from this single source. After screening the 219 articles, some articles were identified as having a brief mention of “process safety” but no detailed work on safety. These articles were not considered further. 35 of the 219 articles had more specific discussions of process safety and process intensification. 14 of the 35 articles had further investigated process safety in process intensification using some quantitative methods.

36% of the papers used Individual Risk (IR) as a quantitative indicator to measure the safety improvement achieved through intensification. 28% of the papers used the Fire and Explosion Damage Index (FEDI). The remaining papers used the Process Stream Index (PSI), Process Route Index (PRI), Inherent Safety Index (ISI), and the Inherent Safety Key Performance Indicator (IS-KPI). 80% of the papers using the IR indicator considered the cost and environmental impact simultaneously. IR is the most used indicator in multi-criteria comparison methodologies developed to compare the performance of PI processes. A common goal of process intensification is to achieve cheaper, more sustainable, and safer processes in chemical manufacturing. These comparative studies suggest very small safety improvements in PI processes, when compared to their conventional counterparts.

A limitation of this research is the small number of papers found on the “process safety performance of the PI processes”. In the literature reviewed, computer-aided tools are used to build mathematical models for the safety analysis of PI processes. All the papers reviewed only discuss the safety performance of PI processes in their design phase. There is a lack of discussion of PI plants during the operational phase, i.e. PSM, dynamic risk assessment. No firm conclusion could be drawn as to whether safety improvements can be guaranteed by PI over the whole life cycle.

* 1. Multi-Perspective Process Safety Analysis under Industry 4.0

As part of industry convergence, the chemical process industry is becoming increasingly digitalised and moving towards I4.0. Cloud-based computing, real-time optimisation, and interoperable devices are bringing disruptions to the traditional PSM activities. This work proposes a multi-perspective framework to apply existing safety theories and PSM concepts to computer-aid tools under I4.0, as shown in Figure 1.

The Basic Process Control System (BPCS) is at the bottom of the 5-level pyramid, which was adapted from ANSI/ISA-95, shown in Figure 1 (a). In the chemical process industry, I4.0 technologies enabled streaming of process data, cloud-based process analytics, advanced real-time control optimisation, and the use of interoperable equipment & instruments. Figure 1 (b) shows the Hierarchy of Controls adapted from the Centre for Chemical Process Safety (CCPS). Procedural improvement is at the lowest level of effectiveness in the hierarchy of controls. An example of procedural activity is using computer vision to detect whether personal protective equipment (PPE) is being worn. Automated control on process equipment, i.e. valves, may be considered an active safety barrier, which is the second lowest in the hierarchy, as shown in Figure 1 (b).



Figure 1 (a) Pyramid of Automation, (b) Hierarchy of Controls, and (c) Types of Digital Twin

Figure 1 (c) shows a pyramid of five different types of Digital Twin (DT) with increasing complexity. The lowest level DT requires a model of a physical component in the cyberspace, which can be analytical, empirical, data-driven/machine learning (AI) or regression-based. Flowsheet simulation is a common type of model found in chemical processes, which is (semi-) empirical. In the process safety practice, FE models of process piping, CFD dispersion models of chemical release, or VR tools used for safety training also have the potential to form the basis of DTs. The above mentioned are physics-based models and some have high fidelity. Due to the different levels of model abstraction, these models are heterogeneous. It is difficult to achieve data exchange between these models.

* 1. Case Study: Multi-Perspective Safety Analysis of an Ammonia System

In this section, safety analysis is discussed from 1) a life cycle perspective and 2) a hierarchy of controls perspective using a case study of an ammonia refrigeration system. The aim is to form a future-proof theoretical framework for the safety analysis of heating and cooling utility systems in the food processing industry under I4.0.

Food products and by-products make up 45% of New Zealand’s total exports and 60% of these products are in refrigerated state (Carson & East, 2018). Meat products require refrigeration after slaughter, while dairy products require refrigeration of raw milk prior to factory processing. Ammonia systems are widely used in NZ for food processing and storage. Anhydrous ammonia (R717) has a zero Ozone Depletion Potential (ODP) and zero Global Warming Potential (GWP). It is also relatively inexpensive, volatile, and has a high latent heat of evaporation.

A waste heat recovery system was retrofitted in an aquatic product processing facility with several ammonia-based chillers (Xie, 2018). The chillers have a cooling capacity of 800kW. The heat recovery system replaced an on-site hot water boiler. The recovered energy is used to heat hot water on site to 40-70 °C and is also sufficient for space heating in winter. Latent heat recovery accounts for 85% of the total energy recovered, which was achieved by a water sourced heat pump. Sensible heat recovered accounts for the remaining 15% by a plate heat exchanger type device. The heat recovery system was installed after the original ammonia refrigeration had been in operation. For life cycle risk analysis, this change in risk profile before and after the retrofit should be captured. A different ranking of hierarchy of controls may be introduced between the existing ammonia refrigeration system, the new water sourced heat pump, and other additional heat recovery equipment.

* + 1. Risk Assessment from the Life Cycle Perspective

Toxic release is a well-recognised risk of ammonia systems. The risk of ammonia release is proportional to the total charge, the rate of release, and the distance between the epicentre and personnel. Retrofitting the heat recovery system has little or no effects on the likelihood of an ammonia release. It is unlikely to change the IR as the location of the ammonia storage space, the total charge and the layout of the ammonia pipework remain unchanged. Using the IR indicator, it can be concluded that ‘no safety improvement’ has been achieved by the retrofit. Ammonia is mildly flammable, and explosive under strict circumstances. The water sourced heat pump was installed close to the refrigeration plant, which may introduce new ignition sources. Compared to the original design state, the FEDI of the ammonia system may be worse due to these new electrical components.

* + 1. Safety Evaluation from the Hierarchy of Controls Perspective

‘Moderation’ is one of the four inherently safer principles. Moderation is usually achieved by reducing the process temperature or pressure. In this case study, the aquatic product processing plant has similar temperature requirements to meat processing plants. For refrigeration (chillers), the temperature requirements are typically at 20-30°C for process cooling, 10°C for boning, 0°C for chilling, and -20°C for freezing. Hot water temperature requirements are 60°C for washdown and 45°C for hand washing. Due to the nature of the relatively mild temperature requirements, the heat recovery system does not significantly affect the process conditions, i.e. temperature or pressure. The heating requirements were met by a boiler prior to the retrofit. At the passive safety barrier level, the overall system safety performance is improved due to the elimination of the boiler. There are minor impacts on the active safety barriers due to changes in the temperature control strategy. The waste heat recovery system may require cooling and heating loads to be matched during operation. The heat recovery equipment also led to changes at the operational procedures level and additional PSM tasks. There is insufficient information to determine whether these will have a negative or positive safety impact.

* + 1. Multi-Perspective Framework for Process Safety Enhancement

To improve the energy efficiency of food processing plants, large utility systems are also gradually introducing I4.0 solutions, i.e. DT, Industrial Internet of Things (IIoT). At the same time, smart equipment may also be retrofitted into the facility with live document tracking the design changes. Existing industry best practice guidelines will soon become obsolete as the new operational strategies emerge.

As part of projects to improve the energy efficiency of industrial process plants, on-site personnel trained to operate boilers will be retrained to operate high-temperature heat pumps, absorption chillers or even hydrogen-powered equipment. These retraining programmes will also provide a good opportunity to improve the safety culture of the company. Meanwhile, asset owners will need to rely on refrigeration service providers during this technology transition. Refrigeration as a service (RaaS) could become the new norm in the specialist refrigeration sector. In the future, the introduction of industrial symbiosis and shared utility systems in large industrial complexes may require more systematic process safety assessment. Figure 2 shows a potential approach to multi-perspective process safety analysis for industrial refrigeration systems. In this framework, multi-physics and multi-timescale modelling is to be achieved with DTs at component, asset, system, and network levels for the safety of an ammonia refrigeration system.



Figure 2 Heterogeneous abstractions in modelling for process safety enhanced DTs

* 1. Conclusions

The literature review conducted in this work showed that computer-aided safety assessment is found in the design phase of PI. There is a lack of published work on the performance of these ‘inherently safer designs’ after their construction. Therefore, there is a lack of validation on whether the inherently safer designs have better safety performance throughout the process lifecycle. There is weak evidence on whether process safety is guaranteed by PI processes.

Computer-aided tools are used in safety analysis and other PSM activities. These tools are based on heterogeneous abstractions for computer modelling. Hence, it is difficult to achieve data exchange between different process-safety-related computer-aided tools.

In the process industry, the current implementation of I4.0 technology is mostly found at the lower levels of the automation pyramid. High-fidelity and multi-physics co-simulation may be required to achieve a ‘Process Safety Enhanced DT’. With the expanding applications of generative AI, a further step change in PSM is expected soon. To provide a new lens on the safety performance of industrial utility systems under I4.0, this work proposes a multi-perspective approach from the perspective 1) the process lifecycle and 2) the hierarchy of controls.

Considering the Sustainable Development Goals (SDGs), natural refrigerants such as ammonia (NH3), carbon dioxide (CO2), and hydrocarbons (propane, isobutane, or zeotropic mixtures) are becoming popular. The refrigeration as a service (RaaS) business model is also gaining momentum in the large industrial utility systems. Future research on safety analysis should be carried out to investigate heat utility system under the new business models and towards the hydrogen economy.

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