CHAPTER 1

1.1 Introduction

The chemical process industry (CPI) is one of the most significant engines among the various such engines that drive improvements in the economy of most countries. However, the activities and processes within CPI are sometimes associated with very high risks. The feature is true at least in the very long run. Despite several decades of safety practice improvement and technological advancement, accident rates remain a constant feature of this industry indicating critical flaws in safety management and prevention strategies. Research indicates that about 95% of accident causes have been identified and are theoretically preventable (Drogaris, 1993; Pasman, 2010); however, in practice, barriers result in problems like poor dissemination of accident knowledge, inadequacy in quality of accident reports, and lack of historical evidence in predictive analysis, which is part of what hinders meaningful advancements about the reduction of accident frequencies (Jacobsson et al., 2010; Lindberg et al., 2010).

The excessive reliance on procedural and organizational controls rather than on fundamental protections often causes safety management to fail when root causes lie hidden in plant design (Kletz, 2003; CCPS, 1998). Consequently, an outer layer of protection rather than innate principles has caused recurring incidents maintained through disproportionate risk management processes and a poor connection of design and risk analyses (Kidam & Hurme, 2012a; Knetgering & Pasman, 2009). As technology evolves, more chemical plants face the inevitable aging of infrastructure and still higher operation thresholds. The complexity added to these chemical plants has produced entirely new accident scenarios and challenges for designers (Leveson, 2004; Kidam et al., 2014).

In context, transforming the process design lifecycle by integrating machine learning technologies emerges as new and radical opportunities for improving inherent safety design. ML applications take from historical accident records to forecast risks, discover weaknesses in the design, and provide actionable suggestions for future preventive measures against hazards. In contrast to these traditional reactive approaches, accident prediction is externalized by ML, allowing decisions to be made based on evidence, which permits designers to take action early in a design phase when their strategies are still cost-effective and most efficient.

Machine learning would revolutionize accident prevention in the chemical, petroleum, and heavy industries by embedding inherent safety and health (ISH) principles within the design lifecycle. Historical accident analyses would be systematically examined to create a framework for disseminating knowledge and a culture of learning from what has happened. The intention is to motivate design thinking that prioritizes safety and to show how critical life cycle assessments would be enabled through ML tools that pave the way for a more secure and sustainable future in the chemical industry.

1.2 Problem Background

The chemical process industry (CPI) has struggled consistently to slash its accident rates despite considerable research and other findings regarding the causes of accidents. It has been shown that 95% of accidents in the CPI might be avoided with the available and current knowledge of accident research (Drogaris, 1993; Pasman, 2010). Unfortunately, there have been no proper channels to disseminate or even make use of accident data so the same accidents keep occurring with almost no learning from the previous incident (Jacobsson et al., 2010; Lindberg et al., 2010). Poor accident reports, improper analysis of data, and weak feedback mechanisms in the learning cycle such as Lindberg and Hasson (2006) are indeed considerable hindrances to effective accident prevention.

Unbalanced risk management in designing plants has also been identified as one of the singular causes of accidents in the CPI (Kidam & Hurme, 2012a). Traditional practices typically depend on procedural safety measures and not on integrating inherently safer design principles, which target the elimination of hazards at source (Amyotte et al., 2011; Kletz, 2003). The safety measure is aimed at short-term cost savings but may attract a higher long-term cost in management and risk (CCPS, 1998). Furthermore, caused of rapid industrialization and technological advances, the complexity of chemical plant design greatly challenges the issue of maintaining safety and health standards (He et al., 2011; Knetgering & Pasman, 2009).

The slow pace of adoption of inherent safety design (ISD) principles since the 1970s is evident by the serious lacunae in the application of ISD at the early design stages (Gupta & Edwards, 2002). It has resulted in the continuing high accident rates in the CPI, as seen in different areas of the world, including the United States, Asia, and Europe (He et al., 2011; Niemitz et al., 2010; Prem et al., 2012). Furthermore, the neglect of ISH in design practices has hampered the industry from minimizing risks efficiently (Kidam et al., 2016a).

In this case, the research provides a machine-learning-driven accident prediction model for the chemical process industry's design life cycle to implement the principles of ISH over time better. Thus, with early identification of design-related hazards, the systematic application of ISH methodologies in the design process would improve safety and health performance with cost savings and reduced risks in the CPI.

1.3 Problem Statement

In the years after developing safety practices and safety technologies, the chemical process industry (CPI) accident rates remained high, mostly because of the failure to disseminate knowledge about accidents and poor learning from accidents. Although many studies and frameworks address inherent safety and health (ISH) in the CPI, the existing methods are not integrated with expertise and usability in early process design. These approaches, particularly HAZOP, are limited to applications since they require exhaustive process data which is hardly available during the preliminary design phase. This gap ensures that hazards associated with designs are not identified and mitigated proactively, hence resulting in recurring accidents and meaningful lessons not learned.

In addition, the traditional methods of ISH are rather complicated, protracted, and knowledge-rich, and demand thorough training and experience to use well, thus rendering them inaccessible for general application. The lack of a common, data-driven framework to integrate accident insights into process design increases this problem. The existing accident reporting and investigation systems are utilized minimally, and the fulfillment of their potential toward informing inevitably safe designs remains quite limited. This is a barrier for designers and engineers in systematically addressing hazards at the early design stages, where changes tend to be more cost-effective and have a deeper impact.

Designing safety into any process right across its life cycle from first conception through research, development, and ultimately deployment can only be accomplished through a machine-learning-guided approach using accident databases to improve predictive capability. It would be made possible through archiving taught accidents but, most importantly, phenomenon-based error modes, the end goals of which should be effective use and sharing of accident knowledge but also an end-user "friendly" tool facility for design decision-making and avoidance of accident recurrence FBI-based.

1.4 Research Questions

This research aims to visualize accident prediction using machine learning to enhance inherent safety design across the process design life cycle in the chemical industry. The research questions are:

1. What are the main causes of accidents in the chemical process industry across the different life-cycle phases of process design?
2. What prioritization should be given regarding safety and health recommendations to prevent accidents at the different design phases?
3. In what way can accident data increase safety and health at early process design decisions?

1.5 Research Aim

This research has been focused on developing predictive models through machine learning to predict and perhaps prevent the likely occurrence of accidents along the entire process design life cycle in the chemical industry. The research will therefore be using the predictions from such inference to be built into the safety design principles within processing operations along the lines of anticipating and mitigating possible risks, thereby ensuring increased performance and thus safety in chemical process operations.

1.6 Research Objective

The main aim of this research is to realize accident learning in the chemical processing industry (CPI) through the integration of health and safety aspects within the development and design of processes. The objectives of the research are as below:

1. To identify, classify, and rank some major accident enablers as possible root causes traced through the life cycle of process design.

2. To identify, classify, and rank several safety and health recommendations regarding points of intervention across the process design life cycle.
3. To evaluate accident database information for inherent safety and health and apply findings at:

    a. Research and Development
    b. Preliminary Engineering Phase
    c. Basic Engineering Phase
    d. Detailed Engineering Phase
    e. Procurement, Fabrication, Commissioning and Start-up
    f. Operation/ Plant modification.

This will enable CPI safety through accident data becoming directly applicable to design decisions at all stages of the process design life cycle.

1.7 Scope of Research

The focus of this study is to sift through a large amount of past accident data and find relevant indications about subsequent safety and health integration at the process design phase in the chemical process industry. The scope includes:

1. Data Collection: At least 500,000 accident investigation reports will be compiled by the research from credible sources which include the US Chemical Safety and Hazard Investigation Board (CSB), the US National Transportation Safety Board (NTSB), US Environmental Protection Agency (EPA), Japan's Science and Technology Failure Knowledge Database (FKD), and EU Major Accident Reporting System (e-MARS) all of which house accidents between the dates of 1990 and 2024.

2. Accident Analysis: This study will focus on accidents related to process safety so that key contributors can be identified in the chemical process industry. These would be classified according to the following design error category: process condition, reactivity/incompatibility, unsuitable equipment/part, protection, construction material, layout, utility setup, sizing, automation/instrument issues but all would be linked to equipment failure types.

3. Classification of Accident Contributors and Root Causes: Their identification will fall into design, technical, human, organizational, and external errors. Thus, root causes will be classified by the process design life cycle, i.e., research and development (R&D), preliminary engineering, basic engineering, detailed engineering, procurement, fabrication, commissioning start-up, and operation/plant modification.

4. Recommendations Assessment: The recommendations in the documents shall be broadly classified as preventive, protective, mitigative, and corrective measures. Safety measures can be further classified as inherent safety, inherent health, passive-engineered, and active-engineered measures. Inherent safety and health recommendations will focus on ISD (Inherently Safer Design): minimization, substitution, moderation, and simplification.

5. Statistical Ranking: Statistical analysis will classify and rank the accident contributors and safety recommendations depending on the occurrence frequency, thus establishing critical design-related issues for CPI accidents.

It further addresses the objective of using accident data to facilitate learning, defining safety actions, and integrating such analysis towards inherent safety and health improvements in every process design phase.

1.8 Significance of Research

The present research has significant value since it advances the safety practices in the chemical industry. The machine learning-involved accident prediction integrates informing about potential hazards beforehand so that proactive measures can be taken to prevent accidents during the design life cycle. The strategy robustly supports inherent safety design by nesting safety principles right into the design phase of the process, making processes inherently safer instead of depending on external protective measures.

Data-driven insights to engineers and safety professionals improve decision-making because they optimize process designs without excessive risk. Prevention of accidents not only increases safety but also reduces economic and environmental consequences, such as costly downtimes, material losses, and environmental damage; hence, safety and profit are ensured in chemical operations.

In addition, this research helps to develop standards in the industry by facilitating technology-enabled approaches to hazard prediction and mitigation. It aligns with Industry 4.0 objectives by integrating machine learning with safety management systems, supporting the chemical industry's transition to digitalization and smart manufacturing. Overall, this research offers a transformative approach to enhancing operational excellence and protecting lives, assets, and the environment.