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Submitted by: TAIBI Hicham

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Under the supervision of: Prof. HADJADJ AOUL Elias

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Examination Committee:

President: Prof. CHEGHIB Hocine — Badji Mokhtar – Annaba University

Supervisor: Prof. HADJADJ AOUL Elias — Badji Mokhtar – Annaba University

Examiner: Dr. ZEROUALI Billel — University of 20 August 1955, Skikda

Examiner: Dr. BENAMIRA Nadir — Badji Mokhtar – Annaba University

Examiner: Prof. BENIDIR Mohamed — Frères Mentouri University – Constantine 1

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Dedication

I dedicate this work

To my dear parents,

To my family,

To all those who have generously supported me,

To my teachers,

To my friends,

Hicham.

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List of Abbreviations

ALARP: As Low as Reasonably Practicable
BBD: Barrier Block Diagram
BORA: Barrier and Operational Risk Analysis
CCR: Central Control Room
DEMATEL: Decision-Making Trial and Evaluation Laboratory
DCS: Distributed Control System
ESDV: Emergency Shutdown Valve
ESP Fan: Electrostatic Precipitator Fan
ETA: Event Tree Analysis
FMECA: Failure Modes, Effects, and Criticality Analysis
FTA: Fault Tree Analysis
HACCP: Hazard Analysis and Critical Control Points
HAZOP: Hazard and Operability Study
HMI: Human–Machine Interface
HOFs: Human and Organizational Factors
ID Fan: Induced Draft Fan
IE: Initiating Event
IPL: Independent Protection Layer
ISO: International Organization for Standardization
LCM: Lafarge Ciment de M'Sila
LOPA: Layer of Protection Analysis
LOTOTO: Lockout, Tagout, Tryout
LPG: Liquefied Petroleum Gas
Nm^3/h: Normal Cubic Metres per Hour
OSHA: Occupational Safety and Health Administration
P&ID: Piping and Instrumentation Diagram
PFD: Process Flow Diagram / Probability of Failure on Demand
PLC: Programmable Logic Controller
PT: Pressure Transmitter
RCA: Root Cause Analysis
RIF: Risk Influencing Factor
rpm: Revolutions per Minute
SIL: Safety Integrity Level
SIS: Safety Instrumented System
SOP: Standard Operating Procedure
STAMP: Systems-Theoretic Accident Model and Processes
SWIFT: Structured What-If Technique
t/h: Tonnes per Hour
VOC: Volatile Organic Compounds

Abstract

The cement industry is one of the most energy- and resource-intensive sectors. Its production process is highly complex and requires strict control of numerous parameters, which, if not adequately managed, may have considerable consequences for the environment, health, and safety.

The firing section of a cement plant, which comprises the preheating tower, rotary kiln, and grate cooler, operates under extreme temperatures of up to 1450°C and high mechanical stresses. The high-volume flows of hot materials, combined with the close interdependence between process stages, present major challenges for managing safety and operability risks, particularly those associated with hot material releases, explosions, and equipment failures. Conventional risk assessments often treat hazardous events in isolation, thereby limiting their ability to account for the influence of technical, human, and organizational factors on these events, on safety barrier performance, and on overall risk. To address this gap, the present study proposes a more integrated approach to risk analysis and the modeling of safety barriers in such harsh environments.

This research proposes a structured methodology that integrates three complementary methods: Hazard and Operability (HAZOP) studies, Barrier and Operational Risk Analysis (BORA), and Root Cause Analysis (RCA). HAZOP studies were conducted to evaluate system-level interactions and identify potential deviations, resulting in 81 credible deviations ranked using a risk matrix. The analysis revealed a risk profile dominated by low- to medium-severity events, with bidirectional interdependencies across material, energy, and control flows amplifying cascading failures and systemic vulnerability.

Based on these findings, two critical scenarios were selected for detailed analysis. BORA was applied to explore how technical, human, and organizational factors influence site-specific operational conditions and the effectiveness of safety barriers. The weighting and scoring system offers a structured framework for benchmarking risk controls against established industry standards. Industry average values serve as reference points to evaluate whether performance improves or declines under different Risk Influencing Factor (RIF) scenarios. The results show that moving toward the best-practice category (A) is associated with a measurable reduction in overall risk, including a lower frequency of initiating events (IEs) and lower probability of failure on demand (PFD) values for independent protection layers (IPLs), whereas deviation from standard practice (C) has the opposite effect. This reinforces the importance of continuous risk-reduction efforts. RCA was subsequently employed to trace underlying causes and link them to systemic weaknesses.

The main contribution of this work is demonstrating how established methods originally developed for the oil and gas industry can be adapted for the first time to new and complex industrial contexts. This approach illustrates knowledge transfer and generates outcomes that are both academically rigorous and practically applicable.

Applied to a real-world case study, the integrated methodology generated actionable recommendations to enhance process resilience and safety. While the findings may have relevance for other thermally intensive industries, adapting the framework to different sectors would require consideration of sector-specific practices and data availability, which should temper broad generalization.

Résumé

L'industrie cimentière figure parmi les secteurs les plus énergivores et les plus consommateurs de ressources. Son processus de production est particulièrement complexe et nécessite un contrôle rigoureux de nombreux paramètres qui, lorsqu'ils ne sont pas maîtrisés de manière adéquate, peuvent avoir des conséquences considérables sur l'environnement, la santé et la sécurité.

La section de cuisson d'une cimenterie, qui comprend la tour de préchauffage, le four rotatif et le refroidisseur à grille, fonctionne à des températures extrêmes pouvant atteindre 1 450 °C et est soumise à des contraintes mécaniques élevées. Les flux importants de matières chaudes et l'étroite interdépendance des différents processus constituent des défis majeurs pour la maîtrise des risques liés à la sécurité et à l'opérabilité, notamment ceux associés aux rejets de matières chaudes, aux explosions et aux défaillances des équipements. Les méthodes conventionnelles d'évaluation des risques traitent souvent les événements dangereux de manière isolée, en prenant insuffisamment en compte l'influence des facteurs techniques, humains et organisationnels sur ces événements, sur la performance des barrières de sécurité et sur le niveau de risque global. Pour répondre à cette limite, la présente étude propose une approche plus intégrée de l'analyse des risques et de la modélisation des barrières de sécurité dans de tels environnements industriels sévères.

Cette recherche propose une méthodologie structurée intégrant trois méthodes complémentaires : l'analyse des dangers et de l'opérabilité (HAZOP), l'analyse des barrières et des risques opérationnels (BORA) et l'analyse des causes racines (RCA). Les études HAZOP ont été menées afin d'évaluer les interactions à l'échelle du système et d'identifier les déviations potentielles, permettant ainsi de recenser 81 déviations plausibles, classées au moyen d'une matrice de risques. L'analyse a révélé un profil de risque dominé par des événements de niveaux de gravité faibles à moyens. Elle a également mis en évidence des interdépendances bidirectionnelles entre les flux de matière, d'énergie et de commande, susceptibles d'amplifier les défaillances en cascade et la vulnérabilité du système.

Sur la base de ces résultats, deux scénarios critiques ont été retenus pour une analyse approfondie. La méthode BORA a été appliquée afin d'étudier l'influence des facteurs techniques, humains et organisationnels sur les conditions opérationnelles propres au site ainsi que sur l'efficacité des barrières de sécurité. Le système de pondération et de notation fournit un cadre structuré permettant d'évaluer les dispositifs de maîtrise des risques par rapport aux pratiques de référence de l'industrie. Les valeurs moyennes industrielles servent de points de référence pour apprécier l'évolution des performances selon différents niveaux des facteurs d'influence du risque (RIF). Les résultats montrent qu'une évolution vers la catégorie des meilleures pratiques (A) est associée à une réduction mesurable du risque global, notamment à une diminution de la fréquence des événements initiateurs (IE) et des valeurs de probabilité de défaillance à la sollicitation (PFD) des couches de protection indépendantes (IPL). À l'inverse, un écart par rapport aux pratiques standards (C) produit l'effet opposé. Ces résultats soulignent l'importance d'une démarche continue de réduction des risques. L'analyse des causes racines (RCA) a ensuite été mobilisée pour identifier les causes sous-jacentes et les relier aux défaillances systémiques.

La principale contribution de ce travail réside dans la démonstration de la manière dont des méthodes établies, initialement développées pour les industries pétrolière et gazière, peuvent être adaptées, pour la première fois, à de nouveaux contextes industriels complexes. Cette approche illustre le transfert de connaissances et permet d'obtenir des résultats à la fois rigoureux sur le plan scientifique et applicables sur le plan opérationnel.

Appliquée à une étude de cas réelle, cette méthodologie intégrée a permis de formuler des recommandations concrètes visant à améliorer la résilience et la sécurité des procédés. Bien que les résultats puissent présenter un intérêt pour d'autres industries à forte intensité thermique, l'adaptation de ce cadre à différents secteurs nécessiterait de prendre en considération leurs pratiques spécifiques ainsi que la disponibilité des données, ce qui invite à la prudence quant à la généralisation des résultats.

الملخص

تُعَدّ صناعة الإسمنت من أكثر الصناعات استهلاكًا للطاقة والموارد، كما تتسم عملياتها بدرجة عالية من التعقيد تفرض ضرورة التحكم الدقيق في عدد كبير من المتغيرات التشغيلية. ويؤدي أي خلل في إدارة هذه المتغيرات إلى انعكاسات خطيرة على البيئة، والصحة، والسلامة المهنية.

يعمل قسم الحرق في مصنع الإسمنت، الذي يضم برج التسخين المسبق والفرن الدوار والمبرّد الشبكي، في ظل درجات حرارة قصوى تصل إلى 1450 درجة مئوية، ويتعرض لإجهادات ميكانيكية عالية. كما أنّ التدفقات الكبيرة للمواد الساخنة، إلى جانب الترابط الوثيق بين مراحل العملية، تولّد تحديات كبيرة في إدارة مخاطر سلامة العمليات وقابلية التشغيل، خاصة تلك المرتبطة بانبعاث المواد الساخنة، والانفجارات، وتعطّل المعدات. وتعتمد معظم منهجيات تقييم المخاطر التقليدية على تحليل الحوادث بصورة منفصلة، مما يحدّ من قدرتها على استيعاب تأثير العوامل التقنية والبشرية والتنظيمية في مجمل الأحداث الخطرة وفي أداء الحواجز الوقائية، وبالتالي في مستوى الخطر الإجمالي. ولمعالجة هذه النقائص، تقترح هذه الدراسة منظورًا تكامليًا جديدًا لتحليل المخاطر ونمذجة أداء الحواجز الوقائية في مثل هذه البيئات التشغيلية القاسية.

وتقدّم هذه الدراسة منهجية مُحكمة تقوم على دمج ثلاث أدوات تحليلية متكاملة: دراسة المخاطر وقابلية التشغيل (HAZOP)، وتحليل الحواجز والمخاطر التشغيلية (BORA)، وتحليل الأسباب الجذرية (RCA). وقد مكّنت دراسات HAZOP من تقييم التفاعلات النظامية وتحديد الانحرافات المحتملة، حيث تم حصر 81 انحرافًا معتبرًا جرى تصنيفها وفق مصفوفة المخاطر. وأظهرت النتائج أنّ ملف المخاطر يتميز بانتشار الأحداث منخفضة ومتوسطة الشدة، مع وجود ترابطات متبادلة بين تدفقات المادة والطاقة والتحكم، الأمر الذي يزيد من احتمالية الإخفاقات المتسلسلة ويعمّق الضعف البنيوي للنظام.

وانطلاقًا من هذه النتائج، جرى اختيار سيناريوهين حرجين للتحليل المتعمّق. وقد استُخدم أسلوب BORA لدراسة أثر العوامل التقنية والبشرية والتنظيمية على الظروف التشغيلية الخاصة بالموقع وعلى كفاءة الحواجز الوقائية. ويوفّر نظام الترجيح والتقييم إطارًا مرجعيًا لقياس أداء ضوابط المخاطر مقارنة بالمعايير الصناعية المعتمدة. وتُستخدم القيم المتوسطة للصناعة كنقاط مرجعية لتقييم ما إذا كان الأداء يتحسن أو يتراجع في ظل سيناريوهات مختلفة للعوامل المؤثرة في المخاطر (RIF). وتُظهر النتائج أنّ الاقتراب من فئة أفضل الممارسات (A) يؤدي إلى خفض ملموس في مستوى الخطر الكلي، من خلال تقليل معدل تكرار الأحداث البادئة (IEs) وخفض قيم احتمال الفشل عند الطلب (PFD) لطبقات الحماية المستقلة (IPLs)، في حين يؤدّي الانحراف عن الممارسات القياسية (C) إلى عكس ذلك. ويؤكد هذا المعطى أهمية التحسين المستمر لأنظمة السلامة. أمّا تحليل RCA فقد أتاح تحديد الأسباب الجذرية وربطها بمواطن الضعف على مستوى النظام.

تتمثّل الإضافة الرئيسة لهذا العمل في إظهار كيفية تكييف منهجيات راسخة طُوّرت أصلًا لقطاع النفط والغاز لتُطبّق لأول مرة على سياقات صناعية جديدة ومعقدة، بما يعزز نقل المعرفة ويوفّر نتائج تجمع بين الصرامة الأكاديمية والجدوى التطبيقية.

وعند تطبيق المنهجية المتكاملة على دراسة حالة حقيقية، أفضت النتائج إلى توصيات عملية قابلة للتنفيذ من شأنها تعزيز مرونة العملية التشغيلية ورفع مستويات السلامة. وعلى الرغم من أن النتائج قد تحمل دلالات مفيدة لصناعات حرارية أخرى كثيفة الاستهلاك للطاقة، فإن تعميم هذا الإطار على قطاعات مختلفة يستلزم مراعاة ممارسات كل قطاع وخصائصه ودرجة توافر البيانات فيه، الأمر الذي يفرض قدرًا من التحفّظ عند إجراء تعميمات واسعة.

General Introduction

In contemporary complex socio-technical systems, dynamic and often non-linear interactions between their components make adverse and unexpected events inevitable, which may compromise not only operational efficiency but also safety and sustainability. The complex interdependencies and external factors inherent in these systems introduce considerable uncertainty and the potential for losses. In this context, risk analysis becomes an essential tool for facing these challenges and supporting informed decision-making. Its methodologies, which combine qualitative and quantitative data, serve as the foundation of comprehensive risk management strategies. This enables a thorough mapping of the risk picture and its controls, positioning organizations to adeptly manage uncertainty, enhance their resilience, and remain agile and responsive in unpredictable scenarios.

A system's risk profile is strongly determined by the integrity and performance of its safety barriers. Accordingly, well-designed systems incorporate multiple barriers to protect people, the environment, and assets from undesired events. These barriers act either to reduce the likelihood of an accident (pre-release barriers) or to limit its consequences once initiated (post-release barriers). However, in complex settings, barrier functions may not be fully achieved; failure or degradation of one or more barrier elements can permit adverse outcomes, particularly when coincident with a hazardous event.

Cement plants serve as a clear example of such a complex socio-technical system. Their safe and sustainable operation relies on the interplay of technical, human, and organizational factors. These large-scale industrial facilities have complex designs that integrate physical, chemical, mechanical, thermal, and electrical engineering to transform raw materials into cement, a vital construction material that is a pillar of modern society.

As a major construction material, cement is produced in most countries. In fact, large-scale production results in enormous energy consumption and significant environmental impacts, contributing roughly 5% of global greenhouse gas emissions. Being a classified installation for environmental protection (ICPE), the cement plant is subject to comprehensive risk and impact studies. It must comply with rigorous standards, guidelines, and regulations to prevent all risks and adverse impacts resulting from its activities. The production process is very complex and involves several parameters, which, if not adequately controlled, can have considerable consequences for the environment, health, and safety, as well as significant energy losses. Its operations present a huge variety of risks due to the complexity of the processes and the hazardous materials involved, especially in the pyro processing section.

The firing zone serves as the thermodynamic heart of cement plants, as clinker formation represents the most critical phase of the process. During this phase, large quantities of hot meal are transported within the heating area. "*hot meal*" is the cement industry term for partially calcined raw materials: a mixture of quarried limestone, alumina, sand, iron, and corrective additives. The hot meal passes through the cyclones, the calciner, the kiln tube, and the cooler. Throughout this multi-stage process, several potential hazards emerge, requiring effective control measures. These hazards encompass a huge range of risks, most notably spillage [1], fires and explosions [1] [2], contact with hot meal, falls from height, contact with moving machinery, emergency response failures, materials engulfment, confined space work, mobile equipment incident [3], risks related to electrical equipment [4, 5], polluted water discharge, respiratory illness [6], and structural collapse [7, 8], among others. The consequences of these risks can be potentially serious, resulting in injury, death and environmental damage.

Clinker manufacturing is a complex process requiring considerable raw mix, energy, and fuel [9]. The combustion process, which reaches a temperature of up to 1450°C in the furnace, is initiated by mixing a large quantity of fuel (Liquefied Petroleum Gas (LPG), coal, or alternative fuel) and oxygen at high pressure, followed by ignition, which triggers a flame in the burner. The risks of spillage of hot materials, fires, and explosions are huge, particularly in the preheating tower and kiln. Factors such as poor combustion, overheating, blockages, flame loss or misfiring, and material buildup may increase the likelihood of these hazardous events.

In view of the interdependence of the firing system and the complex interactions between its components, any deviation in one part (e.g., the preheater tower) can significantly affect the overall stability and increase operational risks. Most costly risks are interconnected and arise from a combination of human error, equipment malfunction, and process deviations.

Technical failures and process deviations are inherent during the clinker manufacturing process. The heating process involves handling massive quantities of hot materials, the accidental release of which can have serious, even fatal, consequences, as in the case of pyroclastic materials from a volcanic eruption. The process also requires the control of a wide range of parameters that are difficult to measure accurately. The harsh operating environment, characterized by prolonged exposure to high temperatures, material friction, heavy loads, mechanical stresses, dust, fumes, vibrations, buildup, chemical attacks from hot materials and corrosive gases, as well as rapid chemical and physical transformations and continuous material transfer, makes equipment highly subject to wear and damage, which increases the risk of process malfunctions and deviations.

In addition, the complex nature of the systems and the continuous production program require human involvement at all stages of the clinker manufacturing process. Many frequent interventions, such as removing cyclone blockages, cleaning hot material leaks, performing maintenance, and conducting inspections, pose significant challenges for the workers. These tasks are particularly dangerous due to a number of factors, including high temperature and gases, confined spaces, heavy lifting, repetitive movements, and cramped environments. Over time, these labor-intensive and time-sensitive tasks place significant workload and stress for workers. This negatively impacts their overall performance and increases the rate of human error and accidents. Furthermore, inadequate ergonomic design can exacerbate these risks by hindering the timely detection of abnormal conditions and the implementation of appropriate mitigation measures. This can impair operators' ability to adapt to changing process conditions and restore stable operations. As a result, the inevitable leakage of hot materials, for example, can create direct contact with employees and may lead to accidents.

Workers are often confronted with time-sensitive scenarios that demand rapid decision-making, such as the emergency removal of sudden cyclone blockages. Under considerable pressure to minimize downtime, they may bypass critical safety measures or make hasty decisions, thereby ineffectively managing operational disruptions. This compromises their ability to adapt to changing conditions and restore stable operations. Furthermore, even minor errors or miscommunication can increase the likelihood of further complications and safety hazards in high-risk environments. In fact, more than 90% of accidents in the cement industry are linked to unsafe behaviors [10].

This recognition of inherent risks, influencing factors, and safety barrier limitations, along with the critical need for their evaluation, provides the fundamental rationale for the present

thesis, which aims to develop an integrated framework for conducting risk analysis and modelling the performance of safety barriers in complex industrial installations, specifically the cement firing system (also referred to in this thesis as the heating area/zone or pyro-processing unit).

The pyro-processing unit is the most critical stage in the manufacturing process, which justifies its selection as the focal point of this analysis. Its importance is accentuated by the following factors:

- The continuous operation 24 / 7 in particular the kiln, where any downtime is highly disruptive to production;
- Hazardous energy is continuously generated, transferred, contained, and dissipated throughout operation, particularly during transient states such as start-up, shutdown, upset events, and process deviations; any loss of control can produce immediate, irreversible, and intolerable consequences;
- Strong bidirectional interdependencies across units, where failures can rapidly escalate and result in severe safety and operational consequences;
- The presence of large quantities of hot materials at high temperatures up to 1450 °C, creating the potential for uncontrolled release;
- Several control parameters, involving considerable operational consequences in the event of losses;
- Product quality and costs;
- The majority of process improvement opportunities lie in this specific area.

Problem Statement

As discussed above, many of the adverse scenarios arising in the cement heating zone are complex and prone to escalation. This is largely due to the interdependence between units and the properties of hot meal, such as its liquid tendency to escape, wide temperature range, and high energy content, which make it especially hazardous. Spilled hot material presents a severe risk, as its surface may appear cool during cleaning while retaining substantial latent heat, thereby posing significant danger to both workers and equipment, similar to the material from a pyroclastic eruption.

To mitigate such scenarios, it is necessary to systematically identify and manage the technical, human, and organizational factors that influence both triggering events and the performance of safety barriers. Since degradation or failure of barriers can directly lead to dangerous consequences, it is essential to maintain their optimal performance throughout the facility's lifecycle in order to prevent abnormal releases and their subsequent aggravation.

Hot materials are present in large quantities throughout the heating zone, which under normal operating conditions functions as a closed system at high temperature and negative pressure. For safe operation, continuous monitoring of critical parameters such as temperature, pressure, and flow rate is required. In practice, however, abnormal and emergency conditions may arise, including overpressure, overheating, false air ingress, backdrafts, loss of flame, cyclone blockages, ring formation in the kiln, snowmen in the cooler, seal failures, and crusher

blockages, among others. Each of these conditions creates potential escalation pathways and therefore requires systematic analysis.

Of these, cyclone blockage and loss of flame are the most frequent unforeseen adverse events that can have major consequences, involving the release of massive quantities of hot materials. Failing to detect, remove blockage, and recover stable operation in real-time increases the likelihood and severity of fires and explosions, resulting in unplanned shutdowns and production losses.

To address and manage these upsurge risk levels, this thesis proposes a hybrid methodology that integrates the strengths of traditional risk analysis approaches with consideration of risk-influencing factors. Such a framework improves the capacity to anticipate and evaluate deviations, while providing a more adaptive basis for modeling safety barrier performance under real operating conditions in the cement firing system. The overarching objective is to prevent uncontrolled releases and, more critically, escalation scenarios such as fires or explosions.

Based on a case study, the main scenarios examined in this work will be hot material spills, and explosions.

Methodology

The firing system operates under extreme temperatures with complex hot material flows and tightly interdependent processes. These inherent characteristics pose major challenges in controlling safety and operability risks, particularly those linked to hot material releases, explosions, and equipment failures. Traditional safety assessments often fail to capture the full extent of these interdependencies and the combined influence of technical, human, and organizational factors, underscoring the need for more integrated and comprehensive risk management frameworks.

To address this gap, the present research adopts an integrated approach combining HAZOP, BORA, and RCA, as summarized in Figure I.1. The methodology is structured into four main steps:

1. HAZOP Analysis: Based on the thermodynamic behavior of the hot meal and key process variables (temperature, pressure, and flow rate), HAZOP is conducted to systematically identify potential safety and operability deviations;
2. BORA Assessment: For the critical scenarios identified by HAZOP, BORA is applied to evaluate the effectiveness of safety barriers, modeled as Independent Protection Layers (IPLs). Two representative scenarios are considered: *(A) uncontrolled release of hot meal* and *(B) explosion*;
3. Root Cause Analysis (RCA): RCA is then used to systematically trace both technical and non-technical causes underlying accident scenarios, mapping their potential consequences. While RCA is traditionally a post-event tool, it is also applied proactively to scenarios from HAZOP and BORA to anticipate root causes and guide preventive actions;

4. Recommendations: Finally, targeted recommendations are suggested to mitigate the identified risks and reinforce preventive measures against future accidents.

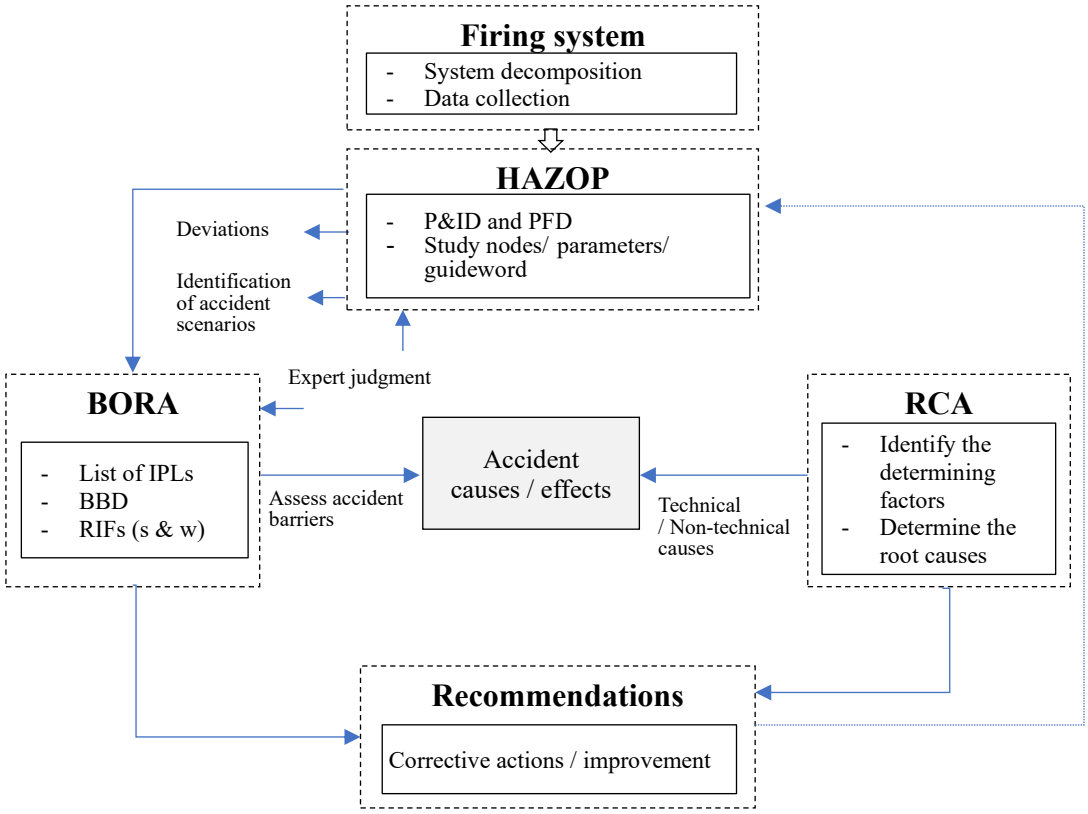


Figure I. 1: Integrated HAZOP–BORA–RCA Methodological framework

This framework systematically addresses the identification, assessment, and mitigation of accident scenarios. It integrates the strengths of HAZOP, BORA, and RCA to provide a complementary approach to hazard analysis, safety barrier evaluation, and the continuous improvement of corrective actions. By covering both preventive and reactive dimensions of risk management, it provides robust control over safety and operability risks inherent in complex cement manufacturing operations.

The following section outlines the organization of the thesis and provides an overview of its five chapters.

- **Chapter 1** outlines the risk analysis process and reviews the main methods, emphasizing their advantages and limitations.
- **Chapter 2** examines the concept of safety barriers, their classification, functions, performance, and role in preventing and mitigating major accident scenarios.
- **Chapter 3** presents the theoretical foundations of the BORA method, including its underlying principles and the consideration of risk-influencing factors. It also examines its practical implementation through a case study of an industrial firing system.
- **Chapter 4** presents the application of the proposed integrated risk analysis methodology to the clinker manufacturing process. It addresses the assessment of accident scenarios,

safety barrier performance, and risk-influencing factors, while exploring the transferability of approaches initially developed in the oil and gas sector.

- **Chapter 5** evaluates the feasibility of the proposed methodology, examines the robustness of the results through sensitivity analysis, and provides practical recommendations for loss prevention strategies in the cement industry, with particular focus on pyro-processing operations.

Chapter

1

Foundations of Risk Analysis — Background and Methods

1.1 Introduction

Adverse events are inevitable in all industrial domains, from manufacturing to the operation of complex infrastructure system. Some events are minor, while others disrupt operations and lead to serious health, safety, and environmental consequences. A thorough risk analysis is essential for identifying critical system vulnerabilities. However, modern industrial systems are becoming increasingly complex. They are characterized by interdependencies, high variability, and rapid technological progress. This presents substantial challenges for traditional assessment methods, which often fail to accurately quantify risk and convey associated uncertainties. As such, these environments require not only a complete understanding of system components, but also an adaptive approach to deal with the evolving nature of risk factors.

From a foundational perspective, risk is the measure of uncertainty about future events and their potential consequences for defined objectives. Contemporary risk science often represents risk as a set of triplets: scenarios, their likelihoods, and their consequences. This explicitly captures both epistemic uncertainty and the natural variability of events. Accordingly, risk analysis addresses three foundational questions: What can go wrong? How likely is it? And what are the consequences? It proceeds by identifying hazardous scenarios, modeling causal pathways and barrier performance, and estimating potential outcomes.

This chapter lays the foundations for risk analysis. It begins by describing the iterative processes of risk identification, analysis, and evaluation. It then illustrates how these processes guide subsequent decisions regarding risk treatment, monitoring, and communication. Finally, the chapter presents various risk analysis methods tailored to the specific context and research problem of the industrial facility under study.

1.2 Risk Analysis

Risk analysis is a systematic study that aims to identify and describe what can go wrong, why it might occur, how likely it is, and what consequences it may produce. Its main objective is to describe the risk, that is, to present an informative picture of risk scenarios, their likelihoods, and their impacts. The level of detail in a risk analysis depends on the context and the purpose of the analysis and the available information, data, and resources. The analysis may be conducted with varying levels of detail and complexity. It may take the form of a qualitative, semi-quantitative, quantitative approach, or a combination of these, and relies on the application of various flexible approaches and techniques [11, 12].

A proper understanding of the risk analysis process requires a clear definition of key concepts: risk, hazards, consequences and uncertainty.

1.3 Definitions of Risk

Risk is a multidimensional concept that goes beyond the simple combination of probability and severity. It also encompasses the uncertainty of the consequences of an activity in relation to specific objectives.

1.3.1 Definitions Based on Probability and Severity/Consequence

Most traditional definitions characterize risk as a combination of an event's probability and the severity of its effects.

According to Haimes (2011), risk is commonly defined as *"a measure of the probability and severity of adverse effects"* [13].

Similarly, ISO/IEC Guide 51 (2014) defines risk as *"the combination of the probability of occurrence of harm and the severity of that harm". The probability of occurrence includes the exposure to a hazardous situation, the occurrence of a hazardous event and the possibility to avoid or limit the harm* [14].

Aven (2010) defines risk as the combination of the probability of an event and its consequences, which can be expressed mathematically as R=F×M, where F is frequency and M is the magnitude of the consequences [15].

1.3.2 Definitions Focused on Uncertainty and Objectives

ISO standards offer a broader definition that emphasizes uncertainty and an organization's objectives.

ISO 31000 (2009, 2018) defines risk as "*the effect of uncertainty on objectives*" *[16, 17].*

1.3.3 Definitions Focused on Broad Perspective

A broader perspective emphasizes the two fundamental dimensions of risk: consequences and uncertainties [12].

Risk is the two-dimensional combination of consequences and associated uncertainties [15]. This definition means that an activity has consequences (C) and that these consequences are unknown [12]. Uncertainty (U) refers to the fact that events and consequences are unknown, including underlying factors, and its degree depends on the assessor's knowledge.

The concept of risk is inherently linked to two other fundamental notions: hazards and consequences.

A hazard is the potential source of harm that, if realized, leads to a specific set of consequences. A consequence is the *outcome of an event affecting objectives* [14].

Uncertainty encompasses a wide range of concepts, including intrinsic variability that cannot be eliminated (aleatory) and lack of knowledge that can be reduced through research (epistemic), as well as linguistic vagueness and decision-related ambiguity shaped by values and judgments. It may arise from assumptions, data variability, model limitations, unpredictable events, systemic issues, or the limits of human cognition. While not all uncertainty can be fully understood or controlled, recognizing its presence enables the implementation of proactive measures, such as early warning systems and resilience-building strategies, to cope with unexpected circumstances [18].

1.4 Risk Assessment Techniques as Per ISO/IEC 31010

The international standard ISO/IEC 31010:2009/2019 serves as a guide for how to select and apply risk assessment techniques, complementing the principles and processes defined in ISO 31000 "*Risk management — Principles and guidelines*". It provides a comprehensive taxonomy of methods for systematically identifying, analyzing, and evaluating risks in different sectors and contexts.

Within this framework, and as shown in Figure 1.1, risk analysis is a fundamental component of risk assessment, which comprises three sequential stages: risk identification, risk analysis, and risk evaluation. These stages form part of the broader iterative risk management framework, with each playing a critical role in recognizing and managing risks.

Risk identification is the systematic process of identifying sources of risk, potential impacts, and triggering events. This process relies on suitable tools, updated information, and expert input, while also considering possible cascading and cumulative impacts, and scenarios. This supports more thorough analysis and informed decision-making.

Risk analysis is the process of thoroughly understanding risks by examining their sources, causes, potential consequences, likelihood, and existing controls; it provides essential input for deciding whether risks require treatment. This analysis considers the complexity of risk impacts, such as cascading, cumulative, and interdependent effects—and emphasizes that both qualitative and quantitative approaches may be used, depending on available information, resources, and the decision context, with all assumptions and uncertainties clearly communicated to support decision-making [16].

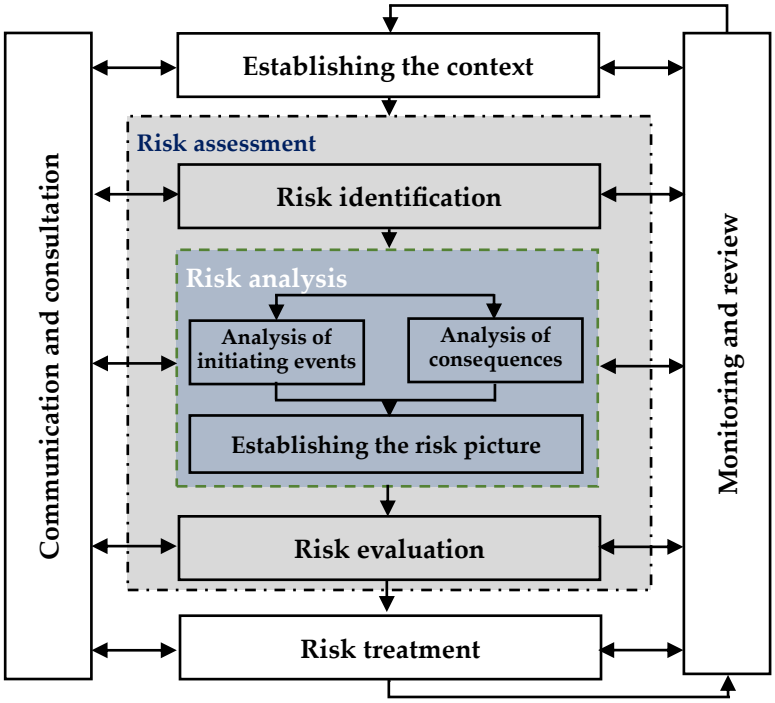


Figure 1.1: Risk management process (adapted from (Iso, 2009))

Risk evaluation is the process of comparing analyzed risks against established criteria to support informed decisions on which risks require treatment and how to prioritize them; it takes into account organizational risk tolerance, broader legal and stakeholder contexts, and may

result in further analysis, maintaining controls, or other actions based on both the level of risk and the organization's established attitude toward risk [16].

The selection of an appropriate tool or technique is essential for effective risk assessment. Although each method uses a distinct approach, their common objective is to systematically identify potential hazards and establish a solid framework for risk management. The ISO/IEC 31010:2019 standard provides guidance on this process and recommends selecting techniques based on key characteristics such as their intended application, organizational scope (enterprise-wide, departmental, or process/equipment level), relevant time horizon (short-, medium-, or long-term), decision level (strategic, tactical, or operational), data requirements, level of expertise required, qualitative or quantitative orientation, as well as the time and resources needed [18].

1.5 Type of Risk Assessment Technique

ISO/IEC 31010:2019 classifies risk assessment techniques into distinct categories to address specific aspects of the risk management process. Examples include expert elicitation methods (such as brainstorming and the Delphi technique), risk identification tools (like checklists, FMEA, FMECA, HAZOP, and SWIFT), and analysis approaches for sources and causes (including the cindynic approach and Ishikawa/fishbone method). There are specialized techniques for analyzing controls (e.g., bow tie analysis, HACCP, LOPA), understanding consequences and likelihood (Bayesian analysis, ETA, FTA, Markov analysis, Monte Carlo simulation), and those that explore dependencies and interactions (causal mapping, cross impact analysis). Other methods measure risk directly (value at risk, toxicological risk assessment), evaluate significance (ALARP, SFAIRP), support choice among options (cost/benefit analysis, decision tree), and facilitate the recording and reporting of risks (risk registers, S-curves) [18].

In Tzanakakis (2021), risk assessment techniques are organized into six main categories: look-up methods such as (checklists and PHA), supporting methods (structured interviews, brainstorming, and the Delphi technique), scenario analysis (RCA, FTA, ETA, and cause-and-effect analysis), function analysis (FMEA, FMECA, and HAZOP), controls assessment (bowtie analysis), and statistical methods (Monte Carlo simulation) [19].

1.6 Methodological and Logical Classifications

Risk assessment techniques are commonly classified by their methodological approach, which can be qualitative, semi-quantitative, quantitative, or hybrid, but other classifications exist based on different criteria, such as inductive or deductive, deterministic vs. probabilistic, or static vs. dynamic.

1.6.1 Qualitative vs. Quantitative

Qualitative methods, for example brainstorming, depend mainly on expert opinion and descriptive information. They are useful when dealing with complex situations or when data are scarce, because they allow risks to be categorized and prioritized in a flexible way.

In contrast, quantitative approaches such as Monte Carlo simulations use numerical data and models to quantify risks, i.e., to estimate the probability and impact of risks.

The combination of qualitative insights and numerical data in semi-quantitative and hybrid methods links the dimensions of risk analysis that are subjective and objective.

Further exploration of these methodologies will be conducted in Chapter 2.

1.6.2 Inductive vs. Deductive

From a logical perspective, inductive methods, i.e., a "bottom-up" procedure, such as FMEA, ETA and HAZOP begin with specific causes or events and work toward to maps their possible outcomes. They explore "*what could happen*" if certain events or failures occur.

On the other hand, deductive methods, i.e., a "top-down" procedure, like FTA, RCA and Cause-Consequence Analysis, start from a known outcome and work backwards to identify root causes. They answer "*how could this happen*" [18, 20].

1.6.3 Deterministic vs. Probabilistic

Deterministic methods are based on the assumption of fixed values or scenarios, which neglects uncertainty. Although these methods are simple and clear, they often lack feasibility when applied to complex systems. Within this framework, sensitivity analysis explores how modifications in a single parameter affect the overall result, whereas worst-case scenario analysis emphasizes potential hazards stemming from the most unfavorable possible conditions. On the other hand, probabilistic methods directly consider uncertainty by introducing probability distributions into the evaluation. As an example, Bayesian analysis improves risk predictions through iterative updating of probabilities as new evidence is collected, while stochastic modeling applies random inputs to simulate diverse potential scenarios [18, 20].

1.6.4 Static vs. Dynamic

Static methods assess risk using historical or fixed data, providing a one-time evaluation under the assumption of steady-state conditions. They depend greatly on prior experiences and fail to account for changes in operations, human behavior, or emerging threats. Therefore, static risk analysis is most suitable for stable, predictable contexts in which risk factors remain relatively constant over time [21]. A common example is a Risk Register, which documents risks and their attributes at a specific moment [18].

Dynamic methods, on the other hand, emphasize continuous and adaptive risk evaluation. This approach accounts for changes over time, such as evolving system conditions or time-dependent risks. It allows updating risk profiles in response to new data, threats, or environmental changes. This makes it ideal for unpredictable, high-risk settings like cybersecurity or emergency response, where risks evolve and immediate action is necessary [21]. Examples include Dynamic Fault Tree Analysis [22] (which incorporates time-dependent failure probabilities) and Markov Analysis (which models state transitions over time to assess risk) [18].

Each of these methods possesses distinct advantages and limitations. Given their intended application throughout this thesis, a detailed analysis will be provided for the HAZOP, FTA, LOPA, and RCA methods, each of which has unique advantages and limitations.

1.7 Hazard and Operability (HAZOP) Studies

A HAZOP (Hazard and Operability Study) is a structured and systematic examination of a process, procedure, or system. Its purpose is to identify potential deviations from the design's intent and explore their possible causes and consequences [18]. This qualitative technique is widely applied to determine operational deviations in parameters like temperature, pressure, or flow rate, etc. This systematic approach is not only useful in the initial design phase, but also throughout the entire life cycle of the plant [23].

HAZOP was first developed as a technique for systems in which fluid or other material flows are involved in the process industries and is now a major component of process safety management. It was standardized in 2001 through IEC 61882 and relies on the expertise of a multidisciplinary team, supported by design and operating documents such as P&IDs and PFDs [24].

During a HAZOP study, the first step is to break down the process into simpler sections, known as study nodes. Deviations are then generated by combining process parameters with specific guide words [25]. Once deviations are identified, the subsequent step is to determine the causes and consequences. Lastly, safeguards are developed to alleviate or eliminate the risks associated with these deviations. The procedure is then repeated for each node in the system [23].

Despite their widespread acceptance and use, HAZOP methodologies have significant advantages and limitations that need to be examined in detail.

One of the main advantages of HAZOP is its structured methodology and reliance on a multidisciplinary team, which allows for the comprehensive identification of potential hazards and operability issues. This method proved to be effective in revealing potential dangers that may not be immediately evident during the initial planning phases. Its comprehensive scope allows teams to contemplate various scenarios, improving their understanding of risk factors [26]. In addition, HAZOP's participatory nature encourages the interdisciplinary collaboration between the interested parties, promoting diverse perspectives in the evaluation of potential risks [27].

However, despite its advantages, a remarkable challenge lies in the significant dependence on the skills and experience of the facilitator and team members, who can introduce subjectivity and bias in the process [28]. HAZOP's effectiveness depends on the team's ability to think critically about potential deviations; If the participants do not have the competence of the pertinent domain, the significant dangers can remain unidentified or scarcely evaluated [29]. In addition, the scope of HAZOP can also impose limitations. It focuses mainly on the identification of the dangers from deviations in the design and operation, but can be underacting latent risks associated with external factors or operational changes. As the industries evolve, in particular with the greater connectivity and the emergence of digital technologies, new risks may present that traditional HAZOP methodologies are poorly equipped to fully understand [30]. Moreover, as a qualitative method, it does not quantify risk with numerical values and may be less effective at identifying complex, multi-component failures or human-error-driven incidents.

Although HAZOP is particularly strong in the early stages of process design, it may encounter difficulties during the operational phases. For example, complexity and operational

variability in real time can be misaligned with the static nature of traditional HAZOP studies [31]. Another concern that surrounds HAZOP is the potential for incomplete analysis due to time constraints or resources limitations. In a sector characterized by tight deadlines and budgetary constraints, the pressure to rush often leads to an insufficient exploration of all paths and scenarios [32]. In addition, the need for a thorough recording of discussions, danger identifications and recommendations during HAZOP sessions can be managed badly, negatively influencing the traceability and usefulness of the results [33].

Over and above that, HAZOP's reliance on systematic procedures can unintentionally lead to a “box check” logic, where teams conduct the analysis out of obligation rather than a sincere effort to identify hazards [28]. This phenomenon can reduce the quality of the results, as the focus is shifted from identifying the actual hazard to simply performing the study.

HAZOP's integration with other risk assessment methods can help mitigate some of these limitations. For example, its combination with a quantitative risk approach can provide a visual representation of risk priorities, facilitating a more effective decision-making process regarding risk control measures [26]. These additions can help to fill the gaps in analysis, aligning HAZOP with other methodologies to produce a more complete understanding of potential dangers. Moreover, a successful implementation requires thorough training and a collaborative environment as well as periodic revaluation and updates to incorporate different insights and perspectives.

1.8 Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is a systematic, top-down technique widely used to identify and analyze the factors contributing to a specific undesired event, known as the “top event”. The process begins by defining the top event and then methodically traces its immediate and contributing causes, which may include hardware or software failures, human errors, or other relevant factors. These causes are illustrated in a tree diagram, using logical gates like AND and OR to display the interrelationships: AND gates require all input events to occur for the top event, while OR gates imply that any one input can trigger the top event [18].

FTA (see Figure 1.2) can be performed qualitatively to map out the different potential pathways leading to failure, or quantitatively to calculate the probability of the top event's occurrence. Quantitative analysis relies on logic and Boolean algebra. This ensures that events under AND gates are collectively sufficient and individually necessary, while events under OR gates represent all possible failure scenarios [34].

FTA is an invaluable tool for mitigating risks, as demonstrated by its successful application in various critical sectors where the implications of failure can be catastrophic, such as aviation, medical care, and nuclear energy [35]. It was standardized in 1990 through IEC 61025, FTA is useful in the design and operation stages. In the design stage, it helps compare options. Whereas in the operation stage, it helps understand how major failures might occur and which pathways are most critical. Effective FTA requires a thorough understanding of system behavior under various conditions. It also requires detailed diagrams and quantitative data. For example, failure rates, frequencies, and repair statistics for all base events. For complex situations, the use of software and a strong grasp of probability theory and Boolean logic is essential. The outputs of FTA include a graphical representation of all pathways to the top event, a list of minimal cut

sets and if data permits, the calculated probability of the top event as well as the significance of each contributing factor [18].

One of the main remarkable advantages of FTA is its systematic approach to identifying potential failures, which leads to a broad understanding of risk within a system. Its graphical representation makes it possible to visualize complex relationships between several components and their failures. This technique not only helps identify weak points [36] but also enables the evaluation of both individual components and their interactions at the system level. Thus it provides a more solid evaluation of possible operational failures [37], ultimately helping to prioritize risk management efforts.

Moreover, FTA provides a framework for both qualitative and quantitative evaluation of the top event. It can be used as a valuable tool to identify potential hazards and avoid redundant design modifications. It can also be used as a diagnostic tool, predicting the top event in a system breakdown or failure [36].

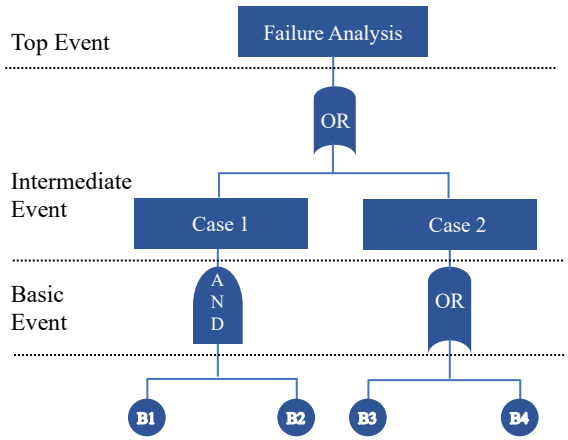


Figure 1.2 Basic Fault Tree Structure

However, despite its advantages, the FTA comes with various limitations and challenges in the practical application. The relevance of FTA is often limited in modern, dynamic environments due to its inability to incorporate real-time data and dynamic variations [38]. Furthermore, its development for complex systems is a challenging process that requires substantial experience and a profound understanding of the system. The method's reductionist approach can ignore critical interdependencies and interactions between the different failure modes, which can lead to an incomplete risk assessment [39]. In addition, FTA's dependence on subjective inputs can introduce biases and inconsistencies into the analysis, particularly when appropriate data is unavailable or when estimates are based on personal experience instead of empirical evidence [40]. This limitation makes it difficult to effectively handle the ambiguities and uncertainties of basic events [41].

1.9 Layer Of Protection Analysis (LOPA)

LOPA is a semi-quantitative risk assessment methodology used to identify and evaluate the effectiveness of multiple layers of protection that prevent or mitigate hazardous events [42]. It aims to identify potential hazards and high-risk scenarios, assess the probability and impact of each scenario, identify and assess the effectiveness of existing safeguards and determine the

required risk reduction to meet safety targets [43]. Risk tolerance criteria are defined based on these assessments to ascertain whether the current layers of protection are adequate or if additional measures are required [44].

LOPA is not governed by a single, prescriptive standard but is instead a semi-quantitative risk assessment technique that is widely accepted in the process industries. Its application and principles are consistent with the requirements of functional safety standards like IEC 61511, which outlines a framework for managing SISs. Annex F of IEC 61511-3 specifically provides guidance on LOPA as a method for determining Safety Integrity Levels (SILs), and it is further detailed in IEC 31010.

LOPA analyses how much a set of controls reduces risk. It can be considered as a specialized type of event tree analysis, often performed after a HAZOP study.
LOPA works by first identifying a specific cause-consequence pair, and then identifying the Independent Protection Layers (IPLs) that prevent the scenario from reaching its undesired outcome. An IPL is any device, system, or action that is:

- Independent: It must be separate from the initiating cause and any other protection layers for the same scenario.
- Effective: It must be capable of preventing the negative consequence.
- Auditable: Its reliability can be verified and proven.

These layers can include design features, physical protection devices, interlocks and shutdown systems, critical alarms and manual intervention, post-event physical protection, and emergency response systems [18].

Figure 1.3 presents an example of LOPA analysis

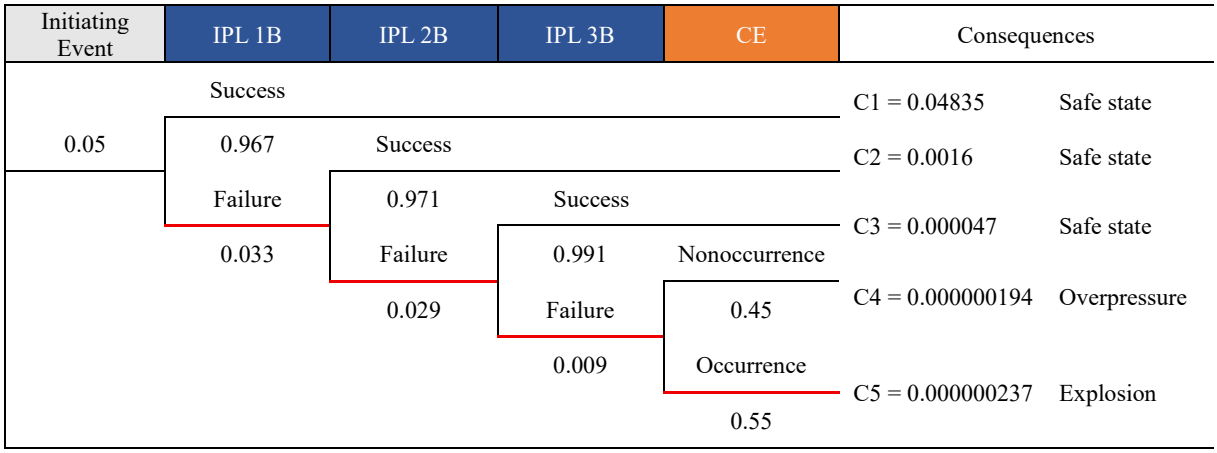


Figure 1.3: An example of LOPA analysis

The frequency of occurrence of the undesired consequence can be found by combining the frequency of the initiating cause "event" with the probabilities of failure (PFD) of each IPL.

$$Frequency_{Undesired\ Consequence} = Frequency_{Initiating\ Cause} \times PFD_{IPL1} \times PFD_{IPL2} \times ..... \times PFD_{IPLn} \quad (1)$$

The central advantage of LOPA is found in its structured evaluation of risk scenarios together with the identification of independent protection layers (IPLs). It not only helps determine the need for additional protection measures, but also provides a clear reason for the allocation of

resources towards the most critical safety systems. LOPA enables organizations to prioritize their risk management efforts based on quantified evaluations of severity and probability, thereby supporting informed decision-making without overwhelming analytical loads.

Furthermore, its capacity to adapt to various sectors contributes to its significant versatility, making it highly relevant in a wide range of contexts, including oil & gas, health, and energy production. This has shown remarkable efficacy in sectors such as chemical processing and mining, which are characterized by complex operating environments and inherent risks [45, 46].

In spite of its advantages, implementing LOPA presents sector-specific challenges, as the inherent complexity and variability of industrial processes make precise application difficult. In industries with highly interconnected systems, such as chemical manufacturing or oil and gas production, interdependencies further complicate the identification and evaluation of protective layers [47, 48].

In addition, improper treatment of initiating events and IPLs can result in significant calculation errors. A common erroneous assumption is that all IPLs offer equivalent reliability, which is rarely the case. Their effectiveness is highly dependent on design as well as operational context, including potential failure modes and external challenges [48]. Furthermore, LOPA accuracy depends on the quality and availability of data on the likelihood of IEs and the reliability of protective layers performance. In sectors where historical data is scarce or non - reliable, evaluations may be less robust, resulting in an incomplete understanding of the real risks involved.

1.10 Root Cause Analysis

Root cause analysis (RCA) is a systematic problem-solving methodology widely used to investigate adverse events and accidents in various industries. Standardized in IEC 62740, it aims to find out the root causes of problems, ensuring that corrective actions are effectively directed to avoid recurrence of similar incidents [49-51]. The goal is to understand not only what went wrong, but why it happened [52].

RCA plays a crucial role in industrial processes by identifying the root causes of process or equipment failures, thereby enhancing quality, dependability, and safety [50]. Rather than being a single technique, it incorporates a variety of tools, such as Events and causal factors (ECF), Causes tree method (CTM), Why-because analysis (WBA), Fault tree and success tree method, Fishbone Diagram, Mind mapping, 5 Whys and Causal analysis for systems theoretic accident model and process (STAMP) (CAST) among others. RCA is fundamentally retrospective and heavily relies on the identification of an incident [53].

The steps in RCA (see Figure 1.4) are as follows: define the problem (what happened, when, where, and who is involved); collect data; identify the root causes; and develop solutions. This systematic approach to data collection and analysis allows for a detailed examination of incidents, while also promoting collaboration between teams [54] and fostering a culture of continuous improvement [55]. Ultimately, RCA helps identify and analyze recurring issues, enabling decision-makers to implement viable solutions.

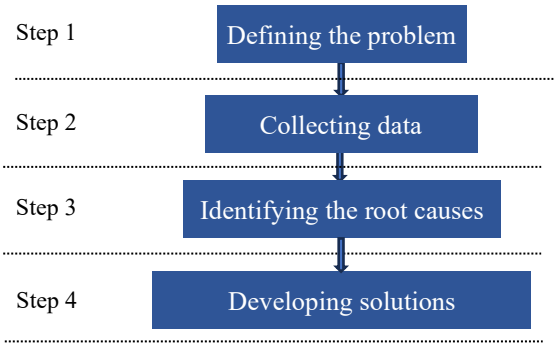


Figure 1.4: RCA main steps

RCA can be carried out at various levels of decomposition. For example, it can be conducted from the system to the component level, or different events or outcomes can be selected as the starting point. The appropriate level for conducting the analysis depends on the focus event. Furthermore, RCA can be applied to any focus event whether success or failure which offers benefits such as deeper insight into events, identifying problem sources to enable corrective action and prevent recurrence, revealing causes behind positive outcomes for repeatability, finding more effective responses to issues, ensuring efficient achievement of investigation objectives, enhancing consistency across similar investigations, and increasing objectivity in event analysis [53].

Despite its widespread use, the implementation of RCA can face challenges that compromise its effectiveness in real-world situations, most notably cognitive bias and poor application. Cognitive bias, such as confirmation bias, may cause investigators to prioritize evidence that supports their pre-existing views while discounting contradictory information [51]. Additionally, a superficial or misguided application of RCA often results in incomplete diagnoses and the implementation of temporary measures, rather than viable solutions [56].

After reviewing the main risk analysis methods, it becomes clear that no single approach is sufficient to capture the full range of risks present in complex systems. Table 1.1 gives a comparative overview, outlining the typical strengths and limitations of the methods considered. Since each method highlights certain aspects while overlooking others, a thorough risk analysis should move beyond reliance on a single methodology. Instead, it benefits from an integrated framework that better accounts for the systemic complexity and interdependent nature of modern systems.

Table 1.1: Summary and classification of risk analysis methods

Method	Strengths	Limitations	Standard	Application	Classification			Risk assessment process				
								Risk identification	Risk analysis			Risk evaluation
					Qual/quant/ semi-quant	Inductive/ Deductive	Deterministic Probabilistic		C	P	Level of risk	
HAZOP	- Systematic and structured approach - Identifies deviations and potential hazards - Encourages multidisciplinary team discussions	- Time-consuming and resource-intensive - Subjective; depends on team expertise - Does not quantify risk	IEC 61882	Identify and analyse risks	Qualitative	Inductive	Deterministic	✓✓	✓	✗	✗	✗
LOPA	- Semi-quantitative; balances qualitatives and quantitative aspects - Identifies independent protection layers (IPLs) - Provides risk ranking and decision-making support	- Limited to predefined scenarios - Requires accurate failure rate data - Assumes independence of protection layers	Referenced and guided by the IEC 61511 Listed in ISO/IEC 31010:2019	Analyse controls	Semi-quantitative	Deductive	Both	✓	✓✓	✓	✓	✗
FTA	- Deductive, top-down approach to identifying root causes - Quantifies probabilities of failure - Useful for system reliability analysis	- Requires detailed knowledge of system components - Complex for large systems - Cannot easily model dependencies between failures	IEC 61025	Analyse likelihood Analyse causes	Qual/quant	Deductive	Both	✓	✗	✓✓	✓	✓
ETA	- Forward-looking, identifies possible event outcomes - Supports probabilistic risk assessment - Useful for evaluating safety system effectiveness	- Needs precise event probability data - Can become large and complex for multiple branching scenarios - Does not easily capture dependencies between events	IEC 62502	Analyse conseq. and controls	Qual/quant	Inductive	Probabilistic	✗	✓✓	✓	✓	✓

Table 1.1 (continued)

RCA	- Systematic process to identify underlying causes - Applicable across industries and event types - Can use multiple tools and techniques - Helps prevent recurrence by addressing true source of problems	- Effectiveness depends on correct method/tool selection and application - Can be time-consuming, especially for complex issues - May be limited by cognitive bias and incomplete information	IEC 62740	Analyse causes	Qualitative	Both (depending on the technique applied)	Both (depending on the technique applied)	✓	✓	✗	✗	✗
Bowtie Analysis	- Visual representation of risks, causes, and consequences - Clearly links preventive and mitigative barriers - Easy to communicate to stakeholders	- Does not provide quantitative risk values - Can oversimplify complex systems - Highly dependent on expert judgment	No IEC standard Listed in ISO/IEC 31010:2019	Analyse risk analyse controls describe risk	Qual/semi quant	Both	Both	✓	✓✓	✓	✓	✓
Bayesian Networks	- Probabilistic and data-driven approach - Incorporates uncertainty and conditional dependencies - Updates risk assessment dynamically as new data becomes available	- Requires extensive data for accurate modeling - Complex to develop and interpret - High computational demand	No IEC standard Listed in ISO/IEC 31010:2019	Identify risk estimate risk decide between options	Quant	Inductive	Probabilistic	✗	✗	✓✓	✗	✓✓
Consequence/ likelihood matrix (risk matrix or heat map)	- Easy to use - Allows for rapid ranking of risks according to their significance. - Provides a clear visual display	- Subjective if it has not been properly calibrated and validated - It can oversimplify complex risks	No IEC standard Listed in ISO/IEC 31010:2019	Report and Evaluate risks	Qual/semi quant	Inductive	Deterministic	✗	✓	✓	✓✓	✓

Legend: ✓**:** applicable**;** ✓✓**:** fully applicable**;** ✗**:** not applicable.

1.11 Conclusion

Risk analysis methods are widely used across many sectors, providing systematic approaches to identify, evaluate, and manage risks. Their importance has grown as organizations increasingly operate in environments marked by uncertainty and unpredictability. These methods range from qualitative tools, such as expert judgment, to quantitative techniques, such as probabilistic risk assessment.

Risk analysis approaches can also be classified along several dimensions: inductive vs. deductive, deterministic vs. probabilistic, and static vs. dynamic. No single method, however, is sufficient in every context. The choice often depends on the complexity of the system, the availability of data, and the specific aims of the analysis. A combined use of methods is often the most effective approach for comprehensive analysis.

Because of this versatility, risk analysis can be applied across numerous domains, allowing for tailored measures to address diverse challenges. In practice, these measures often take the form of technical, human, or organizational actions, collectively referred to as safety barriers. The following chapter will explore this topic in detail.

Chapter

2

State of the Art in Safety Barriers: Foundational Theory, Taxonomies, and Contemporary Practices

Chapter 2: State of the Art in Safety Barriers: Foundational Theory, Taxonomies, and Contemporary Practices

2.1 Introduction

Recent research has advanced the conceptual understanding of what qualifies as a safety barrier by emphasizing its definition, classification, performance evaluation and critical roles as integrated systems within complex socio-technical environments. It also delves into how these barriers should be designed, monitored, and maintained throughout a system's lifecycle, underscoring their vital contribution to overall system resilience.

This chapter first reviews key findings from recent studies to address current challenges related to safety barriers outlined in the literature. It aims to deepen the understanding of safety barrier concepts and examine available methods that could be used. A detailed classification of safety barriers will then be presented, highlighting which barriers primarily modify likelihood, mitigate possible outcomes, or achieve both. Finally, the assessment of safety barriers and their role in risk reduction will be discussed.

2.2 Background and Context

The implementation of the safety barrier concept is effectively demonstrated by the International Association of Oil & Gas Producers (IOGP) in its 2008 guidelines, utilizing the Swiss Cheese and Bow-Tie models [57].

In the Swiss Cheese model (see Figure 2.1), safety barriers are represented as layered slices, each containing “holes” that symbolize potential weaknesses or failures in safeguards, such as design flaws, human error or procedural gaps. An incident, or “top event”, occurs when weaknesses align across multiple layers, allowing a hazard to spread. This model emphasizes the fallibility of individual barriers and the necessity of implementing multiple, redundant safety measures, particularly in high-risk environments.

The integration of the Swiss Cheese model with the Hierarchy of Controls (HoC), as shown in Figure 2.1, provides a comprehensive visual representation of multi-level safety barriers. Each control, from elimination to personal protective equipment (PPE), contributes either to the prevention of an accident or to the mitigation of its consequences. This combined model highlights three important principles: (1) the necessity of implementing multiple and diverse safety controls to establish a solid defense-in-depth; (2) the variable effectiveness of controls, with higher-level measures (e.g., elimination and substitution) offering stronger protection than lower-level ones (e.g., PPE); and (3) the potential alignment of systemic weaknesses across the different layers, which enables hazard escalation.

The fallibility of these protective measures is highlighted by the fact that even when several safety barriers are in place, accidents can still occur. Thus, safety barriers must be risk-based, and their specifications must be derived from a comprehensive system-level analysis of the associated hazards, threats, vulnerabilities, and risks. This process culminates in the appropriate implementation of engineering and administrative controls, which require continuous validation and verification throughout the system's lifecycle to ensure that risk remains within acceptable limits.

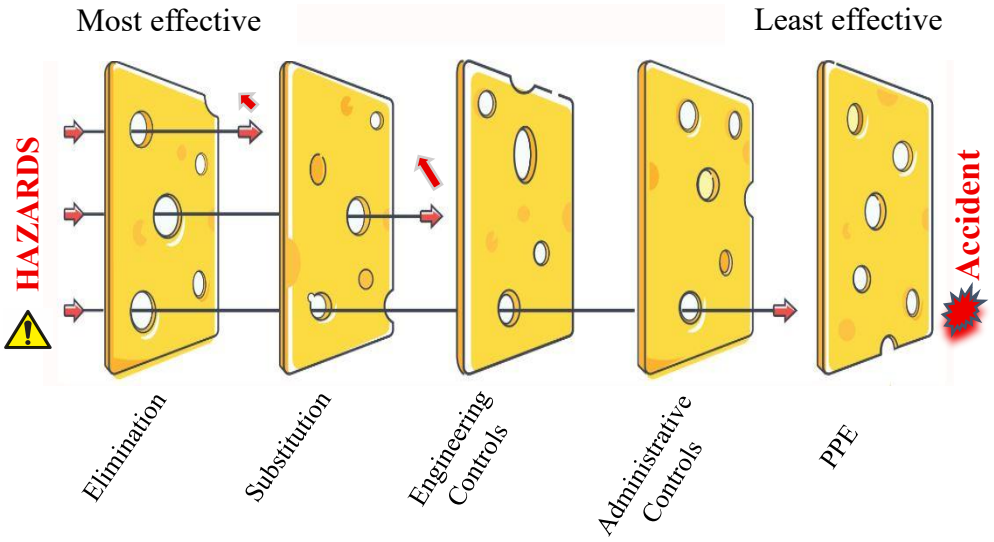


Figure 2.1: Integration of the Swiss Cheese Model and the Hierarchy of Controls

In the second model, the Bowtie method is a semi-quantitative risk assessment tool that graphically depicts the pathways from potential causes (threats) to the ultimate outcomes (consequences) of a central hazardous event, known as the "Top Event". This method systematically identifies the hazard, lists the threats that could lead to a loss of control, and outlines the potential consequences.

The left-hand side of the diagram corresponds to the prevention barriers that are positioned between the threats and the top event to prevent its occurrence. Conversely, the right-hand side illustrates the protective barriers that are placed between the top event and the consequences to lessen their impact. Despite not being governed by an official international standard, its prominence and broad acceptance in both theoretical and applied contexts are largely due to its clarity, focus on controls, and ability to facilitate the effective communication of risk pathways.

Figure 2.2 illustrates a model that combines the traditional bowtie method with the key stages of resilience engineering. The bowtie model visually represents risk by placing the top event at its center. From this central point, the various accident scenarios unfold along paths that extend outwards from left to right.

The left-hand side of the diagram depicts pre-event scenarios, with a focus on identifying threats, preventing them, and monitoring the system's performance. On the other hand, the right side depicts post-event scenarios, emphasizing response capabilities and recovery actions. The different stages—anticipation, monitoring, response, and recovery—are positioned around the central top event, demonstrating their function in improving the system's capacity to withstand and adapt to disturbances. The model demonstrates the comprehensive application of both physical (e.g., sensors, blast walls, dikes) and non-physical barriers (e.g., procedures, training, organizational culture) across all resilience phases. A crucial learning loop emphasizes continuous improvement via feedback, experience, and adaptation. Overall, this framework provides a robust and comprehensive approach to risk management and system resilience.

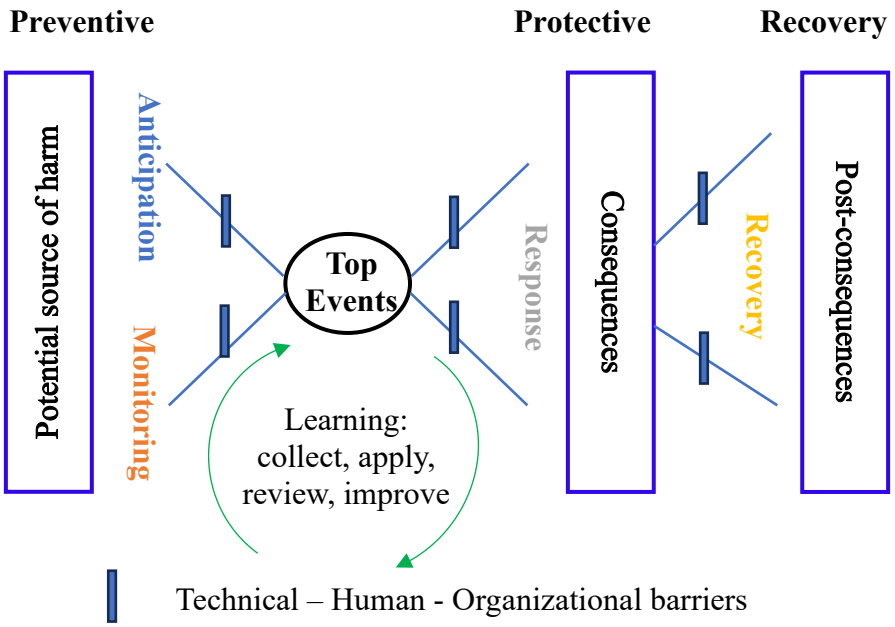


Figure 2.2: Hybrid Bowtie-Resilience Model

2.3 Definitions of Safety Barriers

Although the concept of safety barriers has been extensively discussed in the literature, a universally accepted definition applicable to all industrial sectors is lacking [58-60]. In response to ongoing research and lessons learned from major industrial accidents, a growing number of studies have emerged in recent years emphasizing the critical role of safety barriers in risk management. Various terminologies have been proposed, including layers of protection, defenses, risk-reducing measures [60], safety-critical functions/elements [58], defense-in-depth, as in nuclear power plants [58, 61, 62].

Figure 2.3 presents a word cloud illustrating the most prevalent terms associated with safety barriers, along with the action verbs commonly used to describe their functions.

As established by Sklet's widely recognized research in 2006, safety barriers are defined as "*physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents"*. These means can range from a simple technical unit or human action to a complex socio-technical system. Sklet's work presents a comprehensive overview of the concept of safety barriers, along with their classification and key attributes related to their performance and function [58].

In the ARAMIS project, safety barriers are defined as physical or engineered systems, human actions guided by established procedures, or organizational controls. Each barrier is intrinsically linked to the performance of one or more essential safety functions. These barriers determine how safety functions are implemented within the system. If the barrier is intended to prevent or avoid an event, it is usually positioned upstream of the event in the Bowtie diagram. Conversely, barriers designed to control or limit the consequences of an event should be placed downstream [63].



Figure 2.3: Word cloud about safety barriers and corresponding verbs

The Norwegian Petroleum Safety Authority (PSA, 2013) defines barriers as "*technical, operational, and organizational elements which are intended individually or collectively to reduce the possibility for a specific error, hazard or accident to occur, or which limit its harm/disadvantages"* [64]. Another key definition is that of IOGP (2008): barriers are the functional groupings of safeguards and controls in place to prevent the occurrence of a significant incident [57].

In risk assessment, safety barriers are conventionally defined as deliberate measures implemented to reduce the likelihood and mitigate the consequences of hazardous events. This fundamental definition highlights their crucial role in risk management frameworks, emphasizing the need for a thorough understanding of their complex interactions and overall effectiveness [65].

According to Liu (2025), a safety barrier is defined as "*an entity and/or method introduced to protect an asset from harm caused by existing and potential hazards*" [66]. This definition effectively captures their dual nature: they can be either tangible, physical entities or intangible, procedural, or organizational methods. These barriers are designed to prevent harm by interrupting the causal pathway between a hazard and its potential for damage. Furthermore, their consideration of "existing and potential hazards" explicitly demonstrates a proactive approach to safety, highlighting the critical importance of addressing both established risks and those that may emerge over time.

Building on these foundational definitions, a comprehensive review of the existing literature is crucial for understanding how safety barriers have been conceptualized, categorized, and evaluated across diverse industrial contexts.

2.4 Literature Review on Safety Barriers

Most studies in this field systematically propose various definitions of safety barriers, emphasizing their classification, performance evaluation, and application across diverse industries. Among these, Barkhatov et al. (2022) offer a notable contribution by providing a detailed conceptualization of safety barriers. They define safety barriers as technical safety mechanisms critical for specific functions within industrial settings, particularly in sectors like

oil and gas. Their work further introduces a classification encompassing both technical and administrative safety barriers, alongside performance assessment criteria categorized by efficiency, reliability, and stability [67].

Expanding on the history of safety barrier research, Liu (2020) provided an insightful overview of the concept of safety barriers and discussed the development of research in barrier theory, barrier engineering, and barrier management [60]. Building upon this foundational work, Liu (2025) further extends the definitions, classification, and management of barriers in his book, "*Barrier Engineering: Models and Methods for Technical Safety*," which readers may consult for detailed insights [66].

Likewise, a thorough and systematic review of safety barriers in the chemical process industries is presented by Yuan et al. (2022). The authors focus on the classification, performance assessment and management of these barriers. Safety barriers are categorized based on their function (preventive or mitigative), their nature (physical, procedural, or organizational), and their lifecycle phase (design, operational, etc.). Furthermore, they propose a distinct classification for safety barriers in the process industries, dividing them into three categories: technical, non-technical observable, and non-technical non-observable. The study evaluates various methodologies for assessing barrier performance, paying particular attention to reliability, effectiveness, and resilience. Both qualitative and quantitative assessment approaches are discussed, including risk matrix methods, bow-tie models, and Bayesian networks [62].

In related work, Sobral and Soares (2019) propose a classification of safety barriers and present a methodology to assess the adequacy of safety barriers for a specific hazard that links the safety integrity level (SIL) of the assessed safety barriers to the probability of occurrence of the hazardous event [68].

In other work, Hollnagel (1999) examines the barrier concept through a fundamental distinction between barrier functions, whether preventive or protective and barrier systems, which proposes four different types [69]. The same author further examines the characteristics of this range of barrier systems (physical, functional, symbolic, and intangible) and their relative strengths and weaknesses in [61]. Based on the concept of safety function, Harms-Ringdahl (2009) presents a new method for accident investigation where the analysis proceeds with the identification of safety functions related to the event. Afterwards, they are organized and evaluated whether these functions worked or not [70].

Clarifying the function of safety barrier system and its failures will be effective in reducing potential accidents and their related costs [71]. In a comprehensive review of safety studies in process industrial systems, Zhang et al. (2023) posit that safety barriers are fundamental to system integrity, directly impacting human life and environmental safety through their performance. The primary function of safety barriers is to prevent operations from escalating into catastrophic accidents, thereby emphasizing the importance of reliable safety systems [72].

The systematic review by Qiao et al., (2022) addresses the critical role of safety barriers in risk management across various industries. It aims to provide a comprehensive overview of the field, mapping research networks, summarizing advancements, and proposing future research perspectives based on contemporary theories and methodologies in safety management [59].

Kang et al., (2016) classify safety barriers into three main categories: personnel, organizational, and technological. They further subdivide technological barriers into passive, positive and detection barriers. In addition to this classification, they established a performance evaluation method incorporating three key indicators: degree of confidence, effectiveness, and economic impact [71].

Recent studies show significant progress in research on safety barriers, with a particular focus on digital integration, artificial intelligence (AI) applications, and dynamic performance assessment [66], which are now aligned with the broader emergence of Industry 4.0. This evolution marks a fundamental shift from traditional static approaches toward adaptive, data-driven, real-time monitoring and autonomous decision-making. For instance, the integration of the Internet of Things (IoT) enables predictive maintenance and real-time monitoring [73]. In this regard, the successful deployment of smart sensor networks, such as the "Smartguard" system, has been extensively demonstrated in industrial environments. Studies evaluating their performance report remarkable accuracy, including up to 95% in identifying gas leaks and 96% in detecting obstructions [74]. Similarly, digitization allows the generation and collection of digital operational data, which in turn increases safety assurance and reduce human operation in process control and monitoring [75]. Moreover, dynamic performance assessment supports informed decision-making in barrier establishment, optimization and improvement in a cost-effective manner [76].

In this context, Stefana et al. (2024) applied an automated unsupervised Machine Learning-based clustering technique, an approach that allowed them to systematically navigate and analyze the extensive literature on safety barriers. Their analysis provided a comprehensive overview of the field's main inquiry areas. These include well-established topics such as risk assessment methodologies and quantitative probability estimation, as well as crucial elements like design and management principles, and the practical application of barriers in critical industrial settings. Therefore, their study advocates adopting advanced scientometric methods to gain deeper insights into safety barrier research [77].

Safety barriers, as defined in recent literature, are integrated systems that encompass physical, technical, operational, and organizational elements. Their primary function is to prevent incidents by disrupting the causal chain between a hazard and its potential consequences, while also mitigating the severity of those consequences. Owing to their proactive nature, these barriers demand a comprehensive assessment of both existing and emerging risks. As a fundamental component of system resilience, they enhance the capacity to absorb disturbances, adapt to changing conditions, and recover effectively—ultimately safeguarding assets and minimizing the impact of adverse events.

2.5 Safety Barrier Functions

The functions of safety barriers are multifaceted, uniformly aiming to avert accident risks and diminish their impacts. At its core, a barrier intervenes in a cause-effect pathway, thereby preventing an undesired event [78]. A single barrier can have several safety functions within a system (one or more safety functions) [58, 60].

Key functions can be summarized as follows:

- **Avoid**: Eliminate all potential causes of accidents by modifying the design.

- **Prevent**: Reduce the likelihood of a hazardous or undesirable event occurring.
- **Control**: Limit the extent and/or duration of a hazardous event to prevent escalation or deviations from normal operation.
- **Protect/mitigate**: Reduce the effects of a hazardous event or accident [59, 60, 62, 71, 79, 80].

Hollnagel (2008) introduced a resilience engineering perspective, classifying barriers based on their capacity to "absorb," "adapt," or "respond" to disturbances. This framework emphasizes dynamic and adaptive barriers [61].

As illustrated in Figure 2.4, safety barriers play a dynamic role across the four key stages of system resilience: anticipation, monitoring, response, and recovery. These stages define the evolving purpose of safety barriers in managing potential threats and mitigating undesirable events within a system. In pre-event scenarios, the first two stages focus on proactive hazard management. The anticipation phase aims to identify hazards and prevent their escalation, while monitoring involves detecting early warning signs through technical systems and organizational oversight. The last two stages concern post-event scenarios: the response phase aims to resist and mitigate the impact of undesirable events, whereas recovery barriers enables the restoration of the system through repair, replacement, and rebuilding. These stages are surrounded by a continuous improvement loop—an iterative process of learning from each phase, applying lessons, and reviewing outcomes. This loop helps improve the overall performance of safety barriers and strengthens the system's adaptive capacity.

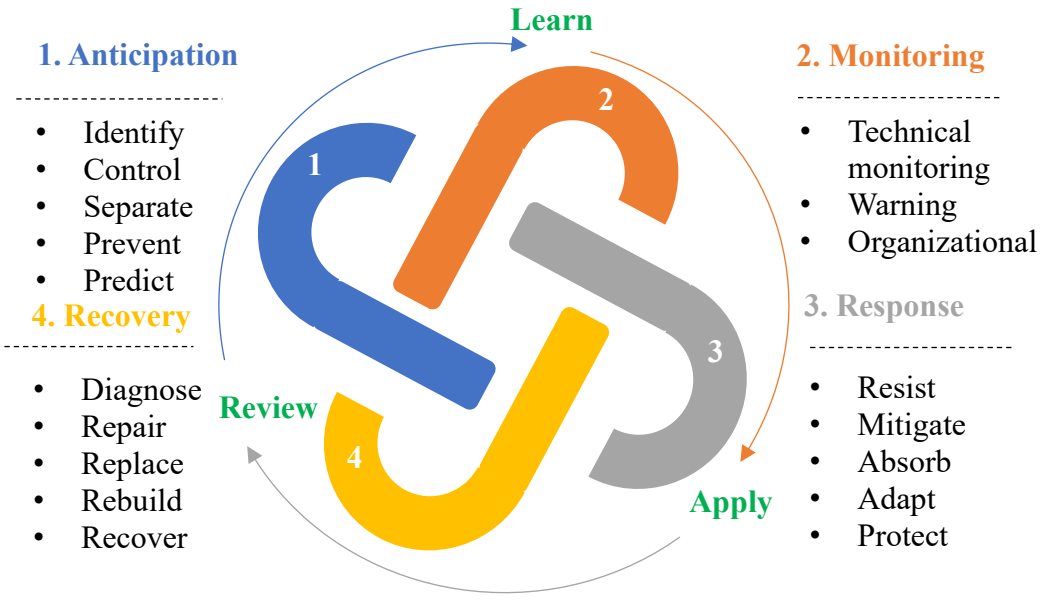


Figure 2.4: Safety barrier functions in different resilience stages

2.6 Safety Barriers Classification

Depending on the purpose of the analysis, safety barriers can be classified in different ways. For a basic risk assessment, a simple distinction, such as between prevention and protection barriers (as in Bowtie analysis, for example), may suffice. Conversely, a more detailed performance assessment, such as that of a complex socio-technical industrial plant, requires a

classification that integrates technical, human and organizational dimensions for a comprehensive understanding. Despite these different classification approaches, the fundamental principles of prevention, protection and recovery remain consistent across all applications.

According to Sklet (2006), barrier systems are defined as *physical and/or non-physical intended measures designed to prevent, control, or mitigate adverse events or accidents* [58]. These barriers can encompass hardware, human actions, or a combination of both, as noted by Hale et al., (2004) and IOGP (2016). [78, 81].

Hollnagel (1999) grouped safety barriers into four main categories.

1. **Material barriers** are tangible obstacles that physically prevent, reduce or stop threats.
2. **Functional barriers** are active or dynamic and operate either by blocking or preventing an action, such as a logical or temporal interlock.
3. **Symbolic barriers** only achieve their purpose through interpretation and include all types of signs and signals, whether visual or sensory. These can also be termed conceptual or perceptual barriers.
4. **Immaterial barriers** (also known as incorporeal barriers in Hollnagel (2008)) depend on the user's understanding and adherence to be effective; examples include rules, guidelines, limitations and laws [69].

Pitblado et al., (2016) classify barriers according to their performance characteristics, distinguishing them as either static (assumed to maintain constant performance) or dynamic (exhibiting a rate of performance degradation). Barriers can be material, human, organizational or a combination of these. In the context of upstream offshore oil and gas operations, they grouped barriers into five main categories:

- **Human or behavioral barriers:** These are based purely on people and organizational factors.
- **Socio-technical barriers:** These combine human elements with hardware components.
- **Active hardware barriers:** This hardware operates only when needed (e.g., a relief valve).
- **Continuous hardware barriers:** This hardware functions with continuous powered operation (e.g., cathodic protection).
- **Passive hardware barriers:** This hardware has no active parts (e.g., a blast wall) [82].

2.7 Fundamental Dimension of Safety Barrier Classification

Barriers can be classified by their nature (physical/non-physical), their function (prevention/ mitigation), and their mode of operation (active/passive).

2.7.1 By Nature or Intrinsic Category

Safety barriers can be distinguished based on their inherent physical (technical) and non-physical (human or organizational) properties.

2.7.1.1 Physical Barriers (also referred to as technical or material barriers)

Are tangible means designed to prevent an event or mitigate its impact by physically obstructing the flow of mass, energy, or information. They function solely through their presence and do

not need any perception or interpretation. Their effectiveness largely depends on their appropriate design, structural integrity and regular maintenance and inspection programs [61, 68, 69]. Examples include primary and secondary containment systems (such as pipes, vessels, dikes, berms, and drainage systems); structural barriers (such as firewalls, blast walls, and physical separation devices); and emergency response equipment (including fire suppression systems and safety relief valves).

2.7.1.2 Non-physical Barriers (also known as non-technical barriers)

Comprise human, organizational, and procedural elements that help prevent hazardous events or mitigate their impact. Unlike physical barriers, they do not rely on tangible structures. Instead, they depend on behaviors, knowledge, rules, or institutional frameworks. Examples include operating procedures, training, safety culture, management systems. These barriers are often more complex and difficult to measure, as their effectiveness largely depends on human and organizational performance [59, 60, 81, 83-85].

2.7.2 By function within the event sequence

Barriers can also be classified by the function they serve at different points along the pathway from threat emergence to consequence:

2.7.2.1 Proactive barrier (frequency-reducing barrier or preventive barrier)

Is a barrier that is installed to prevent or decrease the number of hazardous events from taking place (i.e., probability of a hazardous event) [60, 86]; Example: process control systems, alarm systems, isolation systems, SIS, etc,.

2.7.2.2 Reactive barrier (consequence-reducing barrier or mitigating barrier)

Is a barrier that is usually placed to avoid or mitigate the consequences of one or even more hazardous events [60, 86]. Example: fire suppression systems, emergency ventilation, escape and evacuation systems, etc,.

2.7.2.3 Recovery barriers

Are critical for facilitating a return to safe conditions following an incident. These include emergency response teams (e.g., firefighting, rescue, medical response), damage control systems (e.g., backup power, emergency communications), and business continuity measures (e.g., alternate facilities, backup systems). All of these are designed to mitigate post-event impact and support the restoration of systems [57].

2.7.3 By operational mode

Barriers can be categorized by their operational mode, distinguishing between active and passive types.

2.7.3.1 Passive (No instrumented) barriers

Such as firewalls, dykes, fire insulation, and minimal separation distances serve their function entirely, without a detector, and are constantly ready to work by the sheer existence of their elements [58, 78, 87].

2.7.3.2 Active (Instrumented) barriers

Often require Detection - Diagnosis - Action sequence [58, 68, 78, 87]. Activation may be automatic (hardware) or manual (human barriers) [68, 78]. An active barrier's safety function is not always available; nevertheless, it will be activated in response to a specific situation or circumstance [87].

Passive systems are usually more effective than active systems. Yet, no barriers are unfailing. Therefore, a mixture of active and passive schemes is commonly used to mitigate the effects of loss of integrity and accelerate recovery [57].

Beyond the above classifications, research also distinguishes safety barriers according to whether they are static or dynamic. Static barriers are those that are assumed to perform consistently with predetermined maintenance schedules, while dynamic barriers exhibit rates of performance degradation that require continuous monitoring [88]. Another established categorization differentiates between temporary and permanent barriers: the former are integrated throughout an asset's operational lifecycle, while the latter are employed only for specific periods or under particular conditions [89].

Expanding on these categorizations, digital safety barriers represent a more contemporary classification. These are recognized as technical barriers that integrate digital technologies, and their functional architecture typically comprises three essential subsystems: sensing, analyzing, and executing [66, 90]. Furthermore, the advent of highly interconnected systems has greatly advanced the categorization of cybersecurity barriers as a distinct and critical category [91]. Consistent with this trend, the European Agency for Safety and Health at Work (EU-OSHA) has further categorized smart digital systems into two types: proactive (preventive) and reactive. Regardless of their specific type, these advanced digital systems universally "*leverage digital technology to collect and analyze data in order to identify and assess risks, prevent and/or minimize harm and promote occupational safety and health (OSH)*"[92].

2.8 Attributes and Performance Measures

In systems engineering, an item's performance is inherently connected to its specific function, which defines its intended operation and capability; performance is thus determined by the extent to which the item fulfills its functional requirements. In barrier engineering, however, "function" specifically refers to reducing the likelihood of, or mitigating the impact of, a hazardous event. Accordingly, a barrier's performance is evaluated based on its effectiveness in managing such events once it is implemented and operational [66]. It is widely recognized that the overall effectiveness of available safety barriers influences the level of risk [18]. The efficiency of safety barriers, as defined by Kang et al. (2016), refers to their ability to perform specific safety functions across various contexts using defined measures [71].

To maintain this level of performance and ensure safe operation throughout a plant's lifecycle, regular inspection and testing of all barriers are essential [93]. Indeed, a barrier's efficiency is critically influenced by how it is engineered, provided, utilized during service, regularly tested, and sustained throughout its operational life [87]. Barrier performance standards typically encompass functionality, availability, reliability, and survivability. These specifications thus define both equipment design requirements (initial suitability) and set the necessary maintenance and testing requirements over the asset's entire lifecycle (continued

suitability) [57]. Additional requirements for barrier performance are outlined by Liu (2020) and Johansen and Rausand (2015), including specificity, functionality, reliability, response time, capacity, durability, robustness, auditability, and independence [60, 94]. From a resilience perspective, adaptability and recoverability are also suggested to extend the effectiveness and availability [62].

For more detailed information on barrier performance attributes recognized across various research and publications, readers are referred to the systematic review by Prashanth et al. (2017) [95].

To clarify this further, what follows presents a classification of both traditional and advanced performance indicators, detailing the essential attributes commonly recognized in the literature.

2.9 Traditional Performance Indicators

- **Functionality/Effectiveness**: The ability of the barrier to perform its intended function to prevent accidents or reduce risks to an expected level.
- **Reliability/Availability**: The ability of a barrier to be operational when required. Concepts such as Probability of Failure on Demand (PFD) are commonly used [58-60, 62, 68, 71, 96].
- **Response Time**: The time between the detection of a hazard and the barrier's action [58, 95, 96].
- **Robustness**: The capacity of a barrier to withstand environmental variability [58, 60, 62, 68, 95].
- **Confidence Level**: Related to the Safety Integrity Level (SIL) [59, 60, 62, 68, 71, 96].
- **Triggering Event or Condition**: The specific event or condition that activates the barrier [58].
- **Cost**: The economic aspect of designing, developing, and maintaining a barrier [59, 68, 71].

2.10 Advanced Performance Indicators

In the context of resilience, the practical effectiveness of safety barriers in real-world scenarios is holistically evaluated based on three key capacities: their ability to absorb, adapt to, and recover from adverse events:

- **Absorption capacity** (the ability to withstand disruption): The capacity of the barriers to resist the initial impact of a hazardous event and prevent its progression. This involves their strength, integrity, and immediate functionality in the face of a challenge.
- **Adaptation capacity** (the ability to adjust to changing conditions): The capacity of the barriers to adjust or reconfigure its performance in response to evolving conditions, emerging threats, or operational changes. It highlights the barrier's flexibility and responsiveness.
- **Restoration capacity** (the ability to recover after disruption): The capacity of the barriers to regain their functionality or be rapidly re-established following a disruption or partial failure. It focuses on how quickly and effectively the barrier can be brought back to an operational state after an event [96].

Liu (2025) proposes a bipartite evaluation of safety barrier performance, encompassing risk management and barrier design and operation (see Table 2.1). The risk management perspective evaluates a barrier's ability to mitigate risk to specific assets and its role in the broader risk management framework (e.g., effectiveness and cost). In contrast, the design and operation perspective categorizes measures into capacity, responsiveness, and resilience, which are utilized to determine whether barrier design options and operational strategies adequately fulfill their intended functions within a given context [66].

Table 2.1: Classification of Safety Barrier Performance Measures

Classification	Application	Categories	Sub-categories
Measures in risk management	Employed in managing processes, projects, or assets	Effectiveness	/
		Sustainability	/
		Cost-benefit	/
Measures in barrier design and operation	Utilized for the specification, verification, and performance assessment of safety barriers	Capacity	Strength
			Durability
			Detectability
		Responsiveness	Agility
			Availability
			Robustness
			Validity
		Resiliency	Stability
			Adaptability
			Recoverability

2.11 Performance Assessment

The assessment of safety barriers can be conducted through a variety of methods (see chapter 1), which are commonly classified into three broad categories: quantitative, qualitative, and hybrid approaches [85]. Several barrier analysis approaches are documented in the literature, including: Hazard-Barrier Matrices [97], Safety Barrier Diagrams [87], Hazard-Barrier-Target Model (H-B-T) [98], Energy Flow/Barrier Analysis (EBA) [99], Layer of Protection Analysis (LOPA) [100], Barrier and Operational Risk Analysis (BORA) [101, 102], Barrier-Index Risk Prediction (BIRP) [103], Hybrid Causal Logic (HCL) [101], The Functional Resonance Analysis Method (FRAM) [104], Event Tree Analysis (ETA) [105], Fault Tree Analysis (FTA) [106], Bowtie Analysis [107] , among numerous other methodologies.

More recently, research has shifted towards addressing the complexities and uncertainties inherent in modern industrial systems. For instance, Wang et al. (2025) suggested two innovative models for quantitatively assessing barrier performance in complex chemical processes: the Systems-Theoretic Safety Barrier Model (STSBM) and the Bayesian-Theoretic Safety Barrier Performance Model (BTSBPM). These models allow for a more systematic evaluation by incorporating operational conditions, barrier interdependencies, and uncertainty, thereby improving the accuracy of frequency estimations for real accident scenarios [108].

In a similar vein, Sun et al. (2021) propose a resilience-based performance assessment method for safety barriers. This method tackles the limitations of traditional reliability methods and the challenge of assessing emerging hazards in complex systems. Applied to the wax oil hydrogenation process as a case study, their approach yields a thorough framework that

classifies barriers by function, evaluating their availability in normal and disrupted conditions, and quantifying system resilience based on absorption, adaptation, and restoration capacities [96].

Some researchers focus on formulating and analyzing performance models for a specific type of safety barrier known as safety-instrumented systems (SIS). SISs are a class of technical safety barriers that utilize instrumentation, electrical, electronic, and programmable electronic technologies. When such technical barriers are deployed to prevent major accidents, they can be classified as safety-critical systems [60]. SISs play a significant role as protective layers in industrial process systems and are known by various names, such as emergency shutdown systems, safety shutdown systems, or safety interlocks [109].

In this regard, IEC 61508, the foundational standard for the design and operation of this type of barrier, introduced analytical formulas for major architectures. The primary purpose of these IEC formulas is to calculate key safety performance parameters of SIS, notably the Probability of Failure on Demand (PFD) for low-demand modes and the Probability of Failure per Hour (PFH) for high-demand or continuous operating modes. Typically, an SIS comprises an adequate combination of sensors, logic solvers, and final elements [110], designed to bring the supervised process to a safe state when predetermined conditions are exceeded [111].

2.11.1 Quantitative Assessment Methodologies

Quantitative approaches form the basis of a comprehensive assessment of safety barriers. Such approaches use numerical data, statistical techniques and mathematical models to estimate the probabilities, frequencies or magnitudes of consequences associated with barrier performance. Based on objective, data-driven information, they enable accurate risk quantification and informed decision-making.

In addition to providing a systematic framework for quantifying, ranking, and prioritizing risks, these methods also offer a structured framework for balancing the costs and benefits of safety measures, thus promoting the efficient allocation of resources. Nevertheless, these methods present a number of limitations. In particular, they depend on the availability and quality of data, the assumptions inherent in mathematical models, and the difficulty of representing complex processes numerically. In addition, they often involve inherent uncertainty in their evaluation and can be very time-consuming.

Event Tree Analysis (ETA) and Fault Tree Analysis (FTA) are fundamental quantitative techniques that are essential for systematically examining potential failure scenarios within complex systems. ETA is an inductive, forward-looking approach that meticulously maps out all possible sequences of events following an initiating hazardous event. It details both the success and failure paths of implemented barriers [105]. In contrast, FTA uses a deductive, backward-looking methodology that systematically breaks down an undesirable top event into its various root causes using a logical graphical representation [34, 106].

Both ETA and FTA use probability theory to quantify the likelihood of outcomes, enabling precise evaluation of barrier effectiveness across diverse conditions and contexts. Nevertheless, conventional applications of ETA and FTA typically depend on the availability of established probabilities and the assumption that events occur independently- conditions that are seldom satisfied in real-world process systems, consequently introducing substantial uncertainties into

the analytical framework. Recent methodologies have incorporated expert judgment alongside advanced techniques such as fuzzy set theory and evidence theory to address this issue [112].

In the field of safety barrier assessment, Layer of Protection Analysis (LOPA) is a widely adopted semi-quantitative methodology. This method entails identifying initiating events and their frequencies, assessing the independent protection layers (IPLs) and their failure probabilities, calculating the residual risk by multiplying the probabilities, and comparing the results against acceptable risk criteria [100]. If additional risk mitigation is required following such an assessment, a safety-instrumented function (SIF) may be implemented. The Safety Integrity Level (SIL) of a SIF can then be defined. Common methods for defining the required SIL include the As Low As Reasonably Practicable (ALARP) principle, Risk Matrix, and Risk Graphs. According to IEC standards, the SIL represents one of four distinct levels (ranging from SIL1 to SIL4) allocated to a SIF, and it can be expressed by the average probability of dangerous failure on demand (PFDavg) or the frequency of dangerous failure (PFHavg) [86].

Bayesian Networks (BNs) represent a highly advanced quantitative approach for safety barrier assessment. These probabilistic graphical models establish relationships between root nodes, which represent basic events or initiating conditions, and barrier failure, using probabilities derived from technical data sources and Human Reliability Analysis (HRA). By employing Conditional Probability Tables (CPTs), BNs quantify dependencies and map barrier interconnections, creating a comprehensive statistical framework for performance evaluation [113].

Dynamic Bayesian Networks (DBNs) extend this framework by modeling the evolution of barrier performance over time, integrating degradation, maintenance, and interdependencies. This permits continuous reliability updates based on real-time operational data [83].

2.11.2 Qualitative Assessment Methodologies

Qualitative methods for assessing safety barriers are mainly based on expert judgment, descriptive analyses and scenario-based assessments. These approaches are particularly relevant when empirical data is limited, or when system complexity makes precise quantification difficult. In addition, they provide a valuable contextual understanding that effectively complements numerical analysis by identifying possible failure scenarios, underlying causes and their consequences. In this context, expert judgment approaches are particularly important, as the Barrier and Operational Risk Analysis (BORA) framework exemplifies (see Chapter 3).

Indeed, qualitative methods provide a thorough understanding of complex systems and processes by uncovering hidden risks and proposing context-specific safety measures. However, risks cannot be effectively prioritized, nor can decisions regarding the allocation of mitigation resources be made, without appropriate quantification of the likelihood or severity of potential consequences. They are also limited by their reliance on expert judgement, which inherently introduces a degree of subjectivity and can lead to inter-expert variability, which in turn can compromise the reproducibility of such assessments. This problem is especially

noticeable when expert opinions diverge significantly or when the methodology is not clearly outlined.

Among the various qualitative methodologies available, hazard identification (HAZID) and hazard and operability studies (HAZOP) are two of the most widely used techniques for systematically identifying potential hazards and operational deviations. Their application is based on a structured, team- oriented approach, in which multi-disciplinary experts collaborate to pinpoint possible failure scenarios, evaluate their potential consequences and examine the adequacy of existing safety measures.

The HAZID technique is mainly applied during the initial phases of design or operation to provide an overview of hazards. It generally relies on checklists and the expertise of participants to ensure that a wide range of risk categories is covered. In contrast, HAZOP is commonly conducted at more advanced stages of a project and focuses on the systematic analysis of process deviations at specific process points, also referred to as nodes. To this end, predefined guide words such as “more”, “less”, or “none” are applied to process parameters, enabling the identification of abnormal scenarios, the exploration of their likely causes, the evaluation of system responses, and the proposal of appropriate recommendations [24].

In the context of qualitative assessments, the risk matrix is a commonly used tool, most notably in HAZOP studies. It provides a visual, qualitative framework for ranking risks by combining the probability of an event with the severity of its potential consequences, which in turn facilitates initial risk prioritization and informs decisions on the adequacy of protective measures.

In addition to these, Root Cause Analysis (RCA) is a useful qualitative approach for post-incident investigation. Commonly carried out following an adverse event or near miss, it aims to uncover the underlying causes of the event in order to develop targeted corrective actions that reduce the likelihood of recurrence.

It is also worth noting that other qualitative methodologies have gained in importance, particularly in the analysis of complex systems. The Functional Resonance Analysis Method (FRAM) is a qualitative systems-theory method emphasizing variability and emergent behavior in complex, socio-technical systems, rather than linear causality [114]. Likewise, the Systems Theory Accident Model and Processes (STAMP) conceptualizes accidents as emergent from inadequacies in control structures and feedback within interconnected systems [115].

2.11.3 Hybrid Assessment Approaches

Hybrid methodologies represent an integrated framework that combines both qualitative techniques with quantitative rigor, aiming to exploit the strengths of both to achieve more thorough and context-sensitive assessments. Despite their inherent differences, their integration produces a notably more robust and flexible analytical approach. Qualitative studies, for instance, identify key hazards and scenarios, thereby shaping the scope and assumptions of subsequent quantitative studies. Conversely, the numerical outcomes of quantitative analyses serve to refine qualitative risk assessments and guide the development of targeted improvement efforts. This synergistic combination improves risk identification and prioritization, while

simultaneously ensuring both the precision and objectivity essential for effective decision-making.

In this context, several distinct methodologies have emerged. Foremost among these is Barrier and Operational Risk Analysis (BORA), an integrated hybrid methodology for assessing safety barriers. It systematically uses expert judgment within a structured framework to quantify the revised probability of failure on demand for safety barriers by aggregating expert weights and scores for risk-influencing factors. BORA specifically integrates qualitative insights with quantitative tools such as block-barrier diagrams (BBDs) to map accident scenarios, event trees (ETAs) to model successful and failed barrier responses, and fault trees (FTAs) to analyze the underlying causes of barrier failures. This approach will be discussed in depth in Chapter 3, which shows that it enables a comprehensive, multi-dimensional assessment that combines both contextual understanding and analytical precision [116].

2.12 Industry Standards and Regulatory Framework

Industry standards and regulatory frameworks (see Table 2.2) are fundamental to the establishment, implementation, and ongoing management of safety barriers in high-risk sectors.

Table 2.2: key international and industry-specific standards relevant to safety barriers and risk management

Standard/ Framework	Scope and Focus	Key Points
ISO 17776 (2016)	Offshore petroleum and natural gas industries; managing major accident (MA) hazards in the design of production installations.	Provides requirements and guidance for identifying, assessing, and managing major accident hazards in new offshore installations.
IEC 61508	Generic functional safety standard applicable across all industries; all electrical/electronic/programmable safety-related systems.	Details the functional safety lifecycle, specifying requirements for hardware and software design in safety-critical applications.
IEC 61511	Process industries (e.g., chemical, oil & gas); application of SIS in the process sector, building on IEC 61508.	Focuses on integration and operation of SIS, prior use/concept validation, and sector-specific practices for process safety.
API RP 754	US refining and petrochemical industries; process safety performance indicators.	Defines four-tiered framework of process safety performance indicators, covering both leading and lagging KPIs for PSM systems.
ISO 13849 (2018)	Safety of machinery; safety-related parts of control systems for machinery applications	Addresses the performance of control systems in machinery. Relevant for designing technical (physical) safety barriers.
Norwegian Ocean Industry Authority (Havtil)	Principles for barrier management in the petroleum industry (2013)	Emphasizes performance-based requirements, systematic barrier management, and continuous improvement.
IOGP Report 415 (2008)	Oil and gas industry: Provides guidance on asset integrity management with barrier management as a key component.	Offers guidance for barrier-based risk management and aids in achieving sustainable performance improvement.
CCPS Guidelines (AIChE/ CCPS)	Chemical process industries; comprehensive process safety management framework	Offers detailed methodologies and best practices for all elements of PSM, including specific guidance on barrier management and risk reduction.
SEVESO III Directive (2012/18/EU)	European Union – Major accident hazard control in establishments handling dangerous substances	Mandates comprehensive requirements for industrial operators, including Safety Management Systems (SMS), Major Accident Prevention Policies (MAPP), and Safety Reports that demonstrate the adequacy of safety measures. It also categorizes establishments by substance quantity, imposing differentiated regulations, and aims to limit major accident consequences.

They offer essential guidelines and technical requirements that empower organizations to protect human health, critical assets, and the environment. These frameworks set minimum performance criteria, promote the integration of best practices, support the consistency and interoperability of safety systems, and facilitate compliance with statutory and legal obligations. Furthermore, they significantly contribute to comprehensive risk mitigation strategies by requiring the management of safety barriers throughout their lifecycle. This ensures the barriers' low-cost long-term reliability and effectiveness across all phases of operation.

2.13 Safety Barrier Management

The primary objective of barrier management is to establish and maintain effective protective measures against environmental and operational risks. Accordingly, continuous monitoring, follow-up, and improvement of barrier performance, where necessary, are vital activities that must be carried out throughout the life cycle of a facility [64]. Managing safety barriers is a key activity for maintaining or reducing process safety risks in an operating facility [59, 60, 62, 88, 93, 104]. It is also an integral part of broader risk management strategies [60, 93].

Fundamental principles of barrier management involve coordinated activities to establish and maintain barriers so that they remain functional at all times [59, 60, 93]. This includes the development and upkeep of technical, operational, and organizational barrier elements whose aim is to prevent and/or minimize the adverse effects of accidents. Moreover, the performance of all barriers must be continuously monitored and verified throughout the operation to ensure their reliability and effectiveness [93].

2.14 Critical Issues and Research Challenges in Safety Barrier Management

The effective management of safety barriers is complicated by several critical issues that can be broadly categorized as conceptual, technical/methodological, or organizational challenges.

2.14.1 Conceptual Challenges

Conceptual challenges in safety barrier management mainly originate from basic ambiguities in how key terms are defined and understood. The persistent lack of clear distinctions between safety barriers and general safety measures often results in inconsistent implementation and evaluation across organizations. Furthermore, standards and regulations vary widely across industries. This inconsistency makes it hard to harmonize barrier standards, standardize performance criteria, and verify compliance effectively [60, 87]. Additionally, existing barrier frameworks critically lack the integration of human and organizational factors [59, 62]; traditional approaches tend to marginalize these factors, commonly viewing them as sources of error rather than as essential, dynamic components of the system itself [117].

In light of these issues, the conceptual challenges inherent in the management of safety barriers require a critical reevaluation of the definitions of key concepts, the development of a coherent regulatory framework, and supplementary attention to human and organizational factors. Adopting a socio-technical perspective is essential, as it highlights the interdependence between engineered safety measures and the organizational and cultural dynamics in which they operate. By facing these facets, organizations can improve their management of safety barriers, leading to better safety results and a strong resilience against accidents. Ultimately, a deeper understanding of the interactions and synergies among diverse barrier types, whether technical,

operational, or organizational, is essential, particularly within the intricate context of modern sociotechnical systems.

2.14.2 Technical/ Methodological Challenges

Technical and methodological limitations present significant challenges. Initially, quantifying and modeling the performance of safety barriers is inherently complex due to uncertainties in barrier reliability and the difficulties of capturing interactions among diverse barrier types. For example, technical systems often rely on human intervention, and that variability [118] can lead to underestimating risks.

In addition, the increasing complexity of contemporary systems and the uncertainty associated with emerging risks render conventional evaluation methods inadequate for accurately assessing the performance of safety barriers [96]. They usually depend on deterministic models that assume the linear relations between variables, neglecting the inherent uncertainties and the dynamic interactions present in real-world systems. Consequently, these models can lead to a very simplified understanding of safety barriers, not to capture the complexities of human behavior, organizational culture and environmental variables that can influence the efficacy of the barrier.

Such approaches are static and fail to account for degradation, aging, and changes in operational conditions [119, 120], highlighting the need for methodologies to quantify these degradation mechanisms [59, 118]. Also, they are insufficient for capturing real-time changes, adaptive performance, or predictive degradation [121].

Moreover, many dynamic assessment techniques require comprehensive historical data, which may be unavailable, incomplete, nonexistent, or inapplicable to new or atypical scenarios. In many cases, a lack of comprehensive incident databases in most industries leads to a scarcity of data on rare events, which is crucial for developing reliable predictive models [62]. Available data may also be biased or inaccurate, further compromising the validity of any quantitative assessment. This situation is exacerbated in emerging technologies or new processes, where historical precedents are lacking, requiring a robust approach to data collection that encompasses quantitative and qualitative dimensions. This dependence on established data limits the adaptability of assessments and increases the risk of underestimation or overestimation [122]. Also, the most complex challenges associated with dynamic methodologies stem from technical and computational limitations, especially related to data integration and synchronization.

Unlike static assessments with established validation frameworks, dynamic models require continuous validation against real-world performance. The limited availability of comprehensive real-world validation data makes it difficult to establish confidence in dynamic predictions, while parameter uncertainty propagation through complex models introduces additional layers of complexity [62].

Furthermore, the integration of emerging technologies such as AI and machine learning faces obstacles related to validation, regulatory acceptance, and cost-benefit analysis [123]. The application of resilience engineering to barrier systems remains in its early stages, requiring improved quantification [124]. Finally, cost-effectiveness analysis adds another layer of difficulty. It is difficult to quantify the benefits of barriers, and their lifecycle management

involves intricate cost structures. This further complicates the inherent challenge of making balance between risk and cost in barrier selection [60].

2.14.3 Organizational Challenges

From an organizational perspective, a major challenge is the full integration of barrier management into existing safety management systems and daily activities, a process that can increase procedural and structural complexity [59]. Barrier failures are frequently attributed to organizational factors such as inadequate training, ineffective maintenance, and poor safety culture, which often stem from management's decisions [125].

Leadership commitment is arguably the most critical factor influencing safety barrier management. Studies consistently demonstrate that strong leadership prioritizes risk management [126] and models desired behaviors [127], whereas weak leadership leads to the prioritization of production over safety and contributes to a weak safety culture. This commitment must be coupled with adequate resource allocation, as the implementation of an appropriate barrier philosophy in design, as well as the maintenance of barrier systems, staff training, etc., will entail significant expenditure [60]. Many cost-sensitive industries, however, operate under constraints that limit their ability to invest adequately in safety measures, even when leadership is committed. Insufficient funding, for instance, may result in outdated equipment, inadequate staff training and regulatory noncompliance.

Communication problems represent another universal impediment; clear communication across organizational levels is essential for the translation of safety policies into effective daily practices. When absent, it can result in misunderstandings, inadequate implementation, and neglect of established procedures. Furthermore, human error remains a substantial challenge [128]. Research indicates that human error accounts for a significant percentage of accidents, underscoring the need for rigorous error management strategies [129, 130].

Finally, the integration of advanced technologies, such as AI and building information modeling (BIM), etc., provides potentially useful options for optimizing barrier management. However, studies have shown that knowledge and technical obstacles significantly impede the adoption of such innovations [131]. In addition, this digital evolution introduces new complexities, including cybersecurity vulnerabilities, interoperability challenges, and the need for specialized technical expertise [132, 133]. This indicates that while technology could potentially streamline safety barrier management, the transition is often obstructed by existing infrastructural, knowledge limitations as well as challenges related to validation, regulatory acceptance, and cost-benefit analysis.

In light of these considerations, further research should address the combined influence of human factors and emerging technologies, together with the sustained impact of a strengthened safety culture. The results may contribute to measures that reduce short-term vulnerabilities while improving the long-term robustness of organizations.

2.15 Conclusion

In conclusion, the literature emphasizes that the resilience of an organization's safety system stems from the complex interdependence of its technical, human, and procedural elements, rather than from their individual components in isolation. This chapter has examined the state

of the art in safety barriers, clarified their conceptual foundations, and reviewed the main classification frameworks that support both systematic risk management and the adoption of modern technologies. Establishing clear definitions and structured taxonomies enables the consistent identification, implementation, and maintenance of effective barriers. The consensus is clear: contemporary practices and future progress increasingly depend on digital transformation. Artificial intelligence and the Internet of Things, for instance, are now integral to predictive safety management, enabling early threat detection and agile responses. Nevertheless, the operational promise of such systems is tempered by emerging regulatory and standardization challenges as existing frameworks struggle to keep pace with technological advances. It is therefore essential that research and practice now turn toward advancing the modeling of barrier interactions, integrating human factors, adopting emerging technologies, overcoming persistent data limitations, enhancing methodological rigor, addressing compliance limitations, and fostering a continuous culture of chronic unease, so that industrial safety can sustainably adapt and thrive amid complexity and change.

The next chapter presents the Barriers Operational Risk Analysis (BORA) as a method for assessing risks in cement firing systems, thereby extending its use beyond the oil and gas sector where it was first applied. The selection of this method was based on the fact that it offers a comprehensive framework, which captures the intricate interplay between technical, human, and organizational factors—moving beyond the linear assumptions of traditional models. Notably, BORA's methodological flexibility incorporates quantitative data and qualitative expert judgment, which is particularly vital in industrial contexts where data gaps are common. With its holistic, systems-based approach, BORA enables the proactive analysis and modeling of safety barrier performance. This makes it an ideal method for analyzing risks in clinker manufacturing operations.

Chapter

3

System Context and Methodology: Cement Firing System and BORA

3.1 Introduction

The cement plant is a classified installation for the protection of the environment and is subject to comprehensive hazard and impact studies. The industry is energy- and resource-intensive, consuming substantial raw materials as well as thermal and electrical energy, and it carries significant risks. This chapter moves from a broad overview of cement manufacturing to a focused examination of the firing system before introducing a practical framework for risk analysis.

The opening section synthesizes the cement production process with particular emphasis on previous studies. It provides a concise overview covering the production three main stages, from quarrying to the final product. Among these stages, the cement firing line is consistently identified as the most critical and accident-prone section of the plant. Therefore, further research is required to better understand and mitigate the operational risks in this pivotal area. Next section describes the firing system, highlighting persistent challenges and critical scenarios such as uncontrolled hot-material and explosions. By framing the firing system as a network of interdependent units rather than a set of isolated components, in which technical, human, and organizational factors influence performance, the chapter sets the stage for a method that can quantify such influences.

The final section introduces the Barrier and Operational Risk Analysis (BORA) method as a structured approach to translate industry-average data into installation-specific risk estimates while explicitly incorporating these socio-technical factors. It outlines BORA's core steps and formulas, summarize its strengths, and note key limitations.

3.2 Cement Production Overview

In a world of increasing urbanization and industrialization, cement stands as one of the pillars of modern society, playing a vital role in infrastructure and development [134, 135]. The production process consists of three main sequential stages, each involving several operations that depend on the successful completion of the preceding one. Initially, a mixture of quarried raw materials (such as limestone, alumina, sand, and iron) and corrective materials is homogenized, ground, and transformed into a powder known as raw meal [136, 137]. This raw meal then undergoes pyroprocessing, where it is introduced gradually into a high-temperature zone to form nodular clinker, the main component of cement. This phase includes drying, preheating, calcination, clinkering, and cooling. Finally, the clinker granules are ground, and, where applicable, mixed with additional materials, and packaged to form the final product [137]. This manufacturing process is both resource- and energy-intensive [138], requiring continuous production to ensure sustained profitability and meet growing demand.

A thorough review of the cement manufacturing process is provided by Madlool et al. (2011), which is highly recommended for further reading [137].

Modern cement plants, which now predominantly use the dry process to achieve greater energy efficiency, are large-scale industrial facilities with complex designs that integrate multiple buildings, steel structures, and robust heavy machinery and equipment. Such intricate engineered designs stem from the fact that each production stage, from quarrying to final product [139], exerts a direct and often substantial influence on product quality, energy

consumption [140, 141], emissions profile [142, 143] and safety [3, 144-146]. Therefore, facility design and operational practices are carefully optimized to balance product performance, sustainability goals, and regulatory compliance.

In this context, as a classified installation for environmental protection (ICPE), the cement plant is subject to comprehensive risk and impact studies. It must comply with rigorous standards, guidelines, and regulations to prevent risks and adverse impacts resulting from its activities. These include the prevention of accidental risks, such as fires, explosions, accidental releases, and spills of toxic substances, as well as chronic risks, such as prolonged exposure to very small quantities of pollutants that may affect public health [147]. In addition to complying with ICPE regulations, adherence to international standards and regulations, such as ISO 9001 for quality management systems [148], ISO 45001 for occupational health and safety management systems [149], ISO 14001 for environmental management systems [150], ISO 50001 for energy management systems (EnMS) [151], OSHA regulations, as well as national and local procedures, is critical. Compliance with these standards and procedures, along with the integration of advanced engineering controls, adherence to best practices, and the fostering of a safety culture, is vital for the cost-effective production of high-quality cement, as well as for achieving safer operations, long-term performance, and more environmentally friendly and sustainable production.

From this perspective, the plant's control system structure is based on the distributed control system (DCS), where programmable logic controllers (PLCs) are scattered throughout the process system, each controlling a specific area of the process. The whole system can be networked for communication and monitoring. The fully developed DCS includes SCADA (Supervisory Control And Data Acquisition) software and HMIs (Human Machine Interfaces) [152]. On the environmental side, the use of alternative fuels and raw materials has emerged as an important environmentally friendly operational strategy for simultaneously addressing energy conservation and pollution mitigation [153]. Several effective measures are being explored to reduce CO2 emissions from the cement industry, including reducing clinker-to-cement ratio, improving energy efficiency, and advancing carbon capture, utilization and storage (CCUS), etc [154]. However, achieving a net-zero emissions footprint in this sector remains a complex challenge [154, 155].

Cement plant operations present a huge variety of risks to workers and the environment due to the complexity of the processes and the hazardous materials involved. Despite the critical nature of these risks, the existing literature remains relatively limited. Most ongoing research efforts focus on environmental issues in the short and long term [156] [157] [158], such as strategies to reduce CO2 [159] [160] [161], NOx [162] [163], SO2 [164], and dust emissions [165], as well as the use of alternative fuels as a sustainable development option [166] [167] [168] among others. Addressing these challenges effectively is essential for the sector's transition toward emission neutrality.

While these studies tackle crucial environmental concerns, recent studies have increasingly employed risk assessment techniques to identify and mitigate occupational and operational risks in cement plants. For instance, Bow-Tie analysis has been used to pinpoint potential risks during various stages of cement production [146] and to assess occupational safety and health risks during the production process in the kiln area due to potential of hot dust and significant heat increases [169]. Additionally, Job Safety Analysis (JSA) and Risk Assessment Matrix

approaches have been applied to identify physical risks (noise, heat, hazardous substances) and accident risks (explosions, fires) [3]. The Failure Mode, Effect and Criticality Analysis (FMECA) technique was used to identify and analyze potential failure modes and assess the effects of failures in the cement kiln [170]. Furthermore, HAZID methodology, a risk matrix, and the hierarchy of control have been integrated to identify and assess risks in the cement rotary kiln, and to propose mitigation strategies for very high-risk levels [171]. Other methodologies include the Fine-Kinney and 3T approaches, which have been used to identify potential workplace hazards, analyze exposure levels, rank risks, and determine risk control measures [2]. Among these hazards, fires and explosions are considered particularly critical risks [2] [1]. The 5x5 L type risk matrix methodology has been applied for occupational health risk analysis [172]. In addition, studies on dust-related risks have assessed the effects of worker exposure to cement dust [173] [174], a major occupational health concern in the cement industry.

The influence of integrated quality, environment, and safety management systems on safety indices such as Injury Severity Rate (ISR), Injury Frequency Rate (IFR), and Frequency Severity Indicator (FSI) has been examined to assess their effectiveness and continuous improvement in cement factories [175]. Likewise, a safety culture framework has been proposed to improve the health and safety of workers while promoting a process of continuous improvement [176]. Furthermore, the Multi-Criteria Decision-Making (MCDM) technique, known as DEMATEL, has been applied to identify the most critical factors that have a negative impact on the environment, human health, and plant species [6]. Finally, an approach has been proposed to better understand the dynamic of the health and safety policies in cement plants [177].

Although these studies focus on minimizing risks to workers and the environment in cement manufacturing, they fall short of providing a comprehensive framework for identifying, analyzing, and assessing operational risks. Based on this research and interviews with frontline personnel familiar with the plant, the cement firing line is consistently identified as the most critical and accident-prone section. Therefore, further research is needed to better understand and address the operational risks in this pivotal area.

3.3 Cement Firing System

The cement heating zone is considered one of the highest-risk areas. It comprises a preheating tower, a rotary kiln, and a cooler, which can be represented in a series block diagram (see Figure 3.1). This area is critically influenced by the type of furnace and its operating mode, as well as by the type and characteristics of the raw materials and fuels used. The system must be heated gradually because its components exhibit different thermal behaviors and properties, particularly differences in coefficients of thermal expansion, thermal conductivity, elasticity, strength, and temperature tolerance.

During the burning process, the material undergoes four transformation phases: dehydration (approximately 80–450°C) and decarbonation (450–900°C) in the preheating tower; clinkerization (1,300–1,450°C) in the rotary kiln; and cooling (from about 1,450°C down to ~100°C) in a grate cooler [152].

Figure 3.1 provides an overview of the clinker production line and its main units, as well as the associated area risk charts.

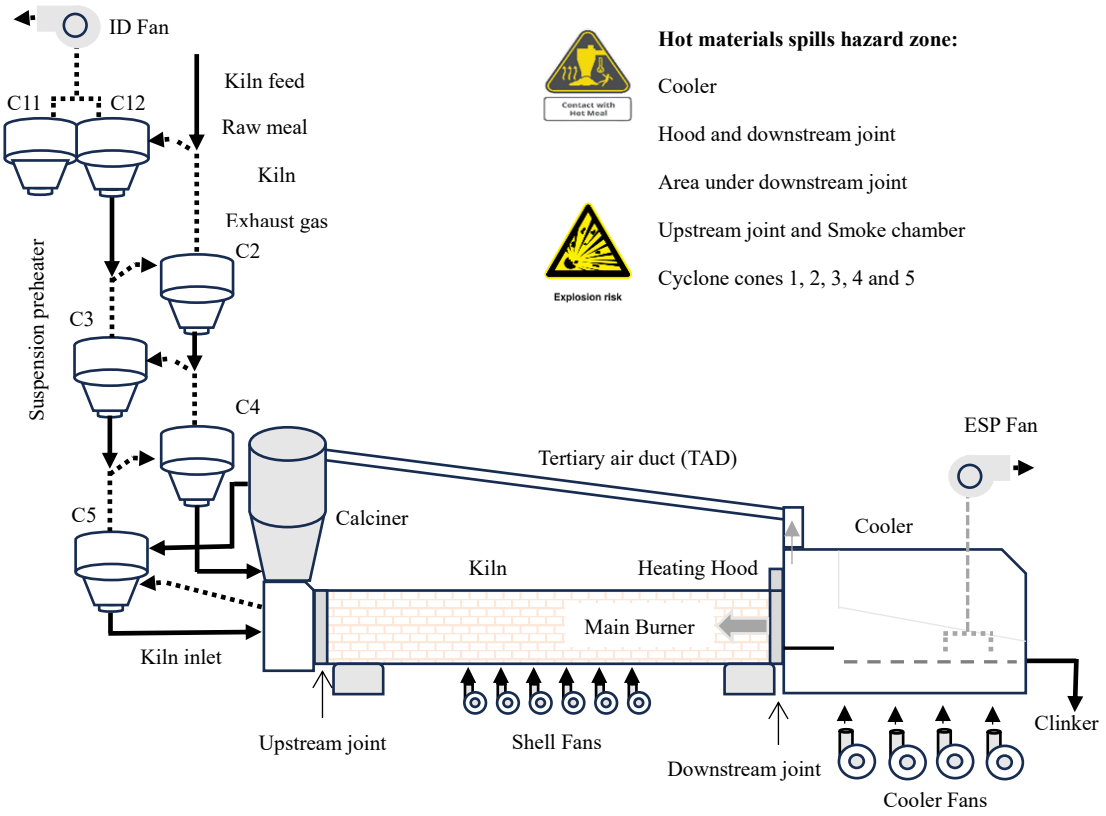


Figure 3.1: Clinker production line/ Area Risk Charts, adapted from (Taibi et al., 2025)

3.3.1 The Pre-heating Tower

The preheating tower typically consists of four to six cyclones arranged vertically and a precalciner. A cyclone is a static device that uses centrifugal force to separate particles from gas streams [178]. It serves two main functions: gas–solid heat exchange and, subsequently, gas–solid separation. Two cyclones are often used at the top stage to increase separation efficiency and capacity. The precalciner is considered an additional combustion chamber between the lowest cyclone stage and the kiln inlet. It's use provides a host of advantages: it reduces the size of the rotary kiln, making it more cost-effective, enhances kiln stability, reduces volatilization and NOx emissions, and helps mitigate buildup and clogging issues.

The preheater operates as a counter-current heat exchanger [137]; hot gases from the rotary kiln are drawn upward by the ID fan, while the raw meal (kiln feed) flows downward through the preheater stages by gravity. This counter-current flow maximizes heat-transfer efficiency and enables the required physical and chemical reactions. As the raw meal is progressively heated stage by stage, its temperature rises from ambient at the preheater inlet to approximately 800–900°C at the kiln inlet, allowing progressive decarbonation of the raw mix (up to about 95% in the precalciner). Meanwhile, the flue-gas temperature drops to roughly 320°C at the outlet of the top-stage cyclone, which is essential to protect the ID fan impeller and shaft from overheating.

It is important to note that all preheater components must be lined internally with suitable refractory materials to protect the shells and internals from high temperatures and to retain heat within the process.

3.3.2 A rotary Kiln

The rotary kiln, often described as the thermodynamic heart of a cement plant for its central role in energy transfer and chemical reactions, is the key subsystem for complete combustion [179], The kiln is a steel tube set at an incline of approximately 3–4° of its total length and rotated at about 1.3–3.5 rpm by a high-power electric motor [180]. Owing to this inclination and slow rotation, the raw meal advances downstream through the kiln, where it is gradually heated and fully calcined by heat from the main burner installed at the outlet end. The kiln shell is lined internally with fire-resistant refractory bricks arranged in rings [181], to protect the steel shell from overheating and corrosion, minimize heat loss, resist chemical attack (e.g., chlorides, sulfur compounds) and abrasion.

The furnaces are generally supported by three support stations. Each support station has 2 rollers and 4 bearings. A kiln shell scanner is widely used to continuously monitor the external shell temperature to prevent overheating [182], while a series of fans cools the shell to an optimal level. The upstream joint connects the kiln to the preheating tower, and the downstream joint connects it to the cooler. These joints are critical for accommodating thermal expansion during heat-up; however, they are also potential weak points where hot material can escape. The main function of the kiln is to transform the material prepared in the preheater into clinker by heating it to a temperature up to 1450°C.

To effectively monitor the operation of the kiln, a range of continuous real-time measurements is required. Several input and output variables should be monitored. The input control variables comprise raw material feed rate, fuel feed rate, kiln rotation speed, ID fan speed, secondary air pressure [183, 184], and secondary air temperature [184]. Kiln output variables are the back-end temperature, O2 (oxygen), and CO content of the flue gas [184], and kiln motor power consumption [183].

In the rotary kiln, where the raw mix is processed into clinker, temperature is the primary factor affecting the quality of cement production [184] and is widely used as an index for monitoring the combustion process [183, 185]. Accurately measuring the temperature of the heating zone using conventional methods is challenging due to the presence of dust, smoke and variable flame position. However, thermal measuring instruments, such as thermocouples, pyrometers, and infrared sensors, often fail to precisely measure temperature since they can only detect a single point or a limited area [185], the presence of a cloud of dust blocks the sensor [186], or sensor fouling due to build-up or coating, leading to signal drift [187]. In practice, the position of the combustion zone varies depending on material movement and operating conditions. Therefore, the temperature recorded by a physical device does not accurately reflect the overall combustion zone conditions [185]. A solution for measuring the temperature of cement kilns is through microwave radiometry [188]. The advantage of microwaves over infrared is that microwaves are less susceptible to scattering by dust than infrared radiation [183].

Despite advanced instrumentation, certain abnormal conditions may not be reliably detected by plant sensors and automation. However, in these cases, an experienced operator familiar with the plant's operation often recognize these abnormalities [183]. Therefore, the technical skills and experience of personnel are crucial to robust kiln combustion control [189].

Moreover, the type of fuel burned is an important factor influencing the combustion process, particularly when burning alternative fuels. Switching to alternative or co-processed fuels reduces energy consumption and lower net CO_2 emissions. However, it is not favorable to the process due to its characteristics, which differ from those of conventional fuels. In practice, many alternative fuels have lower calorific value, higher moisture, and slower combustion, which can cool the main flame, reduce kiln thermal efficiency, and increase induced-draft ID fan power due to higher flue-gas volumes from moisture evaporation. Additionally, they involve the circulation of volatile components, these compounds can adhere to the cyclones and kiln walls, forming deposits that grow larger with each cycle. Hence, it is difficult to deal effectively with the massive amounts of by-products generated and their associated problems, such as improper heat distribution, preheater cyclone blockages, increased emissions of Sulfur dioxide (SO2), the Nitrogen Oxides (NOx), Carbon monoxide (CO) and dust [190, 191], ring formation and corrosion, heat accumulation with the hot spot [191], and wear of the refractory material [192].

3.3.3 The Cooler

The cooler is positioned after the kiln outlet, serving as the final unit in the thermal clinker manufacturing process. It is composed of several fans that generate a flow of cooling air, enabling direct heat transfer between the hot clinker and the cold air [193]. As a mobile grate heat exchanger, it cools the clinker and recovers heat for tertiary combustion air [194]. The cooler is divided into two parts: the hot section, or recuperation zone a largely fixed section just outside the kiln, where the combustion air is heated and the clinker transported by the air blasters; and the downstream cooling zone, which incorporates the moving grate. Upon discharge, the clinker rests on the grate while cooling air from the fans flows upward through it, sharply lowering the clinker temperature to roughly 100–120°C, depending on quality requirements. In grate coolers, a portion of the cooling air typically exits as exhaust air via the electrostatic precipitator (ESP) fan. Hammer crushers then reduce clinker size before it enters the conveying system, making it ready for silo storage and subsequent finish grinding.

3.4 Heating-Zone Upsets

Unplanned stoppages in the cement heating zone arise from a variety of technical and operational problems that affect different subsystems. The most common causes are total power failures, kiln main burner and calciner burner failures, kiln feed interruptions, and cyclone blockages, which further impede material flow and heat transfer. Further factors to be considered include excessive kiln shell temperatures, particularly above 420°C, localized hot/red spots (which are indicative of refractory loss and coating failure), clinker transport failures, grate cooler failures (e.g., grate jams, “snowman” formation, crusher blockage), and seal leaks at the kiln inlet/outlet.

Each of these factors can have a critical impact on safety, resulting in a fire, explosion, or release of hot material. They can also impact production stability, causing trip chains, thermal shocks, and quality loss. These issues underscore the need for robust interlock systems, comprehensive thermal monitoring, effective management of volatile circulation, disciplined standard operating procedures (e.g., shutdown and start-up protocols), a well-trained workforce, and structured maintenance practices, among other controls.

The main variables requiring continuous monitoring during clinker formation are temperature, pressure, and flow rate. Deviations from set limits can trigger a range of operational problems. Dominant concerns include buildups in various parts of the heating system, which may lead to preheater cyclone blockages, hot-meal avalanches, kiln ring formation, snowman formation in the cooler, and crusher blockages. In practice, these unfavorable operating conditions pose potential safety problems. To mitigate them, a combination of physical and procedural barriers is implemented at key points across sub-systems of the heating zone.

Selected safety barriers are classified under a resilience-based framework, as shown in Table 3.1.

Table 3.1: Classification of barrier element functions in the pyro-processing unit

Stage	Function	Physical barrier	Non-physical barrier
Pre-release	Anticipation	Pressure transmitters Thermocouples Visit door (cyclone, cooler) Gas analyzers UV detector flame Security locking systems PPE	Safety distance Safety display. Traffic light Training Leakage gas test SOPs. LOTOTO Emergency exercise
	Monitoring	Alarm system Kiln Thermal Camera Kiln Scanner	Operating discipline Inspection procedures
Post-release	Response	Cardox, air blasters Retention container Emergency Shutdown System	Internal Response Plan (IRP) Specific Response Plan (SRP) Certified firefighting team
	Recovery	Marking	Maintenance Cleaning procedures Start-up procedures Medical emergency
	Learning	/	Post-emergency review Documentation

In general, the firing process can generate hazardous emissions, including dust, particulate matter, carbon monoxide (CO), and sulfur dioxide (SO_2). Workers may experience thermal and chemical burns, injuries, irritation, asphyxiation, and, in severe cases, fatality. Accidental contact with hot materials or surfaces can also result in severe burns and death. In addition, hot materials spills, fires, and explosions are the most hazardous events that can have major consequences, often involving the release of massive amounts of materials at high temperature. It is therefore vital to identify the initiating causes and credible scenarios that could lead to such events and how to manage them effectively to ensure a safe work environment.

3.5 Potential Safety Concerns

The potential hazards identified in the heating area were derived from interviews and on-site inspections, including fires and explosions; contact with hot meal and hot surfaces; uncontrolled hot material spillages; falls from height; contact with moving machinery; emergency response failures; materials engulfment; mobile equipment incidents; electrical hazards; polluted water discharges; respiratory illnesses; structural collapse; and other operational hazards.

Uncontrolled hot material spillages, fires, and explosions are recognized as major concerns. Field inspections and feedback from frontline personnel involved in daily heating zone operations have provided detailed insight into initiating causes and credible consequences of these hazards.

3.5.1 Uncontrolled Hot Material Leakage

Heating the raw mix to high temperatures can lead to hot-material spillages in several areas:

- **In the preheater tower**, due to overheating, overpressure, buildups and blockages, unsafe cyclone-blockage removal, material sampling, cleaning operations, and opening of hatches, portholes, or poking holes.
- **In the kiln**, due to damaged inlet/outlet seals, ring formation, high kiln filling degree, and uncontrolled hot-meal flushes.
- **In the cooler**, due to hot-meal avalanches, crusher blockages, coating falls, snowman formation at the inlet, and opening of inspection doors.

These spillages typically arise from two main root causes: technical factors and human/organizational factors.

a) Technical Factors:

- **Equipment failure**: Hot materials can exert high thermal stresses and chemical attack; combined with fumes, dust, vibrations, and buildups, which can increase the risk of component failure. Additionally, coating or damage to the sensors that monitor temperature, pressure, and material flow can result in inaccurate readings, disrupting feedback and control. Moreover, Temperature fluctuations during clinker production cause thermal expansion/contraction, hot/red spots and localized super-heated, and super-chilled, which can damage refractory bricks and equipment's structural integrity. Also, overheating can make the material overly fluid causing red river, increasing spill risk.
- **Blockages and buildups**: caused by material properties (chemical composition, mineralogical factors, poor homogenization, particle-size distribution, high levels of sulfur, alkalis, and moisture, etc.), volatilization phenomena associated with poor combustion or alternative fuels, excessive dust loading, loss of protective coating, fluctuations in temperature or pressure, and irregular feed rates.

b) **Human and Organizational Factors**: inadequate or undocumented procedures, insufficient training and competency, poor communication, inadequate maintenance and supervision, fatigue and stress, and human error, etc.

3.5.2 Fires and Explosions

The combination of heat, fuel, and combustible materials creates a potentially hazardous scenario that requires careful monitoring and management. The following factors may result in fires and explosions:

a) Technical Factors:

- Misfiring caused by igniter or burner failure, delayed ignition;

- Loss of flame and subsequent accumulation of unburned fuel/gas;
- Flame return and intermittent flame ejection;
- Inadequate off-gas venting;
- Gas leaks, accumulations of combustible dust;
- Buildup and blockages;
- Hot material spills in the event of overheating or overpressure/ Hot material gets on the electric cables;
- Chemical reactions: reaction between water and a hot meal, which inevitably leads to rapid evaporation of water, causing rapid steam generation and dust entrainment;
- Using coal as fuel is a source of fire as it has a higher tendency for spontaneous ignition (auto-ignition) [195].

b) Human and Organizational Factors:

- Inadequate maintenance and procedures;
- Improper management of hot work;
- Human error, e.g., bypassing an interlock;
- Poor communication and coordination.

Proactively mitigating these risks requires real-time monitoring of critical parameters to enable the early detection of operational deviations, such as high temperatures, pressures, flows, or leaks. In response to potential threats, the control system reacts by triggering alarms that initiate a sequence of actions, ranging from operator intervention to automated emergency shutdown systems. The effectiveness of these measures depends on workforce competence, highlighting the importance of operator training and well-established emergency response protocols.

To assess the risk of hot material spillages and explosions in the cement firing system, a Barrier and Operational Risk Analysis (BORA) can be used. This approach is well suited due to its flexibility in integrating real-time feedback and analyzing technical, human, and organizational factors. It also supports estimating initiating event probabilities, analyzing accident scenarios, and evaluating and modeling safety barrier effectiveness.

3.6 BORA Method

The BORA method (BORA Release) has been developed to analyze the risk of hydrocarbon releases from offshore platforms, based on a structured set of hydrocarbon release scenarios and initiating events. It combines qualitative and quantitative, inductive, and deductive risk analysis methods, including Event Trees for scenario modeling, Fault Trees to model barrier system failures and influence diagrams to incorporate Risk Influencing Factors (RIFs) to evaluate how technical, human, operational, and organizational factors affect the performance of safety barriers. The approach includes establishing a basic risk model with industry average frequencies, scoring and weighting RIFs, and then adjusting the generic probabilities/frequencies to quantify installation specific risk and barrier effectiveness [102, 196].

A key feature of BORA is the explicit inclusion of risk influencing factors (RIFs) that capture installation specific conditions, including the technical, human, and organizational factors that may affect barrier performance and significantly influence the accident sequences [102]. The

method has been widely applied in complex industries such as oil and gas [197], particularly on offshore platforms [196, 198], and in marine transportation [199] to assess risk and support safety improvements. Its focus is on analyzing safety barriers that prevent the occurrence of hazardous events, such as hydrocarbon spills [200, 201].

Despite its advantages, BORA results are subject to uncertainty [201] [200]. Outcomes depend heavily on data quality and expert judgment [102] [202]. Uncertainty and subjectivity can make it difficult for experts to assign precise numerical values [198, 200], especially when data is insufficient or the scoring method is inappropriate [201]. The method also requires a deep understanding of the system's barriers and operations [102]. Improper analysis can misidentify critical risks. To keep the assessment manageable, it is important to limit the number of RIFs per event [203] and tailor the BORA application to the specific context of the cement firing system under study.

3.6.1 Steps of the BORA Method

The main steps of BORA are as follows:

- Identify initiating events (IEs).
- Assign generic IE frequencies.
- Develop barrier block diagrams.
- Develop fault trees to model safety-barrier performance.
- Assign generic input data (basic-event probabilities/frequencies).
- Calculate leak frequency based on the generic model.
- Identify risk-influencing factors (RIFs) for initiating and basic events and develop influence diagrams.
- Assign RIF weights and scores.
- Recalculate the pyro-processing-specific risk frequency.

Figure 3.2 illustrates BORA's qualitative and quantitative analyses, and the main steps needed to conduct a study using this approach.

Initiating events (IEs) are deviations from normal operating conditions. If all relevant barrier functions or subfunctions designed to prevent such deviations fail, an uncontrolled release may occur. IEs are commonly grouped into six categories: (1) technical degradation of the system; (2) human intervention introducing latent error; (3) human intervention causing an immediate release; (4) process disturbances; (5) inherent design errors; and (6) external impacts [202].

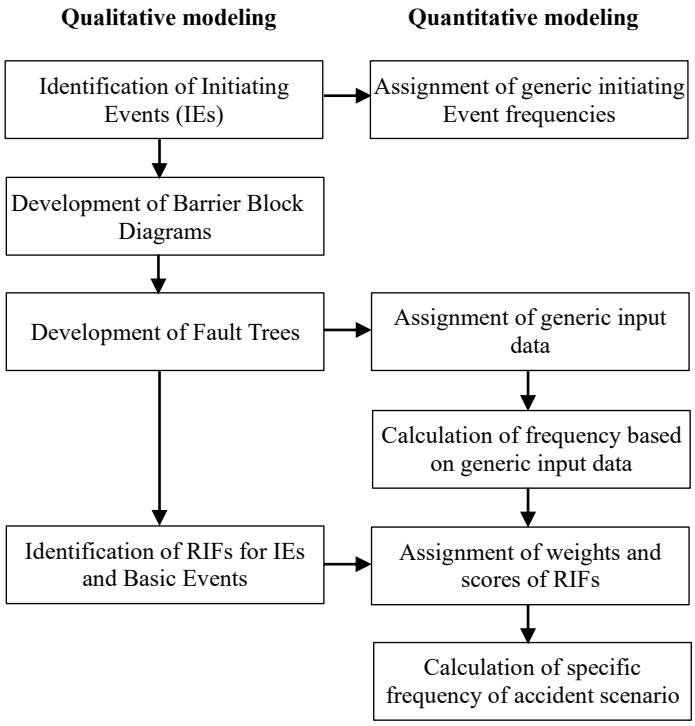


Figure 3.2: Key BORA steps adapted from (Seljelid et al., 2007)

Figure 3.3 highlights the use of Barrier Block Diagrams (BBDs) to depict accident scenarios and show how safety-barrier failures can alter the sequence of events. Specifically, the model comprises initiating events, barrier functions implemented by safety barriers or systems, and potential end events [197, 202]. In other words, it provides a graphical view of the barrier functions in place and illustrates how barrier systems fulfill these functions to prevent an initiating event from escalating into a release.

After defining accident-release scenarios and their corresponding safety barriers in the barrier block diagrams (BBDs), the next step is to use fault tree analysis (FTA) to model safety barrier performance. FTA is used to deduce the causes, or combinations of causes, that can lead to the defined top event and to make explicit the logic of barrier failure[34]. In general, the causes of the top event fall into two categories: technical (unreliability of the technical barrier system) and non-technical (human error during operations). To quantify safety barrier failure probabilities, fault tree input data are required. Historical data can be used to derive generic initiating event frequencies, typically from company databases. Additionally, expert judgment may also be used to establish industry-average values.

Moreover, in the fault trees, the probabilities of initiating and basic events depend on a set of risk influencing factors (RIFs) [202]. For example, the maintenance team's competency and the time pressure to complete a task can affect the likelihood of error when replacing an inlet or outlet kiln seal. Each RIF is assigned a weight (w) to represent its relative importance, and a score (s) to describe its state for the specific installation [202].

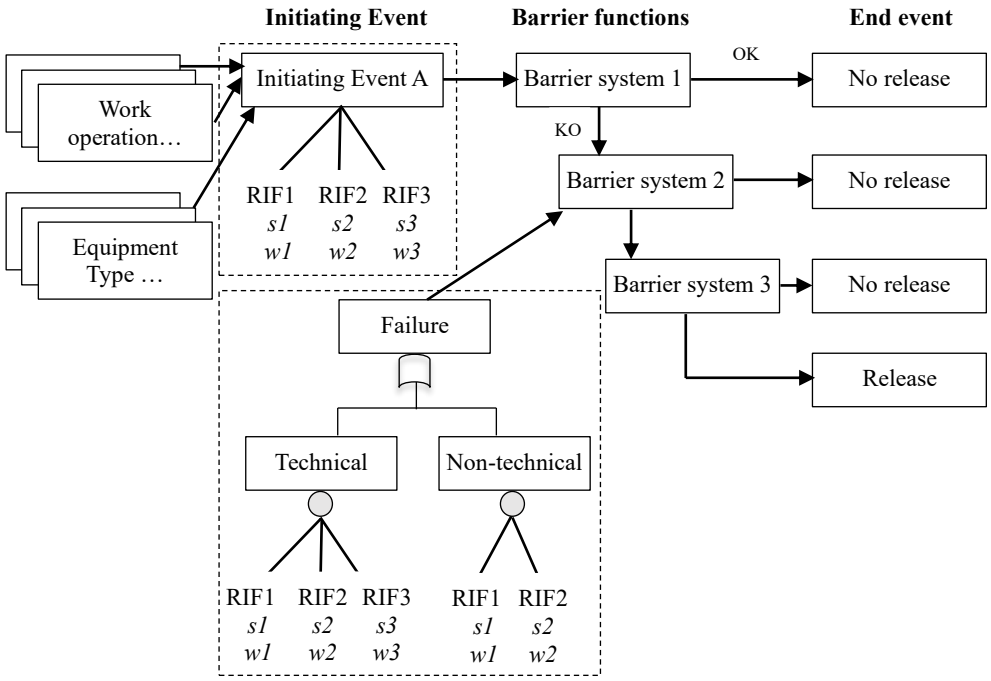


Figure 3.3: BORA generic risk model (Vinnem et al., 2007)

Figure 3.4 shows a comprehensive framework for identifying Risk Influencing Factors.

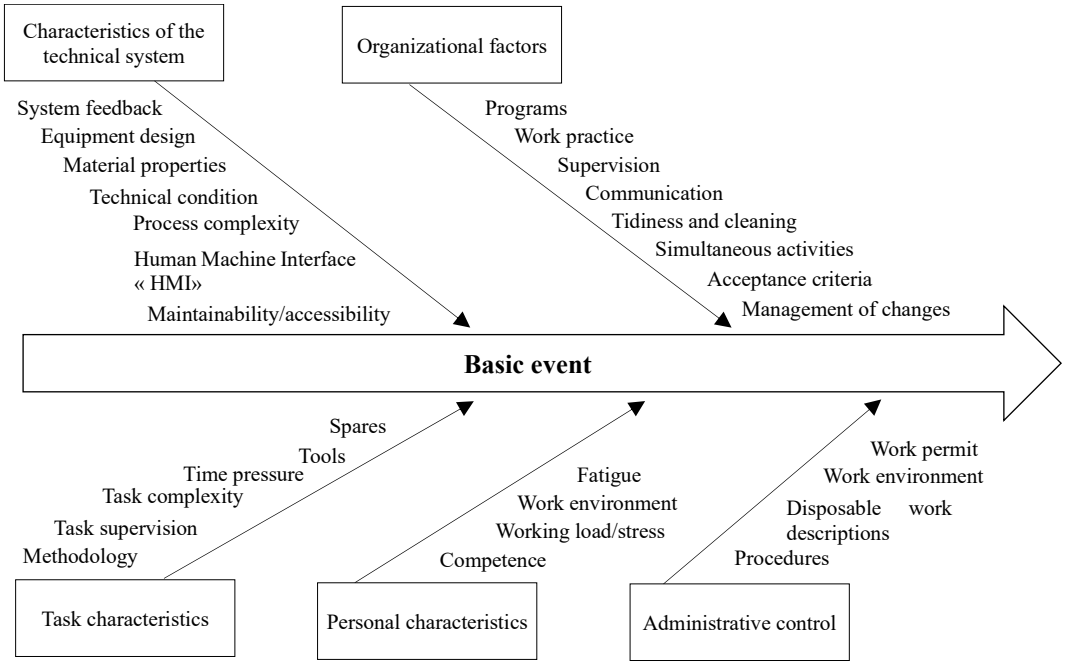


Figure 3.4: A comprehensive framework for identifying Risk Influencing Factors (RIFs) (Taibi et al., 2025)

The framework for identifying risk-influencing factors (RIFs) comprises the following key groups [102]:

- Characteristics of the personnel performing the tasks;
- Characteristics of the tasks being performed;
- Characteristics of the technical system;

- Administrative controls (procedures and disposable work descriptions);
- Organizational factors and operational philosophy.

3.6.2 RIF Weighting and Scoring Method

Risk Influencing Factors (RIFs) were assessed on a five-point scale and assigned quantitative weights of 10, 8, 6, 4, and 2. For each basic event, the weights of the applicable RIFs were normalized so that their sum equaled 1. In parallel, each RIF was assigned a qualitative grade from A to F, where A represents the best standard in the industry, C represents the industry average, and F represents the poorest practice (see Table 3.2) [102].

Table 3.2: Generic scheme for scoring RIFs

Score	Explanation
A	Best practice in the industry
B	Better than industry average
C	Industry average
D	Slightly worse than industry average
E	Considerably worse than industry average
F	Worst practice in the industry

The baseline probabilities/frequencies are adjusted using risk influence diagrams to account for installation-specific RIFs and to assign scenario-specific values. Let A denote a given accident event. The installation-specific probability of A is denoted $P_{rev}(A)$ and is estimated using the following formula:

$$P_{rev}(A) = P_{ave}(A).\sum_{i}^{n} w_i Q_i \tag{2}$$

Where $P_{ave}(A)$ indicates the industry average probability of occurrence of event A, w_i denotes the weight of RIF no. i for event A, Q_i is a measure of the status of RIF no. i, and n is the number of RIFs.

Here

$$\sum_{i}^{n} w_i = 1 \tag{3}$$

The Q_i can be calculated by assigning numeric values to each score (from A to F). Q_i values are established as follows:

- Determine $P_{low}(A)$ as the lower limit for $P_{rev}(A)$ by expert judgment.
- Determine $P_{high}(A)$ as the upper limit for $P_{rev}(A)$ by expert judgment.
- Then put for i =1, 2, … n;

$$Q_i(s) = \begin{cases} P_{low} / P_{ave} & if\ s = A \\ 1 & if\ s = C \\ P_{high} / P_{ave} & if\ s = F \end{cases} \tag{4}$$

Where s denotes the score or status of RIF no *i*.

Hence, if the score "s" is A and $P_{low}(A)$ is 10% of $P_{ave}(A)$, then Q_i is equal to 0,1. If the score "s" is F, and $P_{high}(A)$ is 10 times higher than $P_{ave}(A)$, then Q_i is equal to 10. If the score "s" is C, then Q_i is equal to 1. Furthermore, if all RIFs have scores equal to A, then $P_{rev}(A) = P_{low}(A)$, if all RIFs have scores equal to C, then $P_{rev}(A) = P_{ave}(A)$, and if all RIFs have scores equal to F, then $P_{rev}(A) = P_{high}(A)$.

For s=B, we assume a linear relationship between Q_i (A) and Q_i (C) and use sA = 1, sB =2, sC = 3, sD = 4, sE = 5, and sF = 6. Then,

$$Q_i(B) = \frac{P_{low}}{P_{ave}} + \frac{(s_B - s_A).(1 - \frac{P_{low}}{P_{ave}})}{s_C - s_A} \tag{5}$$

For s=D and E, we assume a linear relationship between Q_i (C) and Q_i (F). Then,

$$Q_i(D) = 1 + \frac{(s_D - s_C).(\frac{P_{high}}{P_{ave}} - 1)}{s_F - s_C} \tag{6}$$

$$Q_i(E) = 1 + \frac{(s_E - s_C).(\frac{P_{high}}{P_{ave}} - 1)}{s_F - s_C} \tag{7}$$

The installation's accident scenario frequency ($f_{Acc,\ scenario}$) rev can be calculated using updated frequencies and probabilities. Human factors, operational conditions, and organizational factors are considered in this new risk value. The following formula is used to determine this ultimate frequency:

$$f_{(Acci,scen)} = f_{rev\ IE_i}.P_{rev\ SB_1}.P_{rev\ SB_2}...P_{rev\ SBj} \tag{8}$$

Where:

- $f_{(Acc,\ scen)}$: Accident scenario frequency;
- $f_{(revIEi)}$: Frequency of initiating event n. *i*;
- $P_{(SB)}$: Probability of failure of safety barriers n. j.

3.6.3 Advantages and Limitations of BORA

3.6.3.1 Advantages

- It integrates technical, human, operational, and organizational factors, allowing platform/installation-specific risk estimation rather than relying only on generic technical data [200].

- It provides a comprehensive framework for modeling safety barriers [204] using barrier block diagrams, fault trees, event trees, and risk influence diagrams. This enables end-to-end tracing of how barrier performance affects scenario frequencies.
- It supports both qualitative and quantitative analyses, including the scoring and weighting of risk influencing factors (RIFs), followed by the adjustment of average probabilities and frequencies to calculate installation-specific results [205].
- It has been extended (e.g., BORA-CIA) to address practical challenges such as sparse data and to prioritize barrier components for maintenance and improvement actions [205], indicating methodological flexibility and ongoing improvement.

3.6.3.2 Limitations

- It necessitates periodic revisions to the inputs (RIF scores/weights, initiating event frequencies, and barrier failure data) to reflect evolving organizational and operational contexts. Extra effort and time may be required in making assumptions about how these factors affect probabilities over time.
- It depends on the availability and quality of data on initiating events and barrier failures. In many applications, such data is usually limited or uncertain, which makes expert judgment necessary.
- Even though it includes non-technical factors, quantification still depends on scoring and weighting schemes for RIFs. This makes it subjective and uncertain when it comes to assessing these risk factors [200].
- It remains in the research and development stage, moreover its practical application is limited in the offshore petroleum industry [206].
- It can be applied in simplified forms, potentially reducing completeness in capturing operational risk [204].

3.7 Conclusion

In summary, the cement industry can be considered as a complex socio-technical system that depends on technical, human, and organizational factors for safe operation. The overview of production and prior studies establishes the foundation; the focused examination of the firing system defines the problem space where risks are critical; and the BORA framework provides a rigorous, integrated approach to deriving plant-specific risk estimates from qualitative and quantitative analyses.

While BORA is a valuable framework, its results are subject to uncertainty. The robustness of findings depends on the quality of available data and the competence of expert judgment, both of which can introduce a certain degree of variability. Furthermore, inappropriate scoring methods may amplify subjectivity. Effective application also requires detailed insight into system barriers and operations; deficiencies in this regard can lead to misidentification of critical risks. To ensure a manageable and context-relevant analysis, the number of RIFs assigned to each event should be kept to a practical minimum, and the BORA approach should be tailored to the specific context of the cement firing system under study.

The next chapter applies the methodology to a real case study, which in turn will lead to relevant findings and recommendations.

Chapter

4

Application of the Methodology: A Cement Firing System Case Study

4.1 Introduction

The cement firing line is one of the most critical and high-risk zones in cement manufacturing. This area is characterized by its inherent complexity and the potential for adverse escalation scenarios. Numerous parameters, such as pressure, temperature, flow, and so on, require precise control, as significant deviations can lead to severe consequences.

Systemic risks arise from the complex interdependencies between process units, where bidirectional flows of material, energy, and control amplify the potential for cascading failures and domino effects, creating substantial systemic vulnerability. The risk is further heightened by the presence of large inventories of hot material. With properties such as high temperature up to 1450°C, high energy content, and, at certain stages, molten behavior—make it especially hazardous and prone to dangerous spills. Such events can be life-threatening, with heat flux and flow characteristics comparable to pyroclastic volcanic eruptions.

This chapter applies an adapted methodology that combines HAZOP, BORA, and RCA to the cement heating zone. The case context and data sources are first established by defining the system boundary, outlining the hazard profile, and summarizing data obtained from expert interviews and plant records.

To illustrate the practical application, a case study was carried out on the heating zone of Lafarge Cement M'Sila (LCM), following a stepwise process from HAZOP deviation identification to revised quantitative risk estimation and recommendations. Two critical scenarios—uncontrolled release of hot material and explosion—were defined from the HAZOP. Initiating events were specified, and the BORA model was developed accordingly. Quantification involved assigning updated initiating event frequencies, PFD of IPL, and RIF scores, followed by calculation of scenario-specific frequencies. Root cause analyses were then performed to trace underlying causes to systemic weaknesses. The chapter concludes with recommendations and an action plan to improve resilience and operational safety.

4.2 Case Study: The Lafarge Ciment M'SILA Plant

Our study was conducted at the Lafarge Ciment M'SILA (LCM) plant, which operates two similar dry process lines for clinker production. Each line comprises a five-stage suspension preheater and an in-line calciner to prepare raw materials before they enter a rotary kiln. A grate cooler then cools the final product.

Per production line, the kiln feed rate is approximately 360 t/h (tons per hour) and is fired by an intense flame produced by burning natural methane (CH4) gas, injected at a rate of 9000 Nm^3/h by a single burner installed at the furnace outlet. An additional staged CH4 is injected into the lower region of the furnace inlet smoke chamber at a rate of 13500 Nm^3/h without using a burner. The calciner is heated by hot exhaust gases from the rotary kiln. When gas temperatures exceed roughly 650 °C and mixing conditions are adequate, natural gas achieves auto ignition, initiating calciner combustion, which performs most of the raw meal decarbonation.

The combustion air for the calciner is drawn from the grate cooler through a brick lined tertiary air duct equipped with a modulating damper for flow control. Kiln exhaust gas is dedusted by bag filter before being released, which use compressed-air cleaning, upstream of

the ID fan. While the cooler exhaust is treated by electrostatic precipitators comprising large horizontal chambers energized by high voltage. Both systems are monitored to ensure efficient operation and prevent dust re entrainment.

The Control Center Room (CCR) supervises the firing line and cooler via a SIMATIC PCS 7 distributed control system (DCS). Operators monitor and regulate draft (ID fan), fuel admission, primary/secondary/tertiary air flows, and kiln/calciner temperature and oxygen profiles, as well as particulate control systems and emissions. Safety barriers in the clinker area comprise engineered controls (e.g., isolation valves, flame detector, safety interlocks), administrative and organizational measures (e.g., SOPs, permit-to-work, confined space and hot-work controls, LOTOTO, contractor management, operator training) and emergency preparedness (e.g., alarm and response procedures).

Figure 4.1 shows the PCS 7 HMI, providing a visual representation of critical process variables.

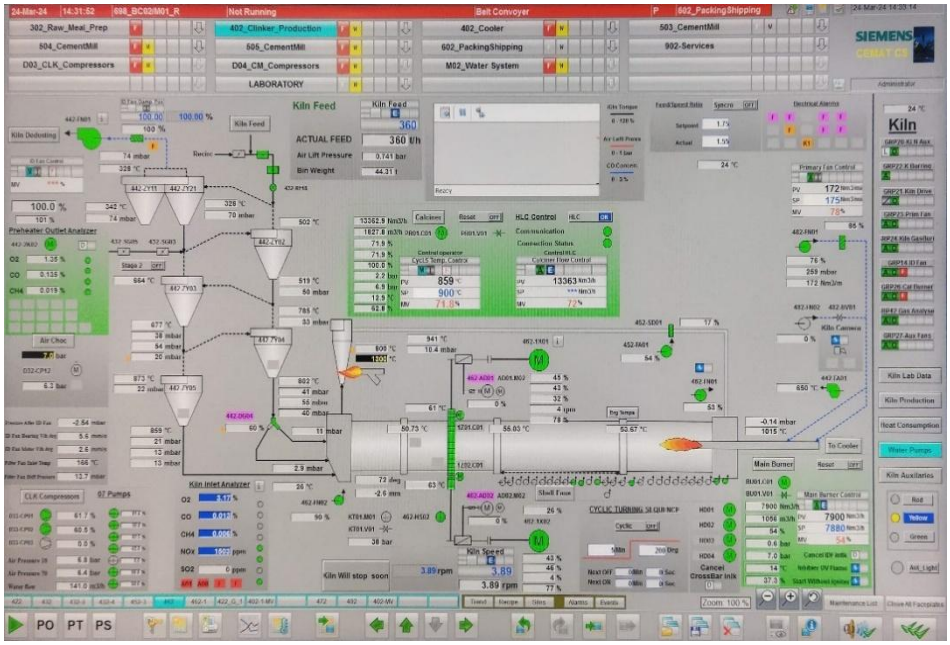


Figure 4.1: PCS 7 system user interface

LCM is actively committed to safety and environmental protection and continually improves its practices through programs that promote hazard awareness and safe work behaviors among employees and contractors. Nonetheless, the plant contains considerable inventories of hot meal and hot, dusty gases. Consequently, the risk of unexpected accidents remains; events or sequences of events can lead to the release of hot materials, fire, or explosion. For example, deviations or failures, such as loss of draft, air–fuel ratio imbalances, blockages, or refractory failure, can trigger loss of flame or uncontrolled discharge. This can result in serious or fatal injuries, as well as damage to the facility or environment.

The study included extensive interviews and meetings with key plant personnel—shift supervisors, kiln operators, manufacturing managers, process engineers, maintenance managers, and safety managers. Most had more than two decades of experience and provided critical insights into system operations and safety barriers relevant to HAZOP and BORA, which formed the foundation of our analysis.

4.3 Methodology Application

4.3.1 Scenario Definition and Initiating Events

To identify potential accident scenarios, we began by conducting a Hazard and Operability (HAZOP) study— a robust and widely used method for systematically analyzing risks, making it an excellent choice for a high temperature process involving hot meal. Following IEC 61882, we worked with a multidisciplinary team and used P&IDs and PFDs to apply HAZOP to the firing system of the LCM cement plant. For the analysis, the system was divided into three nodes: (1) the preheater tower, (2) the rotary kiln, and (3) the grate cooler; the principal equipment is listed in Table 4.1.

The firing system operates under harsh conditions—hot gas temperatures up to 2000 °C, hot meal around 1450 °C, high volume material flows, and tightly coupled endothermic–exothermic reactions that must be carefully managed to maintain clinker quality and overall stability. These demands require precise control of combustion efficiency, feed composition, residence time, burner alignment, and flame shape; moreover, dynamic interactions among the three nodes strongly influence system safety.

Table 4.1: Firing system nodes and associated main components

N°	Node Name	Main function	Main components
1	**Preheating tower**	Preheats raw meal using kiln exhaust gases and initiates calcination.	ID fan, cyclones, riser duct, in-line calciner (pre-calciner), kiln feed system, kiln inlet/smoke chamber.
2	**Rotary kiln**	Heats materials to ~1450°C to form clinker	inlet and outlet seals, refractory lining, main burner, drive system, kiln hood, bag filter.
3	**Grate cooler**	Cools hot clinker from the kiln and recovers heat for reuse (tertiary/secondary air).	Grate cooler, cooler fans, crusher, tertiary air duct (TAD), ESP fan, electrostatic precipitator (ESP).

Rather than being a purely theoretical exercise, the analysis was embedded in day-to-day operations through structured, multidisciplinary workshops involving different specialists. During these sessions, the HAZOP guidewords NO, LESS, MORE, and REVERSE were systematically applied to key variables such as pressure, temperature, and flow. Additionally, up-to-date SOPs and historical data on process disturbances, incidents, and corrective actions were examined to ensure that the identified scenarios reflect operational reality and to map how disturbances could propagate across units within the heating area.

In the context of HAZOP, a risk matrix (often referred to as a heat map) provides a clear and practical tool for evaluating and visualizing risks associated with process deviations. As shown in Table 4.2, the matrix classifies risks into four distinct color-coded categories—tolerable (green), tolerable if ALARP (yellow), intolerable (orange), and unacceptable (red)—to facilitate interpretation and the prioritization of control measures. For instance, a scenario with a “Likely” (B) probability and a “Major” (4) consequence is immediately identified in the red zone, indicating an unacceptable and critical hazard. Such cases require urgent efforts to reduce the

risk, either by lowering its likelihood, mitigating its severity, or both. The matrix thus serves as both an evaluation and a communication tool.

Table 4.3 complements this by defining risk acceptability criteria, describing each risk level, and specifying the corresponding actions. The subsequent HAZOP, conducted in accordance with these criteria, produced the results reported in Appendix (Tables 0.1–0.3) for the preheater tower, kiln, and cooler, respectively.

Table 4.2: Risk matrix

Severity							
	(5) Catastrophic	**5**	5E	5D	5C	5B	5A
	(4) Major	**4**	4E	4D	4C	4B	4A
	(3) Severe	**3**	3E	3D	3C	3B	3A
	(2) Serious	**2**	2E	2D	2C	2B	2A
	(1) Significant	**1**	1E	1D	1C	1B	1A
			E	**D**	**C**	**B**	**A**
LIKELIHOOD (yr)			$<10^{-9}$	$10^{-9}<x<10^{-6}$	$10^{-6}<x<10^{-3}$	$10^{-3}<x<1$	>1
			Rare	Unlikely	Probable	Likely	Almost Certain
			Likelihood				

Table 4.3: Risk matrix description

Risk	Level	Risk qualitative description
High	L1	Unacceptable risk: Terminate activities immediately. Risk reduction is required to either reduce the probability and/or mitigate the severity of the consequences.
Medium	L2	Intolerable: - Tasks should not begin or should be terminated. - For new processes or work activities, add safeguards to achieve ALARP before starting the process or activity. - For existing processes or operational activities, a regionally approved and prioritized risk reduction plan is required to achieve ALARP.
Low	L3	Tolerable if ALARP: Manage existing controls/barriers to ensure continuous risk reduction and demonstrate best practice.
Tolerable	N/A	Broadly acceptable: Manage existing controls/barriers and take opportunities for further risk reduction when appropriate.

4.3.2 HAZOP Study Findings

According to the HAZOP worksheet (see Appendix), a total of 81 potential hazardous scenarios were identified and evaluated using a qualitative 5×5 risk matrix (frequency of occurrence × severity of impact). This approach delineates both localized hazards within each node and broader systemic vulnerabilities arising from node-to-node interdependencies. Deviations were

assessed for causes, consequences and existing safeguards, at each node, and inter-node dependencies were also considered to capture system-level vulnerabilities.

The analysis revealed a diverse risk profile for the firing system:

- High Risks: 14 scenarios (17%)
- Medium Risks: 25 scenarios (31%)
- Low Risks: 34 scenarios (42%)
- Tolerable Risks: 8 scenarios (10%)

This distribution is visualized in the pie chart in Figure 4.2, which illustrates the risk profile of the system under study. While most of the identified hazards fall into the low-to-medium risk categories, the notable proportion of high-risk scenarios highlights the necessity for targeted mitigation efforts.

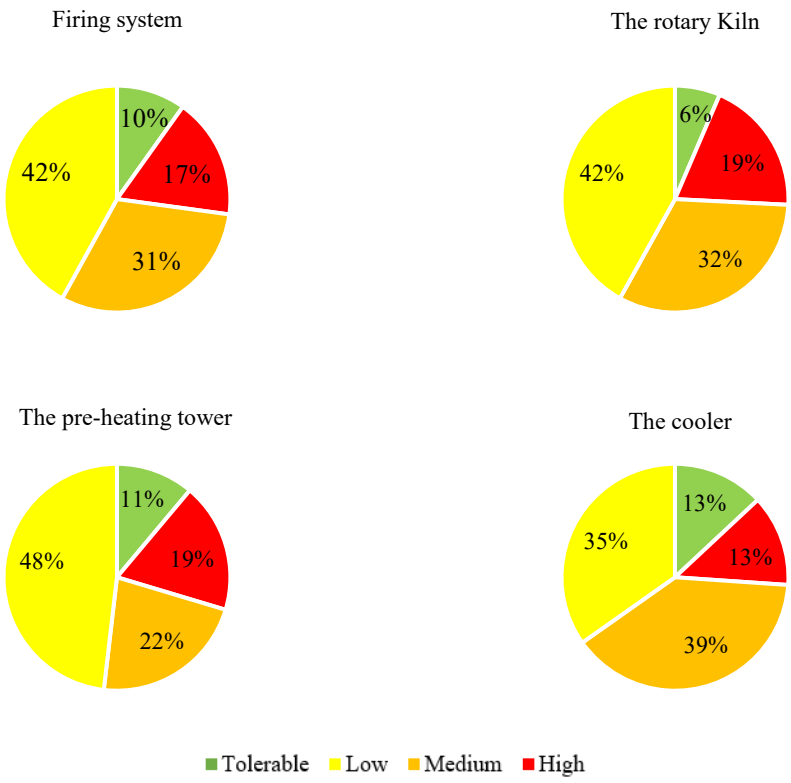


Figure 4.2: HAZOP Risk Profile of the LCM Cement Plant Firing System

4.3.2.1 Interpretation of the HAZOP Results

The HAZOP analysis identified the risk profile of the firing zone, with results revealing critical interdependencies across the three units that give rise to systemic risk. Although most deviations are low-to-medium severity, the system's close coupling and bidirectional interactions mean local disturbances can easily cascade. A disturbance in one node, whether upstream or downstream, can propagate non-linearly, creating emergent hazards at the system level.

For example, blockages in the preheating tower (recurrent deviation) can cause sudden surges of hot meal into the downstream kiln and then the cooler. This sharply increases the risk of thermal and mechanical stresses, elevates emissions, reduces refractory life, and raises personnel risk. Likewise, insufficient tertiary air from the cooler to the upstream calciner can adversely affect combustion stability and calcination kinetics. This increases the likelihood of incomplete combustion, elevated CO, and unburned fuel, thereby creating the potential for an explosion.

In the clinker production line, systemic risks arise from factors intrinsic to its architecture and dynamics. The most significant contributor is the functional interdependence between units, which is a result of the bidirectional exchange of energy (hot gases, heat), materials (hot meal, dust, volatile elements), and control signals. This dynamic exchange makes the kiln line a complex and closely coupled system. Shared equipment, such as the main ID fan, adds further points of coupling. Furthermore, deviations may originate in the upstream sections of the LCM plant, particularly in the stages of raw material preparation and homogenization, and propagate downstream, affecting the stability of the firing system.

This underscores the need for a comprehensive review of control architectures, interlocks, alarm management, and operating procedures to evaluate that they can manage disturbances originating upstream or downstream, stabilize plant operation, and prevent minor events from escalating into high severity incidents. To this end, the next section applies the BORA method to two scenarios: uncontrolled release of hot material and explosion. It identifies the initiating events of these scenarios, models safety barriers performance and maps the possible consequences that may emerge elsewhere in the process.

4.4 BORA application

Based on an analysis of the HAZOP worksheet and interviews with a group of multidisciplinary experts, two critical accident scenarios have been identified.

- **Scenario A**: Uncontrolled Hot Material Leakage. In the preheating tower, the most critical event is a cyclone blockage. This can cause a sudden, massive spill of very hot, fluid, and caustic material, dust, and gas, leading to severe burn injuries and fatal accidents, particularly during accidental discharge or manual removal. This is classified as a high-risk event.
- **Scenario B**: Explosion. In the furnace, the main undesired event is the loss of flame during a cold kiln start-up. This can result in the accumulation of unburned fuel and flammable gases, such as carbon monoxide (CO). Serious explosions can be triggered by subsequent re-ignition or static electricity when a sufficient air-gas mixture is present.

For the purpose of this analysis, accident history analysis, Root Cause Analysis (RCA), and the company's internal databases were used to evaluate the status of Risk Influence Factors (RIFs) and assign their weights within the risk influence diagrams.

4.4.1 Scenario A: Uncontrolled Hot Material Leakage

A cyclone blockage is a frequent operational problem that disrupts and blocks the downward flow of hot furnace feed and the upward flow of hot exhaust gases, often resulting in an unplanned kiln stoppage. Under normal operation, hot meal flows freely through the heating zone; when a blockage occurs, the free-flowing hot meal backs up inside the heating zone. With a kiln feed rate of 360 t/h, a stoppage of just one minute means that approximately 6 tons of hot meal are retained upstream. Therefore, a prompt and appropriate response to cyclone blockage detection is crucial.

As a confined space, the cyclone is prone to clogging due to various factors (see Figure 4.3). Their removal is a dangerous and time-consuming operation. A mass of backed-up hot meal can suddenly flow freely through the system, resulting in a meal surge (a hot meal avalanche). This typically generates a large amount of hot material, dust, and gas, creating a direct safety hazard to personnel.

4.4.1.1 Root Causes of Cyclone Blockage

The frequency of cyclone blockage depends strongly on the preparation of raw materials, the fuel used, and the combustion in the kiln. Several factors influencing the occurrence of cyclone blockage, including:

- Mechanical obstructions or buildups of material;
- Material falling from the walls, such as refractory or deep tubes;
- Tipping valve blockages (e.g., seized articulations, imbalanced counterweights);
- Incorrect geometry of the meal chute (e.g., elbows, internal diameter);
- High temperatures that make materials sticky;
- Chemical imbalances and excess volatile elements resulting from poor combustion or the use of alternative fuels.

Figure 4.3 shows the root cause analysis for this undesired event.

4.4.1.2 Barrier Identification and Modeling for Scenario A

As depicted in the BBD (see Figure 4.4), the main barrier functions include a safety IPL alarm and a safety interlock. Alarms and the operator's response play a critical role as the first layer of protection. In the event of a cyclone blockage, upon detection, the alarm system alerts the operator to the need for action. Unlike automated systems, operators have to manually de-clog cyclones in response to alarms by activating the air blasters. If this manual clearance fails, the safety interlock initiates an automatic kiln stoppage by performing the following sequencing actions:

- shutting off all fuel supply; to the calciner via redundant ESDVs (ESDV 3 or ESDV 4) and to the main burner via redundant ESDVs (ESDV 1 or ESDV 2);
- halting kiln feed (via the kiln feed valve);
- stopping the kiln main drive (via the kiln motor actuator);
- reducing ID fan draft to minimum (via isolation damper).

If the interlock also fails to operate as designed, pressure build-up in the preheater can result, potentially causing large-scale, uncontrolled discharge of hot material or, in worst cases, an explosion.

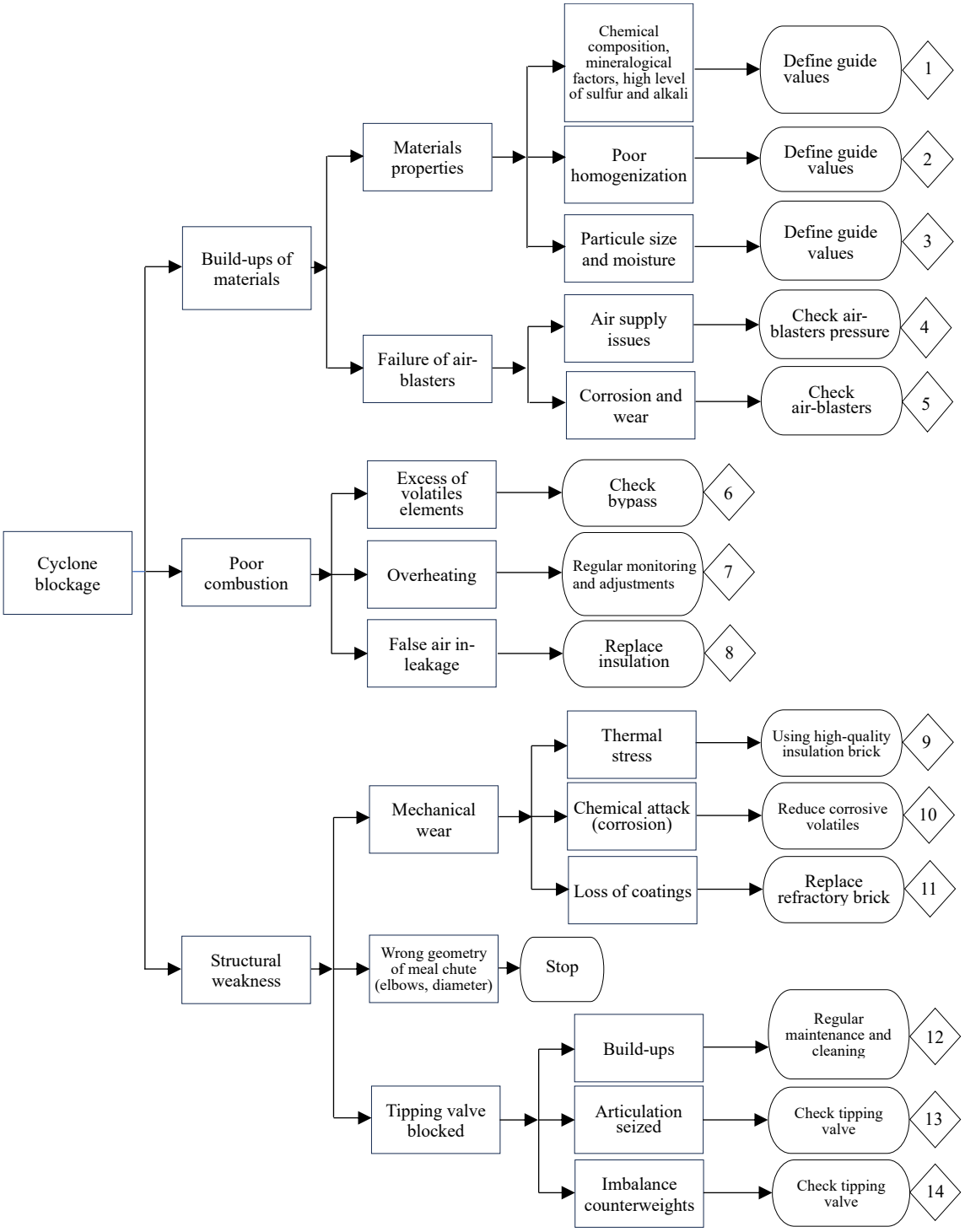


Figure 4.3: RCA for cyclone blockage

The barrier block diagram for scenario A is shown in Figure 4.4. The fault trees for the IPL 1A (safety IPL alarm) and IPL 2A (safety interlock) are illustrated in Figure 4.5 and Figure 4.6. Further, the risk-influence diagrams for the basic events A are shown in Figure 4.7.

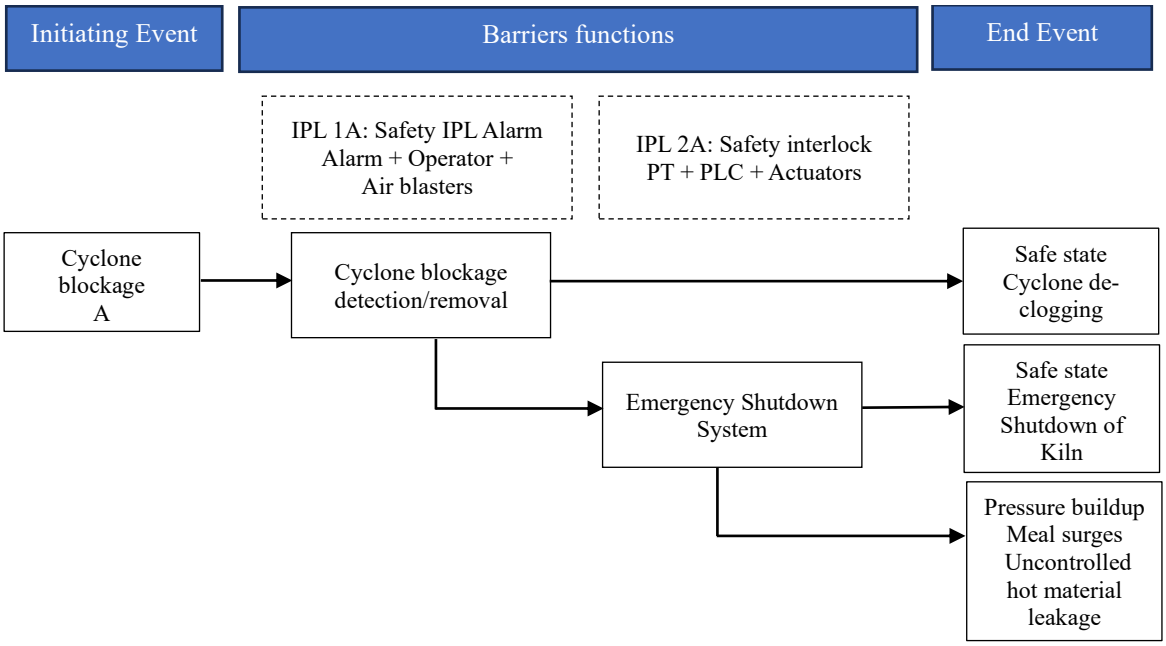


Figure 4.4: Barrier block diagram for uncontrolled hot material leakage scenario

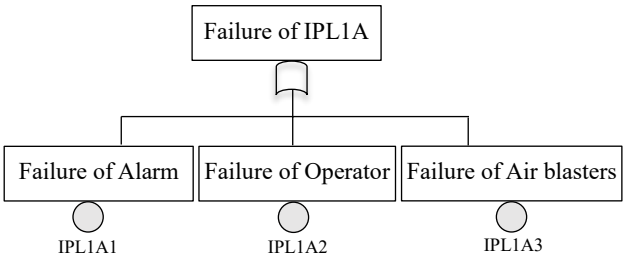


Figure 4.5: Fault tree for barrier IPL 1A

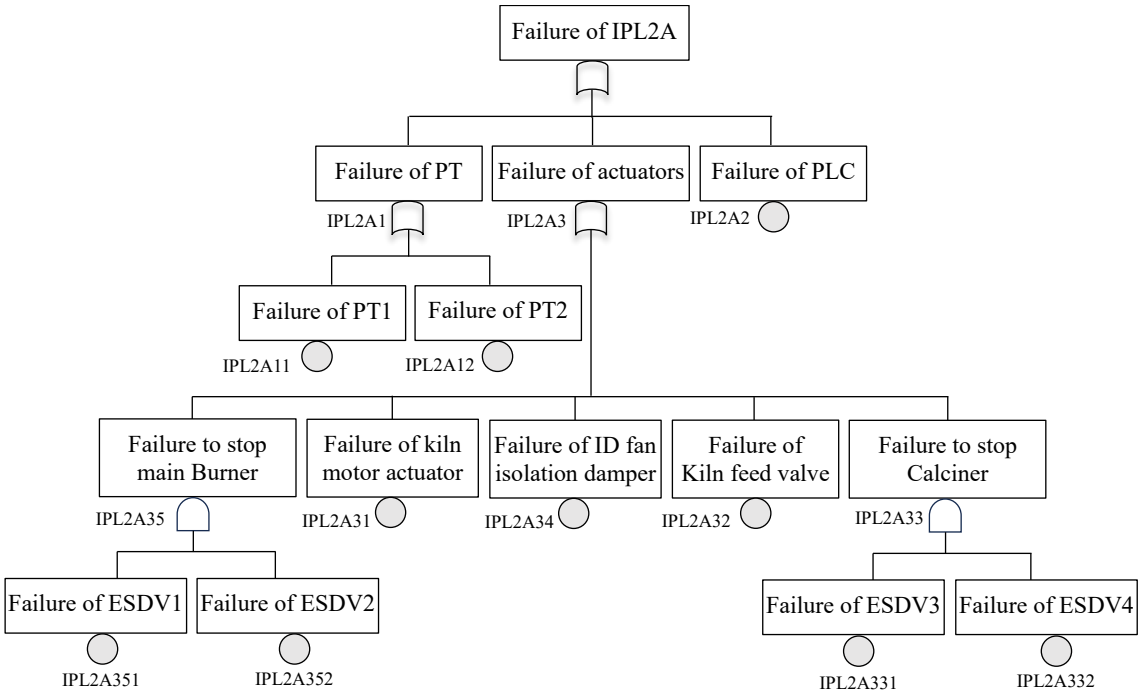


Figure 4.6: Fault tree for barrier IPL 2A

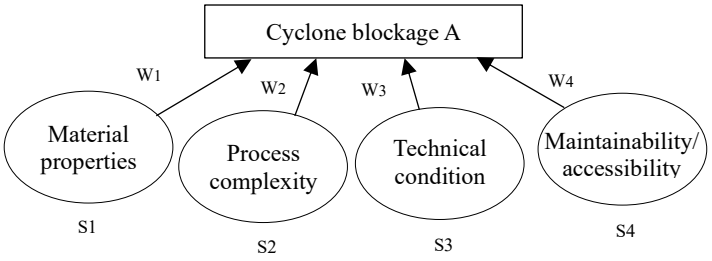


Figure 4.7: Risk influence diagram for initiating event A (cyclone blockage)

4.4.1.3 Frequency and Probability Data for Scenario A

Table 4.4 presents the assigned industry-average frequency for Initiating Event A (cyclone blockage) and the corresponding probabilities of the basic events associated with the credited IPLs elements (e.g., operator response to alarm, ESDV closure on demand). The frequency of the initiating event is set at 0.33 per year and is derived from historical LCM data and expert judgment. The basic-event probability values for each IPL element are taken from published data and validated through expert assessment.

Table 4.4: Assigned average probabilities for scenario A

IPL	Basic events	Assigned data	Data source
IPL1A1	Failure of Alarm	0.0115	Stauffer and Clarke (2016)
IPL1A2	Failure of operator	0.001	Stauffer and Clarke (2016)
IPL1A3	Failure of Air blasters	0.013	Expert judgment
IPL2A11	Failure of PT 1	0.000419	Stauffer and Clarke (2016)
IPL2A12	Failure of PT 2	0.000419	Stauffer and Clarke (2016)
IPL2A2	Failure of PLC	0.0000685	Stauffer and Clarke (2016)
IPL2A31	Failure of kiln motor actuator	0.00015	Expert judgment
IPL2A32	Failure of Kiln feed valve	0.0125	Stauffer and Clarke (2016)
IPL2A351	Failure of ESDV 1	0.00316	Bourareche et al., (2015)
IPL2A352	Failure of ESDV 2	0.00316	Bourareche et al., (2015)
IPL2A34	Failure of ID fan isolation damper	0.047	Expert judgment
IPL2A331	Failure of ESDV 3	0.00316	Bourareche et al., (2015)
IPL2A332	Failure of ESDV 4	0.00316	Bourareche et al., (2015)

4.4.1.4 Scenario A Frequency Results –RIFs Selection, Weighting, and Scoring (A–F)

Table 4.5 presents the normalization method used to assign weights to the Risk Influence Factors (RIFs) for the cyclone blockage event, applied consistently throughout this study. In line with best practice, the number of RIFs for each initiating event is limited; for Scenario A (cyclone blockage), four RIFs are considered:

- **Material properties**: weight 10, identified as the most influential factor affecting blockage frequency;
- **Maintainability / accessibility**: weight 8;

- **Process complexity**: weight 2;
- **Technical condition**: weight 2.

These weights reflect the relative influence of each factor on the likelihood of cyclone blockage, based on expert judgement and normalization criteria described earlier.

Table 4.5: Example of weighting by normalization (cyclone blockage)

RIF	Importance (weight)					Normalized weight of RIF
	High (10)	(8)	(6)	(4)	Low (2)	
Material properties	x					10/22=0.454
Process complexity					x	2/22=0.091
Technical condition					x	2/22=0.091
Maintainability/accessibility		x				8/22=0.364
Weight	10	8	0	0	4	
Total weight	22					1

For the scoring method, each RIF is evaluated based on expert judgement and calculated using Equations (4)-(7).

For example, the status of material properties is set to C (*Industry average*) by expert judgement. According to Equation (4), this corresponds to a score $Q_i(s)=1$. The multiplication factor (MF) is then calculated as: MF=0.454×1=0.454

This methodology is applied consistently to score all other RIFs in this study.

Table 4.6 summarizes the input data, normalized weights, scores, and adjustment factors (MF) of scenario A.

The average frequency of scenario A (uncontrolled hot material leakage) is determined based on its BBD (see Figure 4.4):

$$f_{(Acci,scen\ A)} = f_{IE_A}.P_{IPL_{1A}}.P_{IPL_{2A}} = (0,33).(0,025).(0,06) = 4,95\,E-4\,/\,year \quad (9)$$

The revised frequency of scenario A is calculated using the equation (8):

$$f_{(Acci,scen\ A)rev} = f_{revIE_A}.P_{revIPL_{1A}}.P_{revIPL_{2A}} = (0,379).(0,05).(0,071) = 1,34\,E-3\,/\,year \quad (10)$$

The calculated frequency of uncontrolled leakage of hot materials due to cyclone blockage is 4.95×10^{-4} /year, based on industry-average data. The corresponding revised analysis yields a frequency of 1.34×10^{-3} /year. Consequently, the frequency of scenario A has increased by approximately 170%.

As shown in Table 4.6, we note that the frequency of the initiating event (cyclone blockage) has increased by 14%, from 0.33 to 0.379 per year. The probability of failure of IPL1A has increased by 100% (from 0.025 to 0.05), while the probability of failure of IPL2A has increased by 18% (from 0.06 to 0.071).

Table 4.6: Scenario A, industry average probabilities/frequencies, weights, scores, and revised probabilities/frequencies

Basic event	P_{ave}	P_{low}	P_{high}	Basic event/RIF	Importance Weight	Normalized weight of RIF	Status of RIF (s_i)	Score of RIF (Q_i)	MF $\Sigma w_i.Q_i$	$P_{revised}$
A	0.33	0.165	0.66	P (Cyclone blockage)	-	1	-	-	1.15	0.379
				Material properties	10	0.454	C	1	0.454	
				Process complexity	2	0.091	C	1	0.091	
				Technical condition	2	0.091	D	1.33	0.121	
				Maintainability/accessibility	8	0.364	D	1.33	0.484	
IPL1A	0.025	0.0025	0.25	P (Failure of IPL1A)	-	1	-	-	2.125	0.05
				System feedback	4	0.091	C	1	0.091	
				Procedures	10	0.227	B	0.55	0.125	
				Time pressure	10	0.227	D	4	0.908	
				Working load/stress	8	0.182	D	4	0.728	
				Competence	10	0.227	C	1	0.227	
				Maintainability/accessibility	2	0.046	C	1	0.046	
IPL2A	0.06	0.0198	0.180	P (Failure of IPL2A)	-	1	-	-	1.185	0.071
				System feedback	10	0.25	C	1	0.25	
				Process complexity	4	0.1	C	1	0.1	
				Procedures	10	0.25	B	0.67	0.167	
				Maintainability/accessibility	10	0.25	D	1.67	0.417	
				Technical condition	6	0.15	D	1.67	0.251	

In this scenario, depending on the location of the blockage and the volume of accumulated material, there is a significant risk of direct contact with hot material. Stopping the kiln system is required for manual removal of the cyclone blockage. During this operation, personnel are exposed to multiple hazards, including:

- Sudden spillage or ejection of hot, fluid materials, gases, and dust through cleaning ports and inspection doors;
- Potential engulfment by hot material;
- Falls from height;
- Thermal or chemical burns, skin and eye irritation, and asphyxiation, potentially fatal;
- Layers of hot dust on floors, which may not be visually apparent;
- Blocked escape routes as well as visibility issues due to dust or steam;
- Hot meals can also ignite electrical cables and hoses, triggering a fire or an explosion in the event of gas accumulation.

Given the significant increase in the revised frequency of hazardous hot material releases from Scenario A and the subsequent potential for direct personnel exposure and other operational risks, it is essential to implement an action plan to prevent cyclone blockage. Table 4.7 outlines the specific measures proposed to prevent the initiating event for Scenario A.

A more detailed analysis of these findings is presented in the *Results and Discussion* chapter.

4.4.1.5 Action Plan to Prevent Cyclone Blockage

As shown in Figure 4.3, the primary cause of cyclone blockage is the formation of build-ups, which can occur in different parts of the heating system. Therefore, process parameters should be optimized to reduce build-ups caused by material properties (optimize chemical composition, homogenization, and particle size, keep levels of sulfur, alkalis, and moisture low) and volatilization phenomena created by poor combustion or the use of alternative fuels. Additionally, automatic cleaning devices (air-blasters) should be positioned and maintained to effectively prevent clogging and remove build-ups without human intervention. These systems must be considered safety devices, and their functioning should be monitored by pressure transmitters. These systems must be isolated and depressurized prior to any manual removal of the cyclone blockage.

Moreover, the performance of the cyclone preheater depends heavily on the quality of the refractory bricks and the exhaust gas conditions. Refractory bricks should be replaced as soon as they lose their mechanical or thermal properties.

Finally, controlling combustion processes, performing maintenance, providing training, and optimizing the use of materials will substantially reduce the likelihood of cyclone blockages, minimize the frequency of hazardous releases, and ensure the safety of personnel and operational continuity.

Table 4.7: An action plan to prevent cyclone blockage

Class	N°	Action	Priority
Status/setting equipment	4	Check that the air blaster, including the compressed air supply, is in full operating order.	1
	5		1
	6	Check the bypass system.	2
	12	Check that the flap valves in the meal chutes are moving freely and are correctly adjusted.	1
	13		1
	14		1
Guides values for procedure	1	Optimize kiln feed composition (raw meal): ensure proper chemical composition, efficient homogenization and particle size, and low levels of sulfur, alkalis, and moisture.	1
	2		1
	3		1
	7	Optimize temperature control: maintain stable temperatures and avoid hot spots.	2
	15	Control temperature, pressure, and feed rates to prevent fluctuations.	1
New Materials	8	Opt for new, high-quality insulation and ensure it is properly installed and maintained (flange and flexible joints, inspection flaps, and cleaning doors).	2
	9	Subject refractory bricks to regular safety audits/inspections. Replace them as soon as they lose their mechanical or thermal properties.	2
	10		2
	11		2

Class	N°	Action	Priority
Additional actions	16	Implement a cyclone cleaning procedure each time the kiln is shut down.	3
	17	Perform regular inspection and maintenance.	2
	18	Describe cyclone blockage removal in a safety operating procedure (SOP) and communicate it to staff.	2
	0	Resize the container to contain the full quantity of materials released.	1
Training	19	Provide training and awareness sessions.	2

4.4.2 Scenario B: Explosion

Incomplete combustion commonly causes explosions in clinker production lines, resulting in elevated concentrations of explosive by-products such as carbon monoxide (CO) and unburned methane (CH4).

During cold-kiln start-up on natural gas, loss of burner flame can occur, especially when the temperature falls below the auto-ignition temperature of methane (650°C)—allowing unburned fuel to accumulate if not promptly detected and isolated. In this scenario, the flame went out and the operator failed to detect the incomplete combustion, and the interlock designed to shut off the gas did not function. As a result, natural gas accumulated inside the kiln and smoke chamber to a sufficient concentration, forming an explosive atmosphere that could most likely be ignited by reignition, sparks in chain, static electricity, or hot surfaces.

Several factors can cause a loss of flame, including:

- Dust smothering;
- Infiltration of false air;
- Draft irregularities;
- Ring formation inside the furnace;
- Burner malfunctions;
- Insufficient combustion air due to poor kiln ventilation.

4.4.2.1 Barrier Identification and Modeling for Scenario B

As depicted in the BBD (see Figure 4.8), the main barrier functions include a safety interlock UV flame detector, a furnace camera/operator, and a safety interlock gas analyzer.

The UV flame detector serves as the first layer of protection. In the event of a flame loss, it sends a trip signal to the PLC, closing the control valve.

If this fails, the shift supervisor uses the furnace camera to verify the presence of a flame. However, this device often experiences poor picture quality due to dust accumulation, which can cause contrast delay, and/or optical device issues. In such cases, the shift supervisor then dispatches a roundsman for an on-site inspection. The roundsman manually closes isolation valves 1 or 2 if no flame is present.

If these measures also fail, the safety interlock gas analyzer serves as the final safeguard. When the kiln inlet analyzer and/or the preheater outlet analyzer detect unburned methane (CH4) gas or presence of CO, they trigger a trip signal to the PLC to close the burner fuel supply via redundant ESDVs (ESDV 1 or ESDV 2).

If all these measures fail, unburned gas can accumulate, which, if ignited, could lead to a full-scale explosion.

The barrier block diagram for scenario B is shown in Figure 4.8. The fault trees for IPL 1B, IPL 2B and IPL 3B are illustrated in Figure 4.9, Figure 4.10 and Figure 4.11. Further, the risk influence diagrams for the basic events B are shown in Figure 4.12.

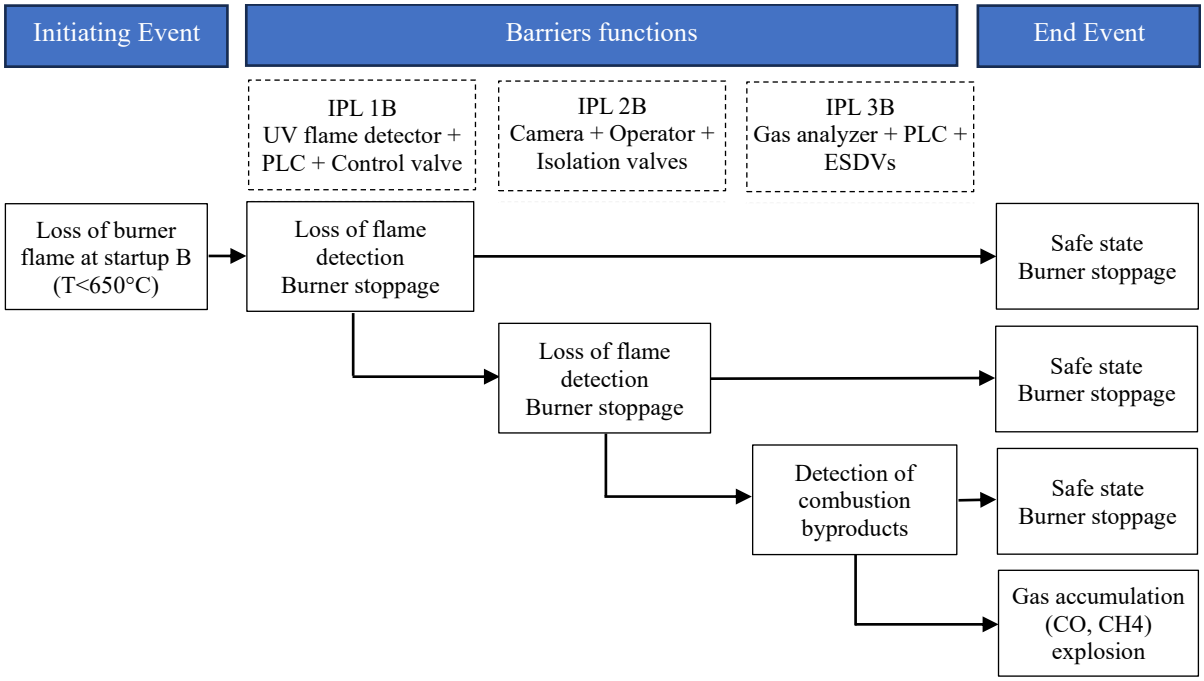


Figure 4.8: Barrier block diagram for explosion scenario

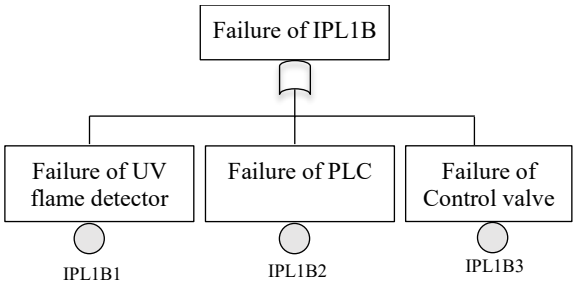


Figure 4.9: Fault tree for barrier IPL 1B

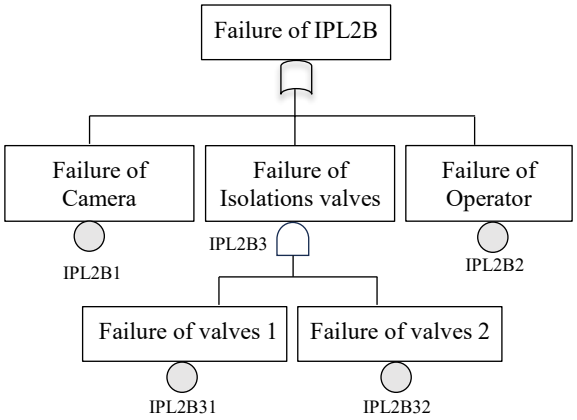


Figure 4.10: Fault tree for barrier IPL 2B

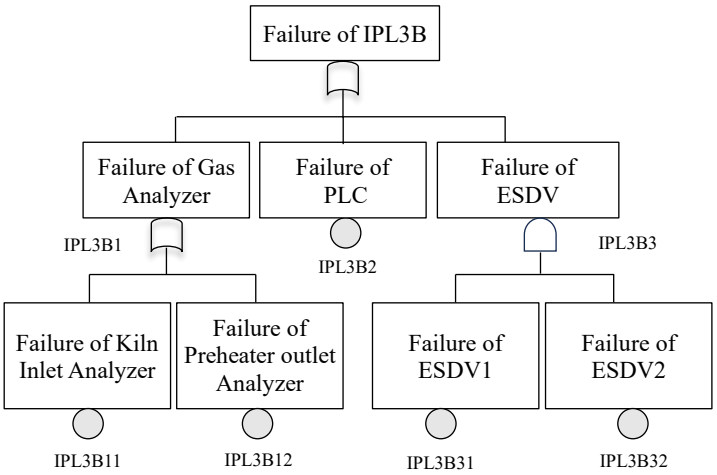


Figure 4.11: Fault tree for barrier IPL 3B

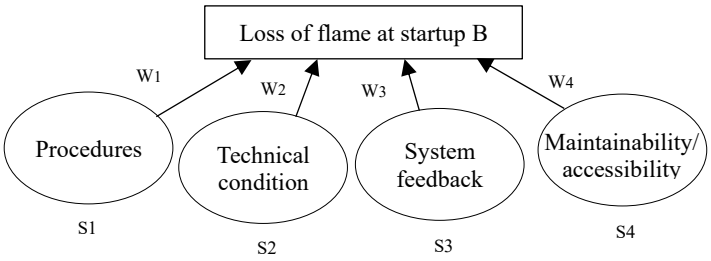


Figure 4.12: Risk influence diagram for initiating event B (loss of flame)

4.4.2.2 Frequency and Probability Data for Scenario B

Table 4.8 presents the assigned industry-average frequency for Initiating Event B (loss of flame) and the corresponding probabilities of the basic events associated with the credited IPLs elements. The frequency of the initiating event is set at 0.05 per year and is derived from historical LCM data and expert judgment. The basic-event probability values for each IPL element are taken from published data and validated through expert assessment.

Table 4.8: Assigned average probabilities for scenario B

IPL	Basic events	Assigned data	Source
IPL1B1	Failure of UV flame detector	0.03	Expert judgment
IPL1B2	Failure of PLC	0.0000685	Stauffer and Clarke, (2016)
IPL1B3	Failure of control valve	0.00316	Expert judgment
IPL2B1	Failure of kiln camera	0.0035	Expert judgment
IPL2B2	Failure of operator	0.001	Stauffer and Clarke, (2016)
IPL2B31	Failure of isolation valve 1	0.0125	Stauffer and Clarke, (2016)
IPL2B32	Failure of isolation valve 2	0.0125	Stauffer and Clarke, (2016)
IPL3B11	Failure of kiln inlet analyzer	0.00143	Expert judgment
IPL3B12	Failure of the preheater outlet analyzer	0.00143	Expert judgment
IPL3B2	Failure of PLC	0.0000685	Stauffer and Clarke, (2016)
IPL3B31	Failure of ESDV1	0.00316	Bourareche et al., (2015)
IPL3B32	Failure of ESDV2	0.00316	Bourareche et al., (2015)

4.4.2.3 Scenario B Frequency Results –RIFs Selection, Weighting, and Scoring (A–F)

As mentioned above, the same steps are followed for the weighting and scoring method as for the cyclone blockage analysis. Table 4.9 summarizes the input data, normalized weights, scores, and adjustment factors (MF) of scenario B.

In scenario B, we adjust Equation 8 to accurately account for the high probability of ignition due to sparks in chains, static electricity, welding operations, etc.

The average frequency of explosion scenario B is determined based on its BBD (see Figure 4.8):

$$\begin{aligned} f_{(Acci,scen\ B)} &= f_{IE_B}.P_{IPL_{1B}}.P_{IPL_{2B}}.P_{IPL_{B3}}.P_{Ignition} \\ &= (0,05).(0,033).(0,0046).(0,0029).(0,55) = 1,21E-8/\ year \end{aligned} \tag{11}$$

The revised frequency of explosion scenario B is calculated using the equation (11):

$$\begin{aligned} f_{(Acci,scen\ B)rev} &= f_{rev\ IE_B}.P_{rev\ IPL_{B1}}.P_{rev\ IPL_{B_2}}.P_{rev\ IPL_{B3}}.P_{Ignition} \\ &= (0,074).(0,072).(0,0066).(0,0035).(0,55) = 6,76\,\mathrm{E}-8/\ year \end{aligned} \tag{12}$$

According to industry average data, the explosion frequency due to flame loss during startup is 1.21×10^{-8} per year. The corresponding revised analysis indicates a frequency of 6.76×10^{-8} per year, representing an increase of approximately 458% for scenario B.

As shown in Table 4.9, we note that the frequency of the:

- Initiating event (loss of flame): increased by 48% (from 0.050 to 0.074);
- IPL 1B failure probability: increased by 118% (from 0.033 to 0.072);

- IPL 2B failure probability: increased by 43% (from 0.0046 to 0.0066);
- IPL 3B failure probability: increased by 20% (from 0.0029 to 0.0035).

Table 4.9: Scenario B, industry average probabilities/frequencies, weights, scores, and revised probabilities/frequencies

Basic event	P_{ave}	P_{low}	P_{high}	Basic event/RIF	Importance weight	Normalized weight of RIF	Status of RIF (s_i)	Score of RIF (Q_i)	$\Sigma w_i.Q_i$	$P_{revised}$
B	0.05	0.01	0.25	P (Loss of flame during startup)	-	1	-	-	1.486	0.074
				Procedures	10	0.333	B	0.6	0.2	
				Technical condition	4	0.133	D	2.33	0.31	
				System feedback	6	0.2	C	1	0.2	
				Maintainability/ Accessibility	10	0.333	D	2.33	0.776	
IPL1B	0.033	0.0033	0.33	P (Failure of IPL1B)	-	1	-	-	2.194	0.072
				Procedures	10	0.28	B	0.55	0.154	
				System feedback	10	0.28	C	1	0.28	
				Technical condition	6	0.16	D	4	0.64	
				Maintainability/ Accessibility	10	0.28	D	4	1.12	
IPL2B	0.0046	0.0004	0.046	P (Failure of IPL2B)	-	1	-	-	1.436	0.0066
				HMI	10	0.23	C	1	0.23	
				Procedures	10	0.23	B	0.55	0.126	
				Competence	8	0.18	C	1	0.18	
				Communication	8	0.18	D	4	0.72	
				System feedback	8	0.18	C	1	0.18	
IPL3B	0.0029	0.0009	0.0087	P (Failure of IPL3B)	-	1	-	-	1.203	0.0035
				Procedures	10	0.28	B	0.67	0.188	
				System feedback	10	0.28	C	1	0.28	
				Technical condition	6	0.16	D	1.67	0.267	
				Maintainability/ Accessibility	10	0.28	D	1.67	0.468	

4.4.2.4 Root Causes of Scenario B

The root causes can be grouped into three main categories:

- **Lack of robust procedures**: inadequate start up procedures, improper ventilation settings, incorrect primary air settings, and insufficient monitoring of combustion process indicators (VOC, CO);
- **Quality and reliability of control equipment**: failure of interlocks to automatically shut off gas injection under unsafe combustion conditions (e.g., failure of the smoke chamber gas analyzer or the top preheater gas analyzer, which detect unburnt natural gas in the smoke chamber), and the absence of explosion vents;
- **Human errors**: operator at CCR and shift supervisor on-site.

Figure 4.13 shows the root cause analysis for Scenario B, while Table 4.10 lists the corresponding action plan.

4.4.2.5 Action Plan to Prevent Scenario B

Although explosions are infrequent in the cement industry, they pose a significant risk due to their sudden and potentially catastrophic nature. According to the RCA, installing an explosion vent in the smoke chamber should be the highest priority. In addition, it is vital to control combustion processes and schedule annual testing of interlocked kiln emergency stoppages within a computerized maintenance system.

Furthermore, the kiln's SOP should empower operators to halt the kiln system in case of an emergency. Performing leakage gas tests before start-up is also an essential practice to mitigate this scenario. Finally, the reliable and accurate functioning of the kiln inlet and preheater outlet analyzer systems is critical to prevent buildup problems, fires, and explosions.

Table 4.10: Action plan to prevent an explosion

Class	N°	Action	Priority
Status/setting equipment	1	Check leakages on gas burner	2
	2	Check calibration and range of measurements of Volatile Organic Compounds (VOC) analyzer	2
	4	Define guide values for primary air to have good combustion of natural gas	3
	8	Review kiln startup procedure (set startup temperature to 650°C and check the loops)	3
	9	Check mechanical conditions/settings of ID fan and damper	2
	12	Check improvement potential for existing camera: Define characteristics and compare them with actual, make the decision to buy new one or not	1
Guides values for procedure	3	Review procedure to have correct draft inside the kiln: negative pressure at kiln hood, ID fan working or not, etc.	1
	5	Define guide values for cooler fan flow to avoid disturbing the flame	2
	6	Display the setpoint of the precalciner valve on the main screen / trigger an alarm if the difference between the setpoint and the actual value is greater than 5%	2
	7	Define guide values for correct amount of natural gas	2
Interlocks	15 16	Review settings and interlocks procedures for Kiln	1
Training	11	Ensure reliable communication using walkie-talkies	1
	13	Train operators on gas risk and on new start-up procedure/ empower kiln operators to halt the kiln system in case of an emergency	1
New Equipment	0	Install pressure vents in the smoke chamber	1
	10	Install an automatic ignition burner	3

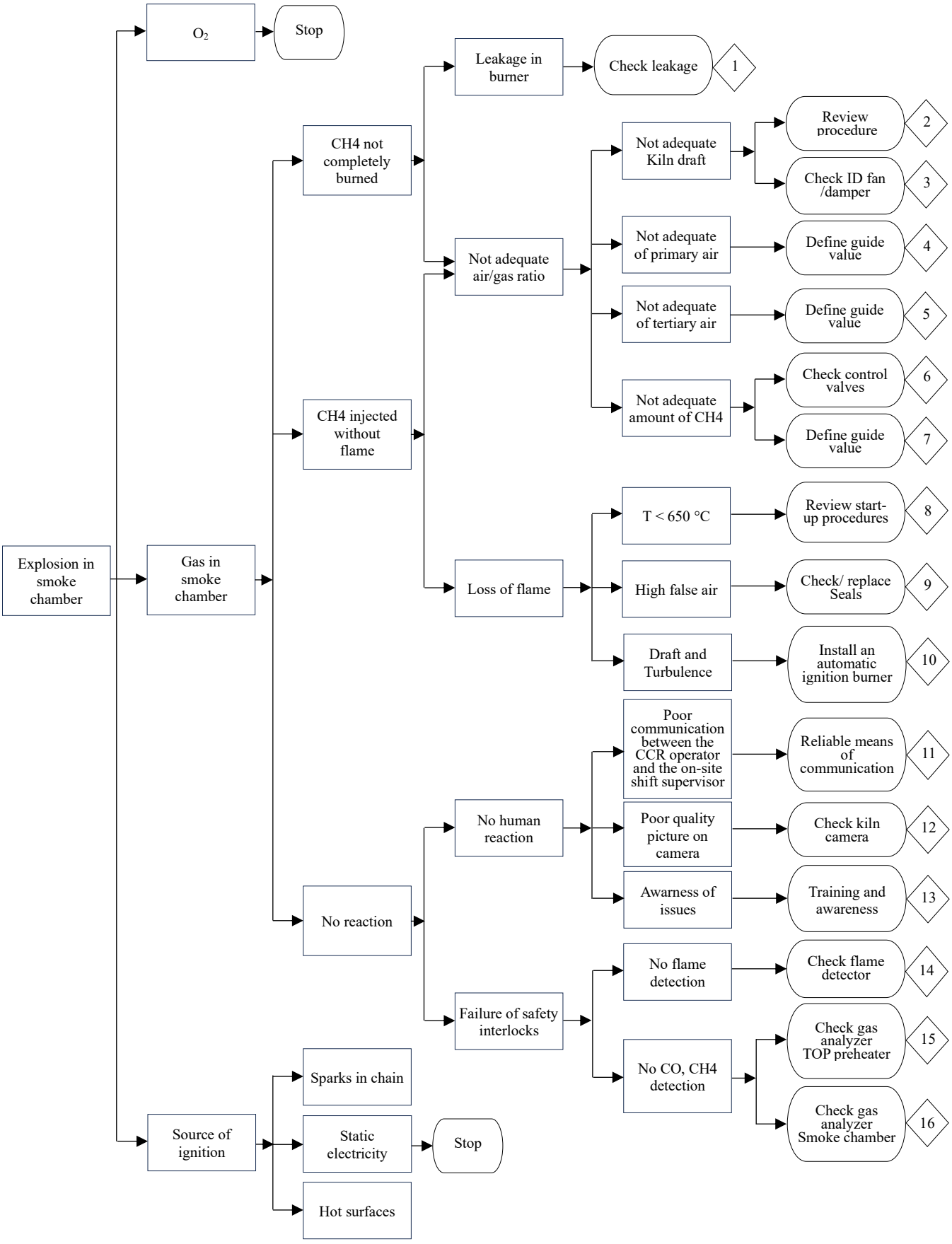


Figure 4.13: RCA for explosion scenario

In conclusion, the most common practices for proactively overcoming these unfavorable scenarios are regular maintenance and monitoring of key operating parameters to maintain safe functioning at peak efficiency, greater process uptime, and increased stability.

Equally important are comprehensive staff training and heightened awareness in advanced technical fields such as clinker chemistry, automation, and emergency management, coupled with consistent system monitoring, enable the real-time detection of emerging or existing blockages, potential malfunctions, or system failures. Through this proactive approach, swift adaptation of corrective measures is enabled, and critical situations are prevented from escalating.

4.5 Conclusion

The clinker manufacturing process is characterized by continuous large-scale flow of materials and intense energy exchange. Typical temperatures reach ~900 °C in the preheater, ~1450 °C in the kiln, and up to ~2000 °C in hot gas and flame zones. This harsh environment gives rise to inherent hazards, including severe thermal cycling that degrades refractories and kiln shells; chemical attack from volatile elements (e.g., alkalis, sulfur, chlorides); flame instability; and buildup formation that can cause recurrent blockages. The resulting risks range from property damage, unplanned shutdowns and serious injuries to adverse escalation levels, such as the uncontrolled release of hot material or explosions under certain conditions.

In this work, two undesirable events, cyclone blockage and loss of flame, are examined. These were identified as the most critical events through a HAZOP study and interviews with frontline personnel at the LCM plant. The subsequent BORA application revealed a revised, increased risk of uncontrolled hot material release due to cyclone blockage and a significantly elevated risk of explosion due to loss of flame. The analysis also identified the most contributing RIFs (Risk Influencing Factors) and causes using RCA.

The next chapter will discuss these results in detail and offer practical recommendations to improve process resilience and safety. The findings will inform loss prevention for the cement industry's pyroprocessing operations, highlighting the importance of addressing systemic health, safety, and environmental risks.

Chapter

5

Results and Discussion

Chapter 5: Results and Discussion

5.1 Introduction

The complexity and socio-technical nature of cement firing systems necessitate combined risk assessment tools such as HAZOP, BORA, and RCA. The application of the proposed methodology in a real cement plant has proven both feasible and effective for operational risk analysis. This study represents the first documented application of BORA in this industrial context, addressing a critical gap in cement process safety research.

The findings demonstrate the combined methodology's capacity and flexibility to model key hazards. It facilitates comprehensive modeling of hot material release, fire, and explosion risks in clinker production, providing a structured basis for preventative measures within pyroprocessing operations.

This chapter discusses the results, presents sensitivity and uncertainty analyses, examines the study's limitations and validity concerns, and concludes with practical recommendations.

5.2 Analysis of Findings

5.2.1 Scenario A

In the first scenario, the frequency of hot material leakage due to cyclone blockage has increased by 170%. Cyclone blockage is a relatively frequent operational event that can occur at any time. Predicting its occurrence is difficult because process measurements, such as pressure and temperature in the gas duct at the cyclone outlet exhibit a certain time delay, preventing early detection. This event is often caused by the chemical composition of the raw meal and the hot exhaust gases. Their removal is typically performed while the preheater remains hot, creating a high-risk, time-critical operation that increases both workload and stress on workers. In this context, the observed frequency increase aligns with the inherent operational challenges.

To address this issue, process parameters should be optimized to reduce build-up caused by material properties (chemical composition, efficient homogenization and particle size, low levels of sulfur, alkalis, and moisture) and volatilization phenomena created by poor combustion. In addition, the automatic cleaning devices (air-blasters) should be positioned and maintained to effectively prevent clogging and removing build-ups without human intervention. Their functioning should be monitored by pressure transmitters. Furthermore, the performance of the cyclone preheater is significantly influenced by the type and quality of the refractory bricks used. Refractory bricks must be replaced as soon as they lose their mechanical and thermal properties. Finally, control of combustion processes, maintenance, training, and the optimal use of materials are necessary to prevent cyclone blockage and the resulting high risks and costs.

5.2.2 Scenario B

In the second scenario, the frequency of explosion due to loss of flame during startup has increased significantly by 458%. The initiating event is operationally linked to Scenario A, as uncontrolled hot material leakage often results in an unplanned furnace shutdown and subsequent start-up procedures. Several technical factors can cause this event include dust smothering of the flame, infiltration of false air, draft irregularities, ring formation inside the

furnace, burner malfunctions, and insufficient kiln ventilation causing inadequate combustion air.

Deficiencies in operational procedures, including inadequate startup protocols, and limitations in the quality and reliability of control equipment and human errors further exacerbate the likelihood of this scenario. Considering these factors, and given the relatively low average frequency of explosion, the observed significant increase is consistent with the operational and technical vulnerabilities described.

To avoid this scenario, robust procedures, rigorous maintenance practices, and comprehensive training of personnel are of critical importance.

5.2.3 Interpretation of the Findings

In this study, safety barriers are modeled as Independent Protection Layers (IPLs) using the BORA methodology. In harsh, high-stakes operating environments, their reliability is often influenced by technical, human, and organizational factors (HOFs), all of which affect the probability of failure on demand.

Technical RIFs, such as mechanical wear, thermal stress, and chemical attack (e.g., corrosion), can degrade IPL performance. Meanwhile, HOFs like decision-making under time pressure to prevent costly delays can increase error rates and compromise overall effectiveness.

In continuous high-temperature, mechanically and chemically demanding environments, the performance of IPLs depends not only on their design specifications but also on the influence of Technical RIFs. Operational conditions such as dust loading, exposure to large masses of hot material, intense vibration, and material build-up can accelerate mechanical deterioration, induce thermal stress and cycling, and cause chemical attack from alkalis, sulfur, chlorides, or corrosive gas mixtures, each of which degrades the structural integrity, responsiveness, and reliability of critical safety functions. In addition, limited maintainability and reduced instrumentation reliability further increase the probability of failure on demand (PFD), widening the gap between the IPL's nominal (as-designed) reliability and its actual (as-operated) performance.

Managing these technical RIFs requires a systematic and continuous program that includes risk-based inspections, real time monitoring, optimized proof testing, heat load control, corrosion-resistant materials, redundant and well-calibrated detection systems and reliable actuators, and designs that facilitate safe accessibility and maintenance. Implementing these measures ensures that safety barriers maintain their intended performance under real world operating conditions, thereby lowering the probability and limiting the consequences of catastrophic events such as uncontrolled hot material release, fires, or explosions.

In the resource- and energy-intensive context of clinker manufacturing, the need for continuous production to sustain revenue and meet increasing demand creates persistent pressure on operations staff. This can result in risk-biased decision-making, such as delaying essential shutdowns in response to process deviations or for refractory lining replacement or coating removal. While best practices are well-defined, they are insufficient to manage all potential risks, particularly those related to Human and Organizational Factors (HOFs).

Operators are frequently required to make rapid decisions and take immediate action, especially in time-sensitive scenarios, such as responding to sudden cyclone blockages and loss of flame events. Under pressure to minimize downtime, they must simultaneously interpret multiple sensor readings, analyze complex data, initiate process adjustments, and coordinate team responses. Following the correct sequence of actions outlined in SOPs is inherently challenging in such situations. Even minor procedural deviations or miscommunication can escalate to serious accidents and costly downtime. For example, in scenario A, air blaster systems must be isolated and depressurized before manual cyclone blockage removal. Failure to follow LOTOTO procedures can result in unexpected, uncontrolled compressed air releases up to 10 bar, posing severe injury risks.

Regular inspection and maintenance, training, well-defined best practices, adapted operating procedures, and emergency response plans are crucial for ensuring safe and efficient operations. In this context, simulators, such as virtual cement plants environments, offer a realistic yet risk free training environment [207] in which operators can practice responses to abnormal conditions and enhance their performance in emergency scenarios.

Although the hazard of cyclone blockage and loss of flame in pyro-processing systems is well recognized, some aspects of its behavior remain uncertain. Certain design features, such as upstream and downstream joints intended to absorb thermal expansion during heating, can also function as weak points where hot materials escape, false air infiltrates, and mechanical wear accelerates. Furthermore, operational conditions such as overheating or elevated concentrations of volatile elements can cause the hazard to emerge unexpectedly, increase its probability, or intensify its consequences.

For example, high levels of volatile elements, such as sulfur trioxide (SO_3) and chlorine from fuels or raw materials can react with kiln dust to form hard, sticky deposits. Over time, the progressive accumulation of these deposits, exacerbated by false air ingress, can obstruct the flow of hot materials and process gases, resulting in recurrent blockages in critical sections, including ducts, cyclones, or even the rotary kiln. These obstructions cause potential deviations, increasing the potential for uncontrolled hot material release and severe equipment damage.

Cyclone blockages are often caused by material build-ups, poor combustion conditions, or structural weaknesses (e.g., incorrect geometry of the meal chute, such as elbows or diameter, refractory brick loss). A hot meal avalanche occurs when large amounts of hot material accumulate in the cyclone. When this material suddenly dislodges, it sends them cascading toward the kiln and subsequently into the cooler. However, the cooler often struggles to absorb and dissipate such extreme thermal loads rapidly. This situation is exacerbated by factors such as wear on upstream or downstream kiln seals, the collapse of a ring inside the kiln, or snowman formation at the cooler inlet. These issues can cause severe downstream effects, including crusher jamming, releases of hot meal, gas, and dust, and the ejection of hot clinker from the conveyor.

Spilled hot meal is often difficult to detect immediately and can cause severe injuries or even fatalities if it comes into contact with workers. Evacuation in such events becomes especially difficult due to the immediate effects of the hazard and reduced visibility caused by hot dust or clouds of hot material mixed with smoke from the interaction of hot meal and water. Furthermore, hot meal can also ignite nearby combustible materials, such as electrical cables,

hoses, lubrication oil, and grease, potentially leading to secondary fire or explosion risks that significantly amplify the severity of the incident.

5.3 Sensitivity Analysis

The purpose of this analysis is to evaluate the sensitivity of Scenario A frequency to the new quantification factor (*Qi*) values and to assess the impact of changing scores on the overall risk estimate. For example, the analysis will quantify how shifting material properties, identified as a key RIF for cyclone blockages, across a range of industry practices affects risk (see Table 3.2), both when improving toward best practice (C→B→A) and when degrading toward poor practice (C→D→E→F). Given the system's inherent complexity and the limited availability of detailed operational data, a targeted sensitivity analysis is the most suitable and robust approach at this stage.

The sensitivity analysis is limited to Scenario A as it represents a more relevant and frequent risk. While Scenario B (explosion) is also a potential risk, it is an infrequent event with a baseline frequency very close to zero "1.21×10^{-8} per year"; consequently, proportional changes comparable to those tested for scenario A would not materially alter the overall risk ranking or decision priorities. Moreover, Scenario B can be a direct result of Scenario A, as the latter mostly results in unplanned kiln shutdowns and subsequent startups, which are a key risk factor for explosion. If future evidence indicates a non-negligible increase in scenario B frequency (e.g., a rise in loss of flame events during startup), the analysis plan will be revisited to extend the sensitivity with tailored stress cases and operating assumptions.

For this study, the sensitivity analysis was conducted in a conditional and limited manner, using a one-at-a-time (OAT) approach. Owing to the multiplicative form of the BORA risk model "*see equation 8*", the components were examined separately:

The initiating event frequency was varied while the probabilities of failure on demand of the independent protection layers were kept fixed, and, conversely, each IPL was analyzed individually by fixing the initiating event and the other IPL. This procedure makes it possible to identify the most influential RIFs within each component of the model and to rank them according to their relative contribution to the revised risk of uncontrolled release of hot materials.

The method offers several clear benefits. It is simple to apply, computationally feasible, ensures completeness, adheres to the common assumption that the initiating event is independent of the independent protection layers (IPLs), and produces outcomes that can readily guide the selection of improvement measures. In many cases, detailed operational data are limited, particularly with respect to possible dependencies or correlations among RIFs—for example, the combined impact of inadequate training and deficient procedures. Incorporating such interaction effects would require additional assumptions, which could lead to uncertain or biased results. The proposed approach therefore represents a practical way of identifying the most influential factors and supporting risk-reduction decisions without resorting to comprehensive uncertainty modeling.

Some limitations must nevertheless be acknowledged. The method is essentially local: it does not consider possible interactions between RIFs, nor potential correlations among

organizational and human aspects. For instance, enhanced training may simultaneously reduce time pressure and improve adherence to procedures. Such interdependencies are not captured in the present analysis. Moreover, the combined effect of simultaneous variability across all parameters remains outside the scope of this work.

The adopted approach is practical and well suited to the available data. It provides a transparent basis for prioritizing actions to improve the safety barriers. When more comprehensive information becomes available, the analysis should be extended towards a global sensitivity study that accounts for joint uncertainties and possible interactions between influencing factors.

The script employed for this analysis is provided in Appendix B. The calculations were carried out using the open-source software *OCTAVE*, which offers robust tools for numerical computation and analysis in line with this methodology.

5.3.1 Frequency of Initiating Event (f_{IE})

The BORA analysis shows that the average initiating event frequency is 0.33, while the average occurrence frequency of Scenario A is estimated at 0.000495. These results represent baseline values that can be used as reference benchmarks to assess whether modifications in the risk-influencing factors contribute to an improvement or a degradation in the overall risk profile.

The analysis examined the impact of different 4 RIFs, identified as 1–4, on the frequency of cyclone blockage (f_{IE}), based on their scoring (s) and *Qi*. Each RIF was scored in accordance with recognized industry best-practice standards (see Table 5.1), using a scale from A (best practice) to F (worst practice). For the IE with 4 RIFs, each having 6 possible scores (A–F), the total number of combinations is 6^4=1296. Each case span from the most favorable condition (A–A–A–A) to the worst case (F–F–F–F). Each case reflects a distinct set of operational scenarios.

In this context, values of f_{IE} and $f_{scenario\ A}$ that fall below their respective averages indicate enhanced safety performance. Conversely, if they are higher, this points to potential shortcomings in risk management, thereby highlighting the need for corrective action or reinforcement of safety barriers.

Based on expert judgment, material properties were identified as the most critical risk influencing factor for the IE. To examine the marginal significance of each RIF, a single RIF was fixed at one level—for instance, RIF1 at A—while the remaining three RIFs were varied across all their possible values (from A-A-A to F-F-F). This generates 6^3 = 216 combinations for each fixed level. The average revised frequency of the IE was then determined for the case RIF1 = A, and the process was repeated for RIF1 = B, RIF1 = C, ……, through RIF1 = F. This yielded 6 separate mean values, each representing the marginal influence of RIF1 at a given score.

The same procedure was applied to RIF2, RIF3, and RIF4 in turn, ensuring each RIF was fixed at every score from A to F, while the other three were allowed to vary. As a result, each RIF was associated with its own set of 6 averaged outcomes, reflecting its relative contribution to the IE revised frequency under different scoring conditions and *Qi*. The results are presented in Table 5.2.

The *Qi* values for selected combinations of P_{low} and P_{high}, used throughout the analysis, are presented in Table 5.1.

Table 5.1: Qi for selected combinations of P low and P high

	Case 1 (0.5 – 2)	Case 2 (0.33 – 3)	Case 3 (0.2 – 5)	Case 4 (0.1 – 10)
A	0.5	0.33	0.2	0.1
B	0.75	0.67	0.6	0.55
C	1	1	1	1
D	1.33	1.67	2.33	4
E	1.67	2.33	3.67	7
F	2	3	5	10

The results of the sensitivity analyses are presented in Table 5.2, which highlights the scoring for each RIF. The scoring was deliberately chosen to represent specific operational conditions (case 5 adopted):

- The initiating event's sensitivity to RIFs was based on a typical operating range, case 1 (0.5 – 2).
- IPL 1's sensitivity to RIFs was based on the most extreme range, case 4 (0.1 – 10), to account for staff behavior under pressure during a blockage situation. Where the primary cause of most accidents involving hot meals is improper actions by staff in removing blockages, rather than the failure of safety barriers.
- IPL 2's sensitivity to RIFs was based on a representative, moderate range of variability, case 2 (0.33 – 3).

Table 5.2: Average revised frequency of f IE and of scenario A across cases.

RIFs	Score	Average revised frequency of f_{IE}					Average revised frequency of scenario A				
		Case 1 (0.5 – 2)	Case 2 (0.33 – 3)	Case 3 (0.2 – 5)	Case 4 (0.1 – 10)	Case 5 (adopted)	Case 1 (0.5 – 2)	Case 2 (0.33 – 3)	Case 3 (0.2 – 5)	Case 4 (0.1 – 10)	Case 5 (adopted)
RIF1 (Material properties)	A	2.93E-01	3.20E-01	4.14E-01	6.95E-01	2.93E-01	5.06E-04	6.82E-04	1.29E-03	4.63E-03	1.11E-03
	B	3.30E-01	3.71E-01	4.74E-01	7.63E-01	3.30E-01	5.71E-04	7.90E-04	1.48E-03	5.07E-03	1.25E-03
	C	3.68E-01	4.20E-01	5.34E-01	8.30E-01	3.68E-01	6.36E-04	8.96E-04	1.67E-03	5.52E-03	1.39E-03
	D	4.17E-01	5.20E-01	7.33E-01	1.28E+00	4.17E-01	7.21E-04	1.11E-03	2.29E-03	8.51E-03	1.58E-03
	E	4.68E-01	6.19E-01	9.34E-01	1.73E+00	4.68E-01	8.09E-04	1.32E-03	2.92E-03	1.15E-02	1.77E-03
	F	5.17E-01	7.20E-01	1.13E+00	2.18E+00	5.17E-01	8.95E-04	1.53E-03	3.54E-03	1.45E-02	1.95E-03
RIF2 (Process complexity)	A	3.77E-01	4.60E-01	6.46E-01	1.14E+00	3.77E-01	6.53E-04	9.81E-04	2.02E-03	7.55E-03	1.43E-03
	B	3.85E-01	4.70E-01	6.58E-01	1.15E+00	3.85E-01	6.66E-04	1.00E-03	2.05E-03	7.64E-03	1.45E-03
	C	3.92E-01	4.80E-01	6.70E-01	1.16E+00	3.92E-01	6.79E-04	1.02E-03	2.09E-03	7.73E-03	1.48E-03
	D	4.02E-01	5.00E-01	7.10E-01	1.25E+00	4.02E-01	6.96E-04	1.07E-03	2.22E-03	8.33E-03	1.52E-03
	E	4.13E-01	5.20E-01	7.50E-01	1.34E+00	4.13E-01	7.14E-04	1.11E-03	2.34E-03	8.93E-03	1.56E-03
	F	4.23E-01	5.40E-01	7.90E-01	1.43E+00	4.23E-01	7.31E-04	1.15E-03	2.47E-03	9.53E-03	1.60E-03
RIF3 (Technical condition)	A	3.77E-01	4.60E-01	6.46E-01	1.14E+00	3.77E-01	6.53E-04	9.81E-04	2.02E-03	7.55E-03	1.43E-03
	B	3.85E-01	4.70E-01	6.58E-01	1.15E+00	3.85E-01	6.66E-04	1.00E-03	2.05E-03	7.64E-03	1.45E-03
	C	3.92E-01	4.80E-01	6.70E-01	1.16E+00	3.92E-01	6.79E-04	1.02E-03	2.09E-03	7.73E-03	1.48E-03
	D	4.02E-01	5.00E-01	7.10E-01	1.25E+00	4.02E-01	6.96E-04	1.07E-03	2.22E-03	8.33E-03	1.52E-03
	E	4.13E-01	5.20E-01	7.50E-01	1.34E+00	4.13E-01	7.14E-04	1.11E-03	2.34E-03	8.93E-03	1.56E-03
	F	4.23E-01	5.40E-01	7.90E-01	1.43E+00	4.23E-01	7.31E-04	1.15E-03	2.47E-03	9.53E-03	1.60E-03

RIFs	Score	Average revised frequency of f_{IE}					Average revised frequency of scenario A				
		Case 1 (0.5 – 2)	Case 2 (0.33 – 3)	Case 3 (0.2 – 5)	Case 4 (0.1 – 10)	Case 5 (adopted)	Case 1 (0.5 – 2)	Case 2 (0.33 – 3)	Case 3 (0.2 – 5)	Case 4 (0.1 – 10)	Case 5 (adopted)
RIF4 (Maintainability/ accessibility)	A	3.14E-01	3.54E-01	4.72E-01	8.04E-01	3.14E-01	5.43E-04	7.56E-04	1.47E-03	5.35E-03	1.19E-03
	B	3.44E-01	3.95E-01	5.20E-01	8.58E-01	3.44E-01	5.95E-04	8.43E-04	1.62E-03	5.71E-03	1.30E-03
	C	3.74E-01	4.35E-01	5.68E-01	9.12E-01	3.74E-01	6.46E-04	9.27E-04	1.77E-03	6.07E-03	1.41E-03
	D	4.13E-01	5.15E-01	7.28E-01	1.27E+00	4.13E-01	7.15E-04	1.10E-03	2.27E-03	8.47E-03	1.56E-03
	E	4.54E-01	5.95E-01	8.89E-01	1.63E+00	4.54E-01	7.86E-04	1.27E-03	2.77E-03	1.09E-02	1.72E-03
	F	4.94E-01	6.75E-01	1.05E+00	1.99E+00	4.94E-01	8.54E-04	1.44E-03	3.27E-03	1.33E-02	1.87E-03

By averaging over all possible combinations across all RIFs, scores and cases, the approach implicitly accounts for the possibility of interaction effects between RIFs, even if these are not directly specified. Thus, when scenarios such as fixing RIF1 at score A while varying RIF2, RIF3, and RIF4 are considered, cases like A–F–F–F—where materials properties and the other factors are at their worst scores—are included in the calculation. For example, technical systems (e.g., faulty burners) may interact with suboptimal material properties, particularly under conditions of elevated temperature—conditions under which raw materials are prone to increased stickiness and hence a higher frequency of the initiating event. These scenarios help capture synergistic effects within the aggregate results, even in the absence of explicit isolation of such interactions. Furthermore, this averaging approach minimizes bias that could be introduced through selective scenario sampling and provides a computationally practical framework for analysis.

Figure 5.1 illustrates the relative influence of each RIF by showing how changes in its levels (A–F) affect the average IE frequency.

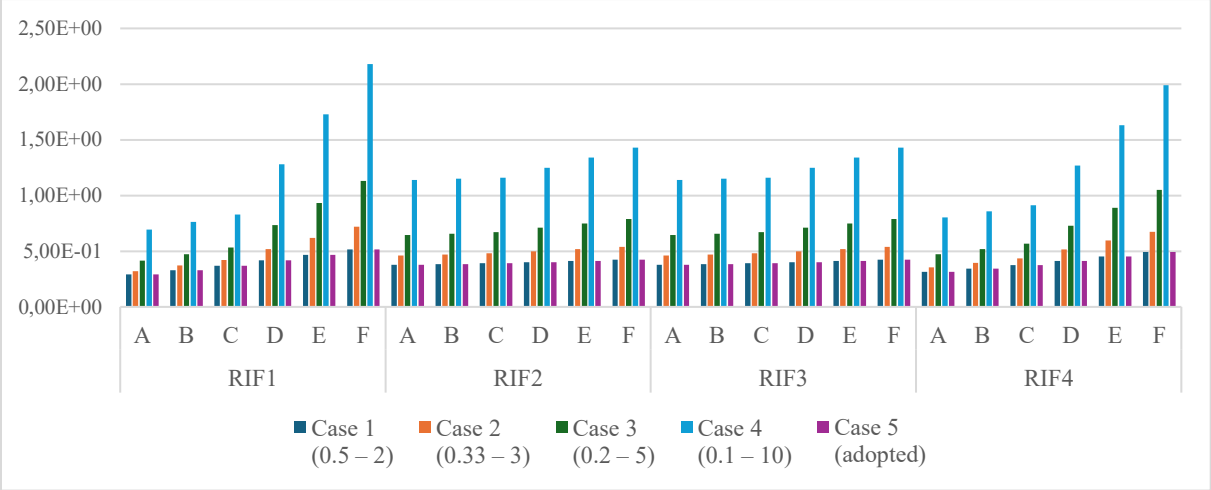


Figure 5.1: Average revised frequency of IE

Figure 5.2 illustrates the relative influence of each RIF by showing how changes in its levels (A–F) affect the average frequency of Scenario A.

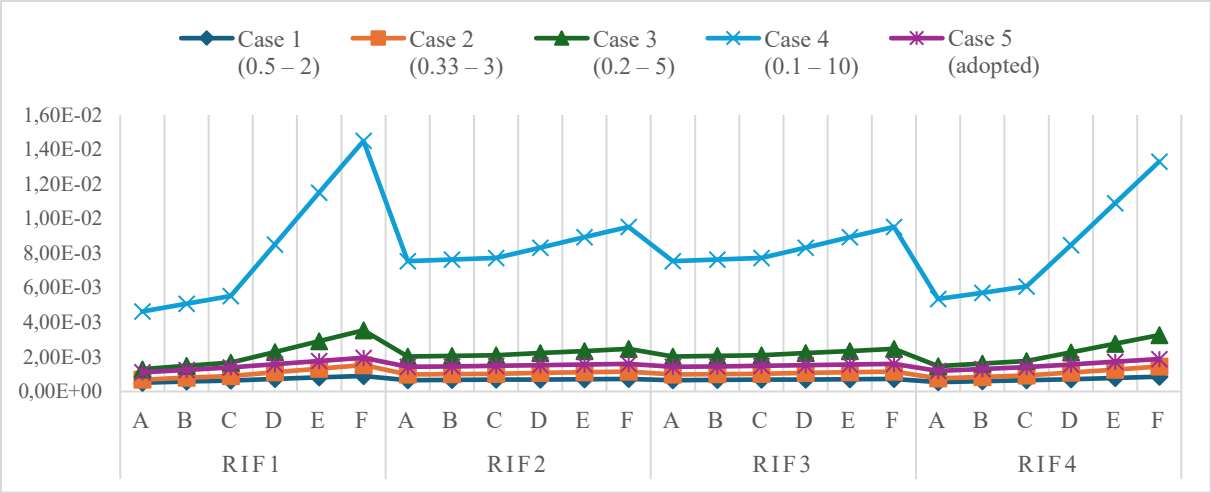


Figure 5.2: Average revised frequency of scenario A (IE)

5.3.2 Interpretation of the results of IE

As showed in Figure 5.1 and Table 5.2, the most influential RIF is RIF 1 (material properties), followed by RIF 4 (maintainability/accessibility). Properties such as chemical composition, particle size, and the presence of sulfur or moisture, can cause a buildup of material and concretion. Although RIF 4 is also a critical factor, in a practical operational context, accessibility to the cyclone is deliberately limited to avoid direct contact and reduce the introduction of false air. This is often achieved by minimizing the size and number of opening visit ports, as well as by limiting the number of workers and the time they spend on a task. Meanwhile, RIF2 and RIF3 show similar, smaller ranges of influence on the IE frequency.

Using an average frequency of f_{avg}=3.30×10−1 /year as the baseline, the analysis shows that the average revised frequency ($f_{avg\text{-}rev}$) and percentage change (P%) rise monotonically as RIF assumptions degrade from A to F across all cases. A similar pattern is observed when referencing the average frequency for Scenario A ($f_{avg\ scenarioA}$=4.95×10−4/ year), a worsening of any RIF from A to F results in a consistent escalation of the average revised release frequency for Scenario A across all configurations, and vice versa.

For example, when degrading RIF1 from A to F in case 4, the $f_{avg\text{-}rev}$ for the IE increases from 6.95×10−1 (+111%) to 2.18×10+0 (+561%). Similarly, for Scenario A, the $f_{avg\text{-}rev}$ rises from 4.63×10−3 (+835%) to 1.45×10−2 (+2829%).

In contrast, the most favorable configuration (A–A–A–A), the $f_{avg\text{-}rev}$ for the IE is reduced to 3.30×10−2 (-90%) and for Scenario A to 2.20×10−4 (-56%).

The results confirm that favorable RIF scores are essential for reducing both the frequency of initiating events and the scenario-specific release frequencies. The analysis further shows that the frequency of cyclone blockage is particularly sensitive to changes in material properties (RIF1). This quantitative observation supports the expert judgment that RIF1 is a critical factor for this initiating event. In addition, the *Qi* values for selected combinations of $P_{low}$and P_{high} demonstrate that *Qi* has a significant influence on the outcomes, as the value of $f_{avg\text{-}rev}$ in Case 4 is higher than in Cases 3, 2, and 1.

The same reasoning extends to the independent protection layers (IPLs). By performing the analysis for each RIF, whether associated with IPL1, which comprises 6 RIFs, or with IPL2, which has 5 RIFs—a direct comparison can be made across all involved factors. This approach ensures consistency in evaluating the marginal influence of each RIF, regardless of its placement within the system hierarchy.

5.3.3 PFD of IPL1 (6 RIFs)

When fixing one RIF and varying the remaining five, each RIF with six possible states gives rise to 6^6 = 46 656 total combinations. when fixing one and varying the rest, this generates 6^5 = 7776 combinations for each fixed level. The average frequency of the PFD IPL 1 was then determined for the case RIF1 = A, and the process was repeated for RIF1 = B, RIF1 = C, ……, through RIF1 = F. This yielded 6 separate mean values, each representing the marginal influence of RIF1 at a given score.

The same systematic procedure was applied to RIF2, RIF3, RIF4, RIF5, RIF6 in turn, ensuring each RIF was fixed at every score from A to F, while the other 5 RIFs were allowed to vary. In this way, each RIF was associated with its own set of 6 averaged outcomes, reflecting its relative contribution to the PFD under different scoring conditions. Detailed numerical results from this analysis are compiled in Table 5.3.

Table 5.3: Average revised PFD of IPL1 and of scenario A across cases.

RIFs	Score	Average revised frequency of PFD_{IPL1}					Average revised frequency of scenario A				
		Case 1 (0.5 – 2)	Case 2 (0.33 – 3)	Case 3 (0.2 – 5)	Case 4 (0.1 – 10)	Case 5 (adopted)	Case 1 (0.5 – 2)	Case 2 (0.33 – 3)	Case 3 (0.2 – 5)	Case 4 (0.1 – 10)	Case 5 (adopted)
RIF1 (System feedback)	A	2.86E-02	3.48E-02	4.89E-02	8.60E-02	8.60E-02	6.96E-04	1.07E-03	2.23E-03	8.41E-03	2.32E-03
	B	2.92E-02	3.56E-02	4.98E-02	8.70E-02	8.70E-02	7.10E-04	1.09E-03	2.27E-03	8.51E-03	2.35E-03
	C	2.97E-02	3.64E-02	5.08E-02	8.81E-02	8.81E-02	7.24E-04	1.11E-03	2.31E-03	8.61E-03	2.38E-03
	D	3.05E-02	3.79E-02	5.38E-02	9.49E-02	9.49E-02	7.42E-04	1.16E-03	2.45E-03	9.28E-03	2.56E-03
	E	3.13E-02	3.94E-02	5.68E-02	1.02E-01	1.02E-01	7.61E-04	1.21E-03	2.59E-03	9.94E-03	2.75E-03
	F	3.20E-02	4.09E-02	5.99E-02	1.09E-01	1.09E-01	7.80E-04	1.25E-03	2.72E-03	1.06E-02	2.93E-03
RIF2 (Procedures)	A	2.62E-02	3.09E-02	4.24E-02	7.35E-02	7.35E-02	6.38E-04	9.45E-04	1.93E-03	7.19E-03	1.98E-03
	B	2.76E-02	3.28E-02	4.46E-02	7.61E-02	7.61E-02	6.72E-04	1.00E-03	2.03E-03	7.44E-03	2.05E-03
	C	2.90E-02	3.47E-02	4.69E-02	7.86E-02	7.86E-02	7.07E-04	1.06E-03	2.13E-03	7.69E-03	2.12E-03
	D	3.09E-02	3.85E-02	5.44E-02	9.57E-02	9.57E-02	7.53E-04	1.18E-03	2.48E-03	9.35E-03	2.58E-03
	E	3.28E-02	4.22E-02	6.21E-02	1.13E-01	1.13E-01	8.00E-04	1.29E-03	2.82E-03	1.10E-02	3.04E-03
	F	3.47E-02	4.60E-02	6.96E-02	1.30E-01	1.30E-01	8.45E-04	1.41E-03	3.17E-03	1.27E-02	3.50E-03
RIF3 (Time pressure)	A	2.62E-02	3.09E-02	4.24E-02	7.35E-02	7.35E-02	6.38E-04	9.45E-04	1.93E-03	7.19E-03	1.98E-03
	B	2.76E-02	3.28E-02	4.46E-02	7.61E-02	7.61E-02	6.72E-04	1.00E-03	2.03E-03	7.44E-03	2.05E-03
	C	2.90E-02	3.47E-02	4.69E-02	7.86E-02	7.86E-02	7.07E-04	1.06E-03	2.13E-03	7.69E-03	2.12E-03
	D	3.09E-02	3.85E-02	5.44E-02	9.57E-02	9.57E-02	7.53E-04	1.18E-03	2.48E-03	9.35E-03	2.58E-03
	E	3.28E-02	4.22E-02	6.21E-02	1.13E-01	1.13E-01	8.00E-04	1.29E-03	2.82E-03	1.10E-02	3.04E-03
	F	3.47E-02	4.60E-02	6.96E-02	1.30E-01	1.30E-01	8.45E-04	1.41E-03	3.17E-03	1.27E-02	3.50E-03
RIF4 (Working load/stress)	A	2.70E-02	3.22E-02	4.45E-02	7.77E-02	7.77E-02	6.57E-04	9.86E-04	2.03E-03	7.59E-03	2.10E-03
	B	2.81E-02	3.37E-02	4.64E-02	7.97E-02	7.97E-02	6.85E-04	1.03E-03	2.11E-03	7.79E-03	2.15E-03
	C	2.93E-02	3.52E-02	4.82E-02	8.17E-02	8.17E-02	7.13E-04	1.08E-03	2.19E-03	7.99E-03	2.21E-03
	D	3.08E-02	3.83E-02	5.42E-02	9.54E-02	9.54E-02	7.49E-04	1.17E-03	2.47E-03	9.33E-03	2.58E-03
	E	3.23E-02	4.13E-02	6.03E-02	1.09E-01	1.09E-01	7.87E-04	1.26E-03	2.75E-03	1.07E-02	2.94E-03
	F	3.38E-02	4.43E-02	6.64E-02	1.23E-01	1.23E-01	8.23E-04	1.36E-03	3.02E-03	1.20E-02	3.31E-03

RIFs	Score	Average revised frequency of PFD_{IPL1}					Average revised frequency of scenario A				
		Case 1 (0.5 – 2)	Case 2 (0.33 – 3)	Case 3 (0.2 – 5)	Case 4 (0.1 – 10)	Case 5 (adopted)	Case 1 (0.5 – 2)	Case 2 (0.33 – 3)	Case 3 (0.2 – 5)	Case 4 (0.1 – 10)	Case 5 (adopted)
RIF5 (Competence)	A	2.62E-02	3.09E-02	4.24E-02	7.35E-02	7.35E-02	6.38E-04	9.45E-04	1.93E-03	7.19E-03	1.98E-03
	B	2.76E-02	3.28E-02	4.46E-02	7.61E-02	7.61E-02	6.72E-04	1.00E-03	2.03E-03	7.44E-03	2.05E-03
	C	2.90E-02	3.47E-02	4.69E-02	7.86E-02	7.86E-02	7.07E-04	1.06E-03	2.13E-03	7.69E-03	2.12E-03
	D	3.09E-02	3.85E-02	5.44E-02	9.57E-02	9.57E-02	7.53E-04	1.18E-03	2.48E-03	9.35E-03	2.58E-03
	E	3.28E-02	4.22E-02	6.21E-02	1.13E-01	1.13E-01	8.00E-04	1.29E-03	2.82E-03	1.10E-02	3.04E-03
	F	3.47E-02	4.60E-02	6.96E-02	1.30E-01	1.30E-01	8.45E-04	1.41E-03	3.17E-03	1.27E-02	3.50E-03
RIF6 (Maintainability/	A	2.94E-02	3.62E-02	5.11E-02	9.01E-02	9.01E-02	7.16E-04	1.11E-03	2.33E-03	8.81E-03	2.43E-03
	B	2.97E-02	3.65E-02	5.16E-02	9.07E-02	9.07E-02	7.23E-04	1.12E-03	2.35E-03	8.86E-03	2.45E-03
	C	3.00E-02	3.69E-02	5.20E-02	9.12E-02	9.12E-02	7.30E-04	1.13E-03	2.37E-03	8.91E-03	2.46E-03
	D	3.03E-02	3.77E-02	5.36E-02	9.46E-02	9.46E-02	7.39E-04	1.15E-03	2.44E-03	9.25E-03	2.55E-03
	E	3.07E-02	3.85E-02	5.51E-02	9.81E-02	9.81E-02	7.49E-04	1.18E-03	2.51E-03	9.59E-03	2.65E-03
	F	3.11E-02	3.92E-02	5.66E-02	1.02E-01	1.02E-01	7.58E-04	1.20E-03	2.58E-03	9.93E-03	2.74E-03

Figure 5.3 illustrates the relative influence of each RIF by showing how changes in its levels (A–F) affect the average PFD of IPL1.

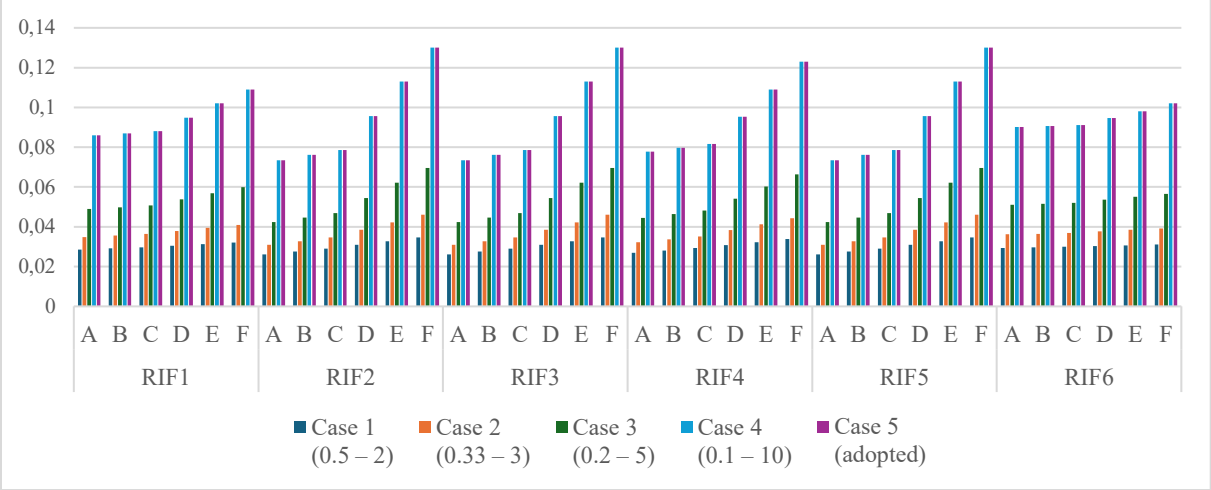


Figure 5.3: Average revised PFD of IPL1

Figure 5.4 illustrates the average influence of each RIF by showing how changes in its levels (A–F) affect the average frequency of Scenario A.

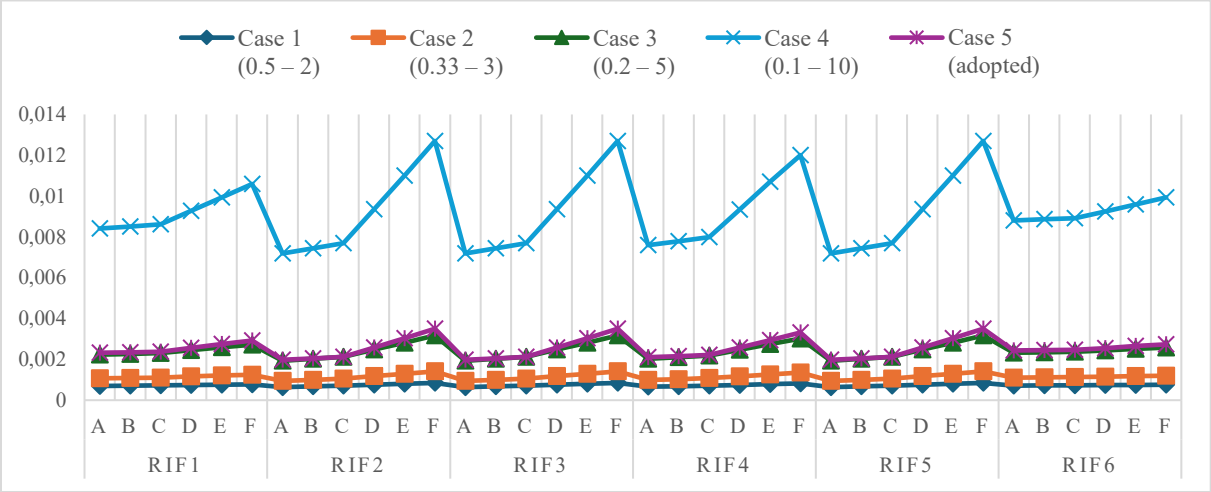


Figure 5.4: Average revised frequency of scenario A (IPL1)

5.3.4 Interpretation of the results of PFD IPL1

As illustrated in Figure 5.3 and Table 5.3, RIF2 (procedures), RIF3 (time pressure), and RIF5 (competence) are the most influential RIFs. They are followed by RIF4 (workload/stress), while RIF1 (system feedback) and RIF6 (maintainability/accessibility) having comparatively lesser, but still measurable, effect.

When a blockage occurs, procedures, time pressure and competence are the most critical RIFs for IPL 1. Cyclone blockages result in production losses and safety issues, putting extreme pressure on operators and technicians to quickly restore the flow. This can lead to rushing and overlooking SOPs. Although other factors, such as workload and maintainability/accessibility, affect how a blockage is managed, their significance varies depending on the operational context.

Using an average frequency of PFD_{avg}= 2.5×10−2 /year as the baseline, the analysis demonstrates that the average revised frequency of scenario A ($P_{avg\ rev}$) rises monotonically as the assumptions are expanded from the adopted ratio to the extreme cases, and as the RIF states deteriorate from A to F, and vice versa.

This quantitative observation also supports the expert judgment that these factors are particularly critical in the event of cyclone blockage.

5.3.5 PFD of IPL2 (5 RIFs)

When fixing one RIF and varying the remaining four, each RIF with six possible states gives rise to 6^5 = 7776 total combinations. when fixing one and varying the rest, this generates 6^4 = 1 296 combinations for each fixed level. The average frequency of the PFD IPL 2 was then determined for the case RIF1 = A, and the process was repeated for RIF1 = B, RIF1 = C, ……, through RIF1 = F. This yielded 6 separate mean values, each representing the marginal influence of RIF1 at a given score.

The same systematic procedure was applied to RIF2, RIF3, RIF4, RIF5 in turn, ensuring each RIF was fixed at every score from A to F, while the other 4 RIFs were allowed to vary. As a result, each RIF was associated with its own set of 6 averaged outcomes, reflecting its relative contribution to the PFD under different scoring conditions. Detailed numerical results from this analysis are compiled in Table 5.4.

Table 5.4: Average revised PFD of IPL2 and of scenario A across cases

RIFs	Score	Average revised frequency of *PFD* $_{IPL2}$					Average revised frequency of scenario A				
		Case 1 (0.5 – 2)	Case 2 (0.33 – 3)	Case 3 (0.2 – 5)	Case 4 (0.1 – 10)	Case 5 (adopted)	Case 1 (0.5 – 2)	Case 2 (0.33 – 3)	Case 3 (0.2 – 5)	Case 4 (0.1 – 10)	Case 5 (adopted)
RIF1 (System feedback)	A	6.19E-02	7.25E-02	9.90E-02	1.71E-01	7.25E-02	6.33E-04	9.35E-04	1.91E-03	7.10E-03	1.46E-03
	B	6.56E-02	7.76E-02	1.05E-01	1.78E-01	7.76E-02	6.71E-04	1.00E-03	2.02E-03	7.38E-03	1.56E-03
	C	6.94E-02	8.25E-02	1.11E-01	1.85E-01	8.25E-02	7.10E-04	1.06E-03	2.14E-03	7.66E-03	1.66E-03
	D	7.43E-02	9.25E-02	1.31E-01	2.30E-01	9.25E-02	7.60E-04	1.19E-03	2.52E-03	9.53E-03	1.87E-03
	E	7.94E-02	1.02E-01	1.51E-01	2.75E-01	1.02E-01	8.13E-04	1.32E-03	2.91E-03	1.14E-02	2.07E-03
	F	8.44E-02	1.12E-01	1.71E-01	3.20E-01	1.12E-01	8.63E-04	1.45E-03	3.29E-03	1.33E-02	2.27E-03
RIF2 (Process	A	6.83E-02	8.30E-02	1.16E-01	2.04E-01	8.30E-02	6.98E-04	1.07E-03	2.24E-03	8.48E-03	1.67E-03
	B	6.98E-02	8.50E-02	1.19E-01	2.07E-01	8.50E-02	7.14E-04	1.10E-03	2.29E-03	8.59E-03	1.71E-03
	C	7.13E-02	8.70E-02	1.21E-01	2.10E-01	8.70E-02	7.29E-04	1.12E-03	2.33E-03	8.70E-03	1.75E-03

RIFs	Score	Average revised frequency of *PFD* $_{IPL2}$					Average revised frequency of scenario A				
		Case 1 (0.5 – 2)	Case 2 (0.33 – 3)	Case 3 (0.2 – 5)	Case 4 (0.1 – 10)	Case 5 (adopted)	Case 1 (0.5 – 2)	Case 2 (0.33 – 3)	Case 3 (0.2 – 5)	Case 4 (0.1 – 10)	Case 5 (adopted)
	D	7.32E-02	9.10E-02	1.29E-01	2.28E-01	9.10E-02	7.49E-04	1.17E-03	2.49E-03	9.45E-03	1.84E-03
	E	7.53E-02	9.50E-02	1.37E-01	2.46E-01	9.50E-02	7.70E-04	1.23E-03	2.64E-03	1.02E-02	1.92E-03
	F	7.72E-02	9.90E-02	1.45E-01	2.64E-01	9.90E-02	7.90E-04	1.28E-03	2.79E-03	1.09E-02	2.00E-03
RIF3 (Procedures)	A	6.19E-02	7.25E-02	9.90E-02	1.71E-01	7.25E-02	6.33E-04	9.35E-04	1.91E-03	7.10E-03	1.46E-03
	B	6.56E-02	7.76E-02	1.05E-01	1.78E-01	7.76E-02	6.71E-04	1.00E-03	2.02E-03	7.38E-03	1.56E-03
	C	6.94E-02	8.25E-02	1.11E-01	1.85E-01	8.25E-02	7.10E-04	1.06E-03	2.14E-03	7.66E-03	1.66E-03
	D	7.43E-02	9.25E-02	1.31E-01	2.30E-01	9.25E-02	7.60E-04	1.19E-03	2.52E-03	9.53E-03	1.87E-03
	E	7.94E-02	1.02E-01	1.51E-01	2.75E-01	1.02E-01	8.13E-04	1.32E-03	2.91E-03	1.14E-02	2.07E-03
	F	8.44E-02	1.12E-01	1.71E-01	3.20E-01	1.12E-01	8.63E-04	1.45E-03	3.29E-03	1.33E-02	2.27E-03
RIF4 (Maintainability/ accessibility)	A	6.19E-02	7.25E-02	9.90E-02	1.71E-01	7.25E-02	6.33E-04	9.35E-04	1.91E-03	7.10E-03	1.46E-03
	B	6.56E-02	7.76E-02	1.05E-01	1.78E-01	7.76E-02	6.71E-04	1.00E-03	2.02E-03	7.38E-03	1.56E-03
	C	6.94E-02	8.25E-02	1.11E-01	1.85E-01	8.25E-02	7.10E-04	1.06E-03	2.14E-03	7.66E-03	1.66E-03
	D	7.43E-02	9.25E-02	1.31E-01	2.30E-01	9.25E-02	7.60E-04	1.19E-03	2.52E-03	9.53E-03	1.87E-03
	E	7.94E-02	1.02E-01	1.51E-01	2.75E-01	1.02E-01	8.13E-04	1.32E-03	2.91E-03	1.14E-02	2.07E-03
	F	8.44E-02	1.12E-01	1.71E-01	3.20E-01	1.12E-01	8.63E-04	1.45E-03	3.29E-03	1.33E-02	2.27E-03
RIF5 (Technical condition)	A	6.61E-02	7.95E-02	1.11E-01	1.93E-01	7.95E-02	6.77E-04	1.03E-03	2.13E-03	8.02E-03	1.60E-03
	B	6.84E-02	8.25E-02	1.14E-01	1.97E-01	8.25E-02	7.00E-04	1.07E-03	2.20E-03	8.19E-03	1.66E-03
	C	7.06E-02	8.55E-02	1.18E-01	2.02E-01	8.55E-02	7.23E-04	1.10E-03	2.27E-03	8.35E-03	1.72E-03
	D	7.36E-02	9.15E-02	1.30E-01	2.29E-01	9.15E-02	7.53E-04	1.18E-03	2.50E-03	9.47E-03	1.85E-03
	E	7.67E-02	9.75E-02	1.42E-01	2.56E-01	9.75E-02	7.84E-04	1.26E-03	2.73E-03	1.06E-02	1.97E-03
	F	7.96E-02	1.03E-01	1.54E-01	2.83E-01	1.03E-01	8.15E-04	1.34E-03	2.96E-03	1.17E-02	2.09E-03

Figure 5.5 illustrates the relative influence of each RIF by showing how changes in its levels (A–F) affect the average PFD of IPL2.

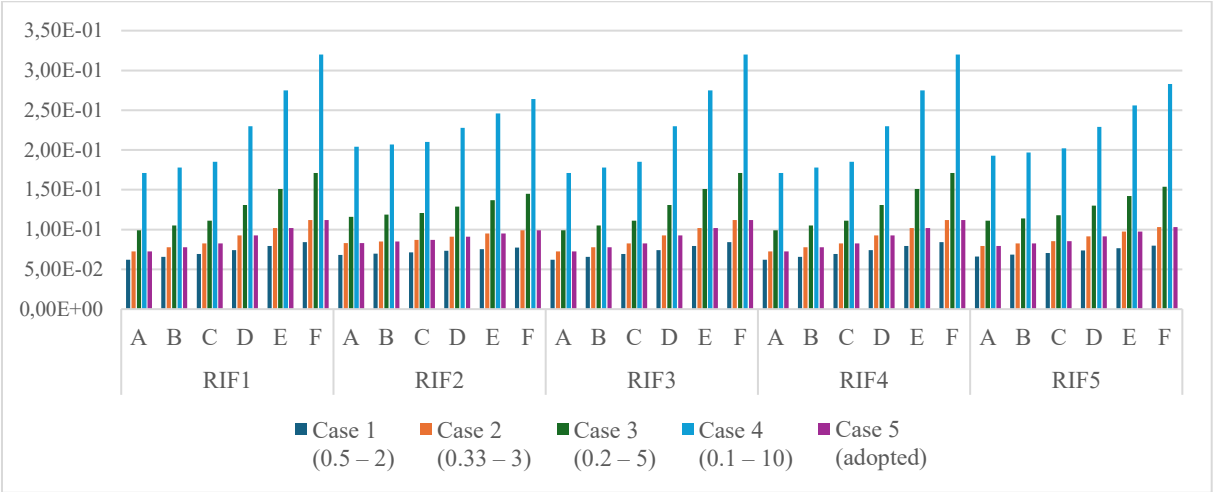


Figure 5.5: Average revised PFD of IPL2

Figure 5.6 illustrates the average influence of each RIF by showing how changes in its levels (A–F) affect the average frequency of Scenario A.

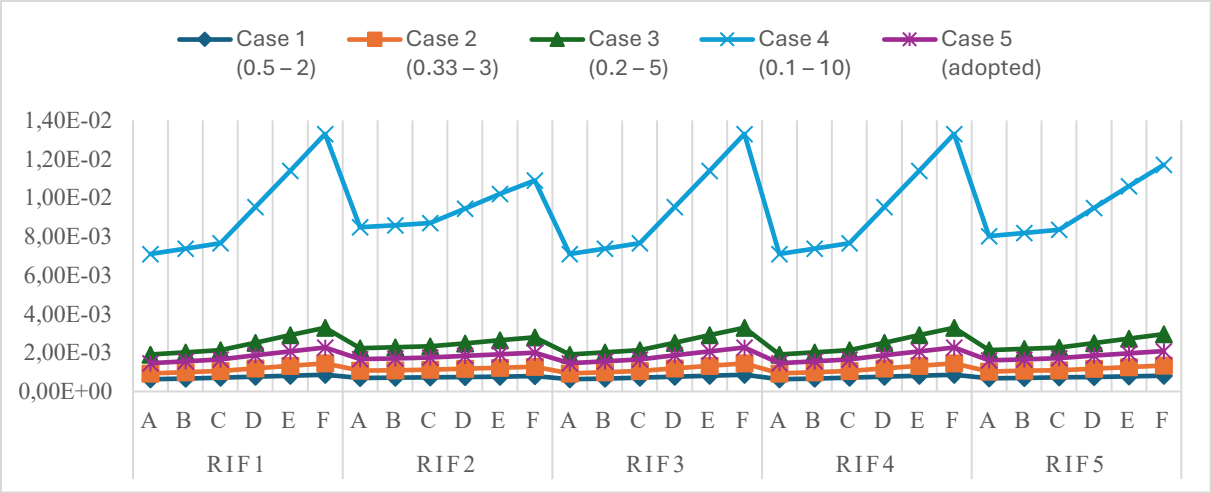


Figure 5.6: Average revised frequency of scenario A (IPL2)

5.3.6 Interpretation of the results of PFD IPL2

As illustrated in Figure 5.5 and Table 5.4, RIF1 (system feedback), RIF3 (procedures), and RIF4 (maintainability/accessibility) are the most influential RIFs. The design and condition of the equipment play a central role in determining the effectiveness with which the safety function of IPL2 is executed. RIF5 (technical condition) follows in its influence, whereas RIF2 (process complexity) demonstrates the weakest but still noticeable effect.

Using an average frequency of PFD $_{avg}$= 6×10−2 /year as the baseline, the analysis demonstrates that the average revised frequency ($f_{avg\ rev}$) of scenario A and the average revised PFD ($PFD_{avg\text{-}rev}$) rise monotonically as the assumptions are expanded from the adopted case to the extreme cases, and as the RIF states deteriorate from A to F, and vice versa.

For instance, degradation of RIF1 from A to F in case 4 results in the $PFD_{avg\text{-}rev}$ for IPL2 increasing from 1.71×10−1 (+185%) to 3.20×10−1 (+433%). In Scenario A, the $f_{avg\text{-}rev}$ increases correspondingly from 7.10×10−3 (+835%) to 1.33×10−2 (+2829%). Conversely, under the most favorable configuration (A–A–A–A–A), the $PFD_{avg\text{-}rev}$ for the IPL2 is reduced to 6.00×10−3 (-90%) and the average revised frequency of Scenario A to 2.49×10−4 (-50%). Under the least favorable cases (F–F–F–F–F), the $PFD_{avg\text{-}rev}$ rises to 6.00×10−1 (+900%), while, in Scenario A, $f_{avg\text{-}rev}$ reaches 2.49×10−2 (+4925%).

This quantitative observation also supports the expert judgment that these factors are particularly critical in the event of cyclone blockage.

In conclusion, enhancement of the RIFs, especially those with a pronounced influence in the A and B categories, provides a measurable but limited improvement. Deterioration of these factors to the D, E, or F levels, however, represents a serious concern. Such a deterioration increases the frequency of cyclone blockage and weakens the performance of both IPLs, thereby raising the likelihood of uncontrolled hot material release.

Therefore, the highest-leverage actions to limit the overall scenario frequency involve a dual strategy. This strategy is more than just theoretical findings; it leads directly to a set of clear operational priorities.

1) Prevention and Control: Priorities should focus on preventing blockages and direct contact, as well as on minimizing blockage size through early detection and rapid diagnosis of critical equipment. This can be achieved by controlling feed properties (e.g., chemistry/mineralogy, homogenization, particle-size distribution, moisture/alkalis/sulfur content, etc.) to keep RIF1 and other RIFs in the B-A band as well as reduce manual intervention: automate air cleaning/blasting cycles where feasible and standardize preheater/cyclone inspection routines. Inspections and maintenance at regular intervals can reveal hidden issues before they escalate into critical failures. Similarly, regular system monitoring enables real-time identification of emerging or existing blockages, potential malfunctions, or failures, enabling the early adaptation of corrective measures.

2) Human and Organizational Factors: Well-defined SOPs are essential to reduce the consequences of a blockage. Experience shows that most accidents with hot meal are caused by inadequate operator actions during a blockage, rather than by a lack of technical safety barriers. This underlines the importance of behavioral change and active involvement of the personnel. Personnel should receive thorough training, be provided with ISO 11612-certified personal protective equipment (PPE), and have reliable means of communication. It is also essential to implement lockout and tagout procedures for energy control (for instance, air blasters should be isolated and emptied before opening any hatch or port hole, and only one door should be opened at a time) and a permit-to-work process to reduce the number of workers and the time spent on the task.

The actions with the greatest impact identified in this analysis extend beyond the specific RIFs under consideration. Although the sensitivity study was limited in scope, the recommendations can be applied to the system as a whole. Strengthening SOPs for RIF 3 (time pressure) and RIF 4 (maintainability and accessibility), for instance, will also reduce the influence of other RIFs, such as operator competence, workload, and physical stress. These measures contribute to a more robust operational framework and lower the probability of unfavorable scenarios. The analysis is, however, constrained by its treatment of the RIFs as independent factors. In practice, interactions may occur between them. The present model gives well-founded conclusions on the dominant risk factors, but a more advanced approach is required to capture the joint effects. Methods such as Bayesian networks or structured expert elicitation may be applied to address these dependencies.

5.4 Conclusion

In this study, the sensitivity analysis was carried out by systematically varying the scores associated with each risk-influencing factor (RIF) to assess their effect on the frequency across updated quantification factor (Qi), while keeping one RIF fixed at a given level. Four the initiating event (IE), while six and five RIFs were included for IPL1 and IPL2, respectively; Each RIF could take one of six possible scores (A–F), resulting in a large number of possible combinations. The procedure was as follows: one RIF was fixed at a specific score (e.g., A), and the remaining RIFs were varied across all possible combinations. The average frequency of the initiating event and the probability of failure on demand (PFD) were then calculated for the fixed score. As an example, by fixing RIF1 at A and varying the three RIFs from A–A–A to F–F–F, the average revised frequency/ probability associated with RIF1 = A was obtained. This procedure was repeated for each score (A–F) of every RIF.

The analysis also demonstrates how changes in critical RIF (e.g., material properties, a key RIF for cyclone blockages) across a continuum of industrial practices influence risk. Improvements toward best practice (C → B → A) reduce the risk, and as deterioration toward less favorable conditions (C → D → E → F) increases it. In light of the complexity of the system and the limited availability of detailed operational data, the applied targeted sensitivity analysis provides a robust and appropriate approach at this stage.

The method provides the marginal effect of each individual factor by averaging over the full range of variation in the remaining RIFs. It may be viewed as a one-factor-at-a-time (OFAT) analysis conducted within the framework of a complete factorial design. While the procedure does not explicitly capture interaction effects between factors, it offers a transparent and systematic means of assessing sensitivity. The results give a basis for comparing the relative influence of the different RIFs and for identifying those factors that contribute most to the observed variability in the scenario of uncontrolled release.

When the RIFs are varied together in aligned scores from A to F, two main effects are observed:

- Improvement at (A/B/C): For scores A–C, the percentage change (P%) is negative in the less severe cases, reflecting a reduction in risk.
- Escalation at (D/E/F): For scores D–F, the frequencies increase sharply, indicating compounding effects when unfavorable states coincide.

The findings show that simultaneous degradation of several RIFs may lead to a disproportionate escalation of risk, whereas consistent adherence to good practice across the RIFs produces measurable improvements.

The analysis was intentionally limited to Scenario A. Scenario B (explosion) was not included because its baseline frequency is currently negligible. However, if future data indicates a non-trivial increase in this event's frequency, the analysis will be revisited to include tailored stress cases for Scenario B.

5.5 Recommendations

The following recommendations are identified as a key to achieving safe clinker production operation:

5.5.1 Process and Equipment Safety

- **Early Detection of Build-ups**: Blockages in the preheater cyclones represent an emergent operating condition that may require immediate shutdown. The consequences range from extended downtime to complete stage filling and uncontrolled release of hot material. The main causes are circulation of volatile components and variations in fuel and raw mix. Build-ups reduce gas flow, increase CO, and may lead to hazardous shutdowns and unsafe cleaning. For this reason, early detection by continuous monitoring and diagnosis of critical equipment is therefore essential. Together with improved combustion control and stable raw mix chemistry, it will reduce the probability of recurrence and contribute to safe and stable operation.
- **Maintenance**: Measuring devices in the heating area should be maintained and tested at regular intervals, preferably through a computerized maintenance system. Refractory and

steel structures in critical sections should be inspected, repaired and, where necessary, replaced during major kiln shutdowns to ensure they remain in optimal condition.

- **Redundancy**: The ID fan is a critical component. Failure without redundancy will stop production, disturb the process flow, and may cause cascading shutdowns. The consequences include backdraft with return of flame and possible explosion in the ESP. A redundant ID fan, together with an excess fan, will stabilize the draft and improve system reliability.
- **Emergency Preparedness**: Hot molten material can suddenly flow like water, escaping through any unsealed areas. It's essential to consider all possible spillage paths and adapt the area accordingly. All walkways and escape routes must be kept clear of obstacles. Well-documented emergency response plans are vital and should be regularly reviewed and updated to handle unexpected events.

5.5.2 Personnel and Training

- **Access control and contact avoidance**: Access to hazardous areas shall be physically restricted to authorized personnel only. Entry shall not be allowed without proper PPE and reliable communication. PPE, in particular ISO 11612-certified equipment for hot material tasks, must be inspected and used. The number of workers, the exposure time, and the size and number of access points shall be minimized.
- **Update and adapt SOPs**: Standard Operating Procedures shall be robust, regularly reviewed, and updated to cover hazardous tasks such as cyclone blockage removal, build-up cleaning, and hot meal spillage. The SOPs must be clearly communicated to ensure consistent understanding and safe execution.
- **Training and awareness**: Improve skills and situational awareness through training. Control room operators should be empowered by the kiln SOP to stop the kiln feed and fuel based on critical sensor signals. However, training deficiencies arise from several factors, in particular failure to adapt training protocols to reflect real world scenarios. In this context, exploring adaptive training models that use virtual reality and learning based on simulation can improve the readiness of the workforce. For example using a firing line simulator can also help operators become familiar with the system and learn how to adapt by adjusting different kiln parameters.
- **Fostering a positive safety culture**: A positive safety culture requires open communication and transparency. Workers must be encouraged to report hazards, unsafe conditions, and near-misses without fear of reprisal. Discussions of near-misses and potential risks shall be integrated into daily routines to strengthen risk awareness and continuous improvement.

5.5.3 Facility Design and Automation

- **Hot material containment**: Redefine emergency hot spill collection areas, specifically under the furnace inlet and outlet seals and in the cooler basement. These areas must be equipped with measures to barricade off a surge of hot material and limit access.
- **Relocation of the Laboratory**: Relocating the laboratory, which stores and handles hazardous materials, away from the CCR would greatly reduce the risk of fire, explosion, or chemical exposure. Its current location beneath the CCR poses a serious threat to personnel and control systems in the event of an incident.

- **Automation**: The application of automation can significantly improve safety in this high-risk areas by separating operators from the hazard. For example, drones can be used to inspect the preheating tower, robots can perform ring-cleaning tasks inside the kiln, etc.

Conclusion and Perspectives for Future Research

General conclusion

This thesis addresses a gap in the application of integrated risk analysis methods, including HAZOP, BORA, and RCA, to the particular operating conditions of cement manufacturing. By combining these methods, the research establishes an integrated framework for identifying hazards, modelling accident pathways, assessing safety barrier performance, and investigating underlying causes in cement firing systems. Its application to the Lafarge Ciment M'Sila (LCM) cement plant demonstrates the applicability of these methods to a high-temperature industrial process characterized by severe operating conditions and interconnected production units.

The HAZOP study identifies critical operational deviations, particularly those associated with uncontrolled hot-material releases, thermal disturbances, and explosion hazards in the pyroprocessing area. BORA extends this analysis by examining how risk-influencing factors affect initiating-event frequencies and the operational performance of safety barriers. The results demonstrate that safety barriers cannot be assessed solely on the basis of their engineering specifications; their effectiveness also depends on operating conditions, equipment accessibility, maintenance practices, and operator response. RCA complements this assessment by identifying the underlying causes of the vulnerabilities and supporting the formulation of corrective measures.

The findings highlight the interaction between technical failures and human and organizational factors (HOFs) in the occurrence and escalation of hazardous events. Equipment deficiencies, deferred maintenance, procedural deviations, communication gaps, and inadequate training can compromise the effectiveness of engineered safety barriers. Safety barrier performance is therefore closely linked to the socio-technical environment in which equipment, personnel, operating procedures, and organizational arrangements interact. This is particularly relevant to cement firing systems, where process complexity, interconnected equipment, and demanding operating conditions make isolated assessments of technical barriers insufficient.

The practical recommendations derived from the analysis address three complementary areas: process and equipment integrity, personnel competence and operational practices, and facility design and automation. They include strengthening containment systems, improving the reliability and redundancy of critical equipment such as the ID fan, providing appropriate explosion-relief provisions, reinforcing hot-work permit controls, and involving operators directly in risk assessments and incident investigations. These measures address both the technical integrity of protective systems and the operational conditions that determine their effectiveness.

Several limitations define the scope of this research. First, the assessment of BORA risk-influencing factors relies partly on expert judgment and semi-quantitative scoring, introducing a degree of subjectivity that makes the results dependent on the experience, expertise, and consistency of the participating specialists. Second, limitations in the availability and detail of historical incident data at the LCM plant require the use of published industrial data to estimate certain initiating-event frequencies and barrier failure probabilities. Third, the application of the Independent Protection Layer (IPL) concept involves simplifying assumptions regarding barrier independence and effectiveness. In a complex cement production environment, interactions between technical systems, operating conditions, and human and organizational

factors may challenge these assumptions, particularly when considering potential dependencies and common-cause failures between protection layers. Fourth, the application focuses on a single cement plant, which limits the generalizability of the findings to facilities with different process configurations, equipment conditions, and operating practices. These constraints should be considered when interpreting the assessment results and their applicability to other industrial settings.

The proposed HAZOP–BORA–RCA framework provides a structured approach to risk assessment in cement firing systems by linking hazardous scenarios, safety barrier performance, and the technical, human, and organizational factors influencing their effectiveness. Its main value lies in addressing the interactions that characterize complex socio-technical systems and translating identified vulnerabilities into practical risk-reduction measures. In this respect, the research contributes to a more integrated understanding of process safety in cement manufacturing, where the effectiveness of protective measures depends on both their technical reliability and the conditions under which they operate.

Perspectives for Future Research

The present work contributes to the application of integrated risk analysis methods (HAZOP, BORA, and RCA) to the cement industry. To strengthen the scientific foundation and improve the practical usefulness of the results, several aspects related to the scope and empirical basis of the study remain to be further developed. While the analysis has so far concentrated on uncontrolled spillage of hot material and explosions within the pyroprocessing line, future studies should include other critical risks, such as structural collapse of preheater cyclones or silos, explosions in electrostatic precipitators (ESPs) resulting from carbon monoxide accumulation and subsequent ignition, as well as backdraft phenomena and occupational hazards. The same approach may also be extended beyond the pyroprocessing stage to quarrying, raw material handling, fuel preparation, and cement grinding operations, while incorporating environmental risks such as accidental emissions and waste co-processing hazards to align the evaluation with contemporary sustainability objectives and regulatory requirements. Furthermore, to move beyond a single-plant case study at LCM, applying the methodology to several cement plants across different regions and operating conditions would clarify how variations in technical design, local maintenance practices, and working conditions influence the risk picture and safety barrier effectiveness.

In parallel, future research should refine the data foundation and analytical methods used in the framework. Because several initiating-event frequencies and barrier failure probabilities in this study were estimated using generic industrial databases and expert judgment, collecting operational failure data directly from the cement sector will be essential to improve the accuracy and credibility of the estimates. This should be complemented by formal uncertainty propagation techniques, such as Monte Carlo simulation or fuzzy set theory, to account for data limitations and expert subjectivity. Moreover, since the present study integrated HAZOP, BORA, and RCA sequentially under static assumptions, a useful step forward would be to combine this framework with dynamic or systemic methods, such as Bayesian networks or STAMP (Systems-Theoretic Accident Model and Processes), to capture variations over time in process conditions, equipment degradation, and organizational aspects. Finally, because human and organizational factors (HOFs) were found to have a decisive influence on barrier performance, incorporating dedicated Human Reliability Analysis (HRA) methods, such as

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HEART (Human Error Assessment and Reduction Technique), into the BORA evaluation stage would allow a more detailed assessment of how operator workload, ergonomics, and time pressure affect recovery actions during process upsets and contribute to risk propagation.

References

[1] S. Khaviya, S. Kavitha, S. Manoj, A risk assessment study on occupational hazards in cement industry, Int Res J Eng Technol, 4 (2017) 12.
[2] A. İnanlı, O. Özbakır, Comparative Analysis of Hazard Identification and Risk Assessment Methods in Ağrı Cement Factory: Fine-Kinney vs. 3T Approach, Karadeniz Fen Bilimleri Dergisi, 14 (2024) 448-467.
[3] G.R. R. Manikandan, T. Rajpradesh, and S. Rajesh, Job Safety Analysis for Various Operations in Cement Industry Using Risk Assessment Matrix, ICAMR 2019. Springer Proceedings in Materials, vol 5. Springer, Singapore. https://doi.org/10.1007/978-981-15-8319-3_44, (2021).
[4] N. Agrawal, Electrical safety practices in cement industry for sustainable operation, in: 2015 IEEE IAS Joint Industrial and Commercial Power Systems/Petroleum and Chemical Industry Conference (ICPSPCIC), IEEE, 2015, pp. 214-219.
[5] G.M. Kemper, W.S. Vilcheck, D.B. Durocher, The journey of an enterprise in a process industry toward improved electrical workplace safety, IEEE Transactions On Industry Applications, 50 (2014) 3072-3078.
[6] K. Zeb, Y. Ali, M.W. Khan, Factors influencing environment and human health by cement industry: Pakistan a case in point, Management of Environmental Quality: An International Journal, 30 (2018) 751-767.
[7] G. Etse, V. Buncuga, A. Danert, Structural Failures & Collapses in Cement Plant Facilities, in: 2021 IEEE-IAS/PCA Cement Industry Conference (IAS/PCA), IEEE, 2021, pp. 1-8.
[8] U.E. Temelli, C. Öngören, B. Sayin, Damage assessment of a cement plant partially collapsed depending on various causes, Journal of Structural Engineering & Applied Mechanics (Online), 5 (2022) 62-76.
[9] C. Valderrama, R. Granados, J.L. Cortina, C.M. Gasol, M. Guillem, A. Josa, Implementation of best available techniques in cement manufacturing: a life-cycle assessment study, Journal of Cleaner Production, 25 (2012) 60-67.
[10] K.A. Krugh, J.R. Sommers, Safety Observation System and Near Miss Reporting Programs: Methods to maintain employee engagement in behavioral based safety practices, in: 2010 IEEE-IAS/PCA 52nd Cement Industry Technical Conference, IEEE, 2010, pp. 1-10.
[11] M. Rausand, Risk assessment: theory, methods, and applications, John Wiley & Sons, 2013.
[12] T. Aven, Risk analysis, John Wiley & Sons, 2015.
[13] Y.Y. Haimes, Risk modeling, assessment, and management, John Wiley & Sons, 2011.
[14] I.I.G. 51, Safety aspects-Guidelines for their inclusion in standards, in, International Organization for Standardization (ISO) Geneva. Switzerland, 2014.
[15] T. Aven, On how to define, understand and describe risk, Reliability Engineering & System Safety, 95 (2010) 623-631.
[16] I. Iso, Risk management–Principles and guidelines, International Organization for Standardization, Geneva, Switzerland, (2009).
[17] I. Iso, Risk management–Principles and guidelines, International Organization for Standardization, Geneva, Switzerland, (2018).
[18] E. ISO, IEC 31010: 2019, Risk management—Risk assessment techniques, in, ISO Geneva, Switzerland, 2019.
[19] K. Tzanakakis, Managing Risks in Railway System, A practice-oriented guide, (2021).
[20] A. Breznická, M. Kohutiar, M. Krbaťa, M. Eckert, P. Mikuš, Reliability analysis during the life cycle of a technical system and the monitoring of reliability properties, Systems, 11 (2023) 556.
[21] M.S. Ab Rahim, G. Reniers, M. Yang, S. Bajpai, Risk assessment methods for process safety, process security and resilience in the chemical process industry: A thorough literature review, Journal of Loss Prevention in the Process Industries, 88 (2024) 105274.
[22] C. Zhu, Y. Jiang, G. Liu, T. Zhang, Integration frameworks and intelligent research in dynamic fault tree: A comprehensive review and future perspectives, Quality and Reliability Engineering International, 39 (2023) 3157-3178.
[23] J. Lee, A. Shigrekar, R. Borrelli, Application of hazard and operability analysis for safeguardability of a pyroprocessing facility, Nuclear Engineering and Design, 348 (2019) 131-145.

[24] IEC 61882, Hazard and operability studies (HAZOP studies)—Application guide., in, International Electrotechnical Commission (IEC), Geneva, Switzerland, 2016.
[25] J. Dunjó, V. Fthenakis, J.A. Vílchez, J. Arnaldos, Hazard and operability (HAZOP) analysis. A literature review, Journal of hazardous materials, 173 (2010) 19-32.
[26] P.K. Marhavilas, M. Filippidis, G.K. Koulinas, D.E. Koulouriotis, The integration of HAZOP study with risk-matrix and the analytical-hierarchy process for identifying critical control-points and prioritizing risks in industry–A case study, Journal of Loss Prevention in the Process Industries, 62 (2019) 103981.
[27] K. Gunaratnam, A. Abdullah, R.A. Bakar, F. Hujainah, Hazard analysis techniques, methods and approaches: a review, International Journal of Advanced Research in Engineering Innovation, 4 (2022) 23-34.
[28] J.-Y. Choi, S.-H. Byeon, HAZOP methodology based on the health, safety, and environment engineering, International journal of environmental research and public health, 17 (2020) 3236.
[29] J. Escande, C. Proust, J.C. Le Coze, Limitations of current risk assessment methods to foresee emerging risks: Towards a new methodology?, Journal of Loss Prevention in the Process Industries, 43 (2016) 730-735.
[30] M.A. de la O Herrera, A.S. Luna, A.C.A. da Costa, E.M.B. Lemes, Risk Analysis: A generalized Hazop methodology state-of-the-art, applications, and perspective in the process industry, Vigilância Sanitária em Debate: Sociedade, Ciência & Tecnologia, 6 (2018) 106-121.
[31] P. Mocellin, J. De Tommaso, C. Vianello, G. Maschio, T. Saulnier-Bellemare, L.D. Virla, G.S. Patience, Experimental methods in chemical engineering: Hazard and operability analysis—HAZOP, The Canadian journal of chemical engineering, 100 (2022) 3450-3469.
[32] N. Hyatt, Guidelines for process hazards analysis (PHA, HAZOP), hazards identification, and risk analysis, CRC press, 2018.
[33] M.R. Othman, R. Idris, M.H. Hassim, W.H.W. Ibrahim, Prioritizing HAZOP analysis using analytic hierarchy process (AHP), Clean Technologies and Environmental Policy, 18 (2016) 1345-1360.
[34] IEC 61025, 2006. Fault tree analysis (FTA), Geneva (Switzerland): International Electrotechnical Commission.
[35] M. Yazdi, J. Mohammadpour, H. Li, H.Z. Huang, E. Zarei, R.G. Pirbalouti, S. Adumene, Fault tree analysis improvements: A bibliometric analysis and literature review, Quality and Reliability Engineering International, 39 (2023) 1639-1659.
[36] F.O. Ehiagwina, O.O. Kehinde, A.S. Nafiu, L.O. Afolabi, I. Olatinwo, Fault Tree Analysis and Its Modifications as Tools for Reliability and Risk Analysis of Engineering Systems–An Overview, Journal Homepage: Www. Ijrpr. Com ISSN, 2582 (2022) 7421.
[37] G. Cristea, D.M. Constantinescu, A comparative critical study between FMEA and FTA risk analysis methods, in: IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2017, pp. 012046.
[38] K. Aslansefat, S. Kabir, Y. Gheraibia, Y. Papadopoulos, Dynamic fault tree analysis: state-of-the-art in modeling, analysis, and tools, Reliability management and engineering, (2020) 73-112.
[39] N. Mahmood, T. Butalia, R. Qin, M. Manasrah, Concurrent events risk assessment generic models with enhanced reliability using Fault tree analysis and expanded rotational fuzzy sets, Expert Systems with Applications, 197 (2022) 116681.
[40] M. Leimeister, A. Kolios, A review of reliability-based methods for risk analysis and their application in the offshore wind industry, Renewable and Sustainable Energy Reviews, 91 (2018) 1065-1076.
[41] M. Yazdi, E. Zarei, Uncertainty handling in the safety risk analysis: an integrated approach based on fuzzy fault tree analysis, Journal of failure analysis and prevention, 18 (2018) 392-404.
[42] F. Yan, K. Xu, A set pair analysis based layer of protection analysis and its application in quantitative risk assessment, Journal of Loss Prevention in the Process Industries, 55 (2018) 313-319.
[43] C. Xie, L. Huang, R. Wang, J. Deng, Y. Shu, D. Jiang, Research on quantitative risk assessment of fuel leak of LNG-fuelled ship during lock transition process, Reliability Engineering & System Safety, 221 (2022) 108368.
[44] P. Baybutt, Overcoming challenges in using layers of protection analysis (LOPA) to determine safety integrity levels (SILs), Journal of Loss Prevention in the Process Industries, 48 (2017) 32-40.

[45] L. Anato, L. Carrero, G. Brouillard, C. Morar, Application and challenges of layers of protection analysis (LOPA) in mining processes: Insights into benefits and limitations, Process Safety Progress, 43 (2024) 469-477.
[46] Z. Abd Rashid, M.F.I.A. Fuad, M.A. Ahmad, N.A. Azhari, H.N.M. Hazimin, M.A.M. Ariff, A. Buang, Layer of Protection Analysis (LOPA) as an Effective Tool for Preventing Major Accidents Hazards: A Case Study of Ammonia Storage Tank, in: 2023 IEEE 14th Control and System Graduate Research Colloquium (ICSGRC), IEEE, 2023, pp. 242-247.
[47] W. Bridges, A. Dowell, More issues with layer of protection analysis—From the originators, Process Safety Progress, 41 (2021).
[48] B.K. Lyon, G. Popov, Managing Risk Through Layers of Control, Professional Safety, 65 (2020) 25-35.
[49] G. Tilocca, D. Sánchez, M. Torres-García, Applying the root cause analysis methodology to study the lack of market success of micro gas turbine systems, Applied Energy, 360 (2024) 122717.
[50] H.M. Mbogu, C.D. Nicholson, Data-driven root cause analysis via causal discovery using time-to-event data, Computers & Industrial Engineering, 190 (2024) 109974.
[51] M.F. Peerally, S. Carr, J. Waring, M. Dixon-Woods, The problem with root cause analysis, BMJ quality & safety, 26 (2017) 417-422.
[52] R. Wolniak, W. Grebski, B. Gajdzik, The usage of Root Cause Analysis (RCA) in Industry 4.0 conditions, Scientific Papers of Silesian University of Technology Organization and Management Series, 2023 (2023).
[53] I. 62740, Root cause analysis (RCA), in, International Electrotechnical Commission, Geneva, 2015.
[54] L. Cuvelier, H. Bencheckroun, G. Morel, New vistas on causal-tree methods: from root cause analysis (RCA) to constructive cause analysis (CCA), Cognition, Technology & Work, 19 (2017) 13-30.
[55] M. Solé, V. Muntés-Mulero, A.I. Rana, G. Estrada, Survey on models and techniques for root-cause analysis, arXiv preprint arXiv:1701.08546, (2017).
[56] O.Y. Abramov, TRIZ-based cause and effect chains analysis vs root cause analysis, in: Proceedings of the TRIZfest-2015 International Conference. Seoul, South Korea, 2015, pp. 288-295.
[57] IOGP, Report 415. Asset integrity – the key to managing major incident risks, in, International Association of Oil & Gas Producers (IOGP), 2008.
[58] S. Sklet, Safety barriers: Definition, classification, and performance, Journal of loss prevention in the process industries, 19 (2006) 494-506.
[59] W. Qiao, E. Huang, H. Guo, Y. Liu, X. Ma, Barriers involved in the safety management systems: a systematic review of literature, International journal of environmental research and public health, 19 (2022) 9512.
[60] Y. Liu, Safety barriers: Research advances and new thoughts on theory, engineering and management, Journal of Loss Prevention in the Process Industries, 67 (2020) 104260.
[61] E. Hollnagel, Risk+ barriers= safety?, Safety science, 46 (2008) 221-229.
[62] S. Yuan, M. Yang, G. Reniers, C. Chen, J. Wu, Safety barriers in the chemical process industries: A state-of-the-art review on their classification, assessment, and management, Safety science, 148 (2022) 105647.
[63] V. De Dianous, C. Fiévez, ARAMIS project: A more explicit demonstration of risk control through the use of bow–tie diagrams and the evaluation of safety barrier performance, Journal of Hazardous Materials, 130 (2006) 220-233.
[64] P.S. Authority, Principles for barrier management in the petroleum industry, PSA, Stavanger, Norway, (2013).
[65] A. Sevcik, O. Gudmestad, A systematic approach to risk reduction measures in the Norwegian offshore oil and gas industry, Risk Anal IX, 47 (2014) 287.
[66] Y. Liu, Barrier Engineering: Models and Methods for Technical Safety, CRC Press, 2025.
[67] V.D. Barkhatov, E.V. Zaytseva, M.V. Lisanov, I.S. Zhukov, Approaches to the Qualitative Assessment of the of Safety Barriers Performance at Oil and Gas Facilities, Occupational Safety in Industry, 12 (2022) 55-62.
[68] J. Sobral, C.G. Soares, Assessment of the adequacy of safety barriers to hazards, Safety science, 114 (2019) 40-48.

[69] E. Hollnagel, Accidents and barriers, in: Proceedings of lex valenciennes, Presses Universitaires de Valenciennes, 1999, pp. 175-182.
[70] L. Harms-Ringdahl, Analysis of safety functions and barriers in accidents, Safety Science, 47 (2009) 353-363.
[71] J. Kang, J. Zhang, J. Gao, Analysis of the safety barrier function: Accidents caused by the failure of safety barriers and quantitative evaluation of their performance, Journal of loss prevention in the process industries, 43 (2016) 361-371.
[72] J. Zhang, H. Ren, H. Ren, Y. Chai, Z. Liu, X. Liang, Comprehensive Review of Safety Studies in Process Industrial Systems: Concepts, Progress, and Main Research Topics, Processes, 11 (2023) 2454.
[73] P. Singh, N. Sunderland, C. van Gulijk, Determination of the health of a barrier with time-series data: How a safety barrier looks different from a data perspective, Journal of Loss Prevention in the Process Industries, 80 (2022) 104889.
[74] M. Bhavani, R. Vasuki, F.E. Solomon, T.M. Prasath, G. Divya, Smartguard: An IoT-Enabled Real-Time Monitoring System for Urban Manhole Safety, in: 2024 Third International Conference on Artificial Intelligence, Computational Electronics and Communication System (AICECS), 2024, pp. 1-6.
[75] H. Pasman, H. Sun, M. Yang, F. Khan, Chapter One - Opportunities and threats to process safety in digitalized process systems—An overview, in: F. Khan, H. Pasman, M. Yang (Eds.) Methods in Chemical Process Safety, Elsevier, 2022, pp. 1-23.
[76] S. Yuan, G. Reniers, M. Yang, Dynamic-risk-informed safety barrier management: An application to cost-effective barrier optimization based on data from multiple sources, Journal of Loss Prevention in the Process Industries, 83 (2023) 105034.
[77] E. Stefana, M. Ramos, N. Paltrinieri, Machine learning-based literature review on the concept of safety barriers against hazardous events, Journal of Loss Prevention in the Process Industries, 92 (2024) 105470.
[78] A. Hale, L. Goossens, B. Ale, L. Bellamy, J. Post, J. Oh, I.A. Papazoglou, Managing safety barriers and controls at the workplace, in: Probabilistic Safety Assessment and Management: PSAM 7—ESREL'04 June 14–18, 2004, Berlin, Germany, Volume 6, Springer, 2004, pp. 608-613.
[79] R. Bubbico, S. Lee, D. Moscati, N. Paltrinieri, Dynamic assessment of safety barriers preventing escalation in offshore Oil&Gas, Safety Science, 121 (2020) 319-330.
[80] B. Hosseinnia Davatgar, N. Paltrinieri, R. Bubbico, Safety barrier management: risk-based approach for the oil and gas sector, Journal of marine science and engineering, 9 (2021) 722.
[81] IOGP, Standardization of Barrier Definitions. Supplement to Report 415, in, International Association of Oil & Gas Producers (IOGP) Auderghem, Belgium, 2016.
[82] R. Pitblado, M. Fisher, B. Nelson, H. Fløtaker, K. Molazemi, A. Stokke, Concepts for dynamic barrier management, Journal of Loss Prevention in the Process Industries, 43 (2016) 741-746.
[83] S. Wu, B. Li, Y. Zhou, M. Chen, Y. Liu, L. Zhang, Hybrid Dynamic Bayesian network method for performance analysis of safety barriers considering multi-maintenance strategies, Engineering Applications of Artificial Intelligence, 109 (2022) 104624.
[84] F. Di Maio, S. Marchetti, E. Zio, A framework of sensitivity analysis for the performance assessment of safety barriers impacted by NaTech accidents, Process Safety and Environmental Protection, 171 (2023) 1022-1030.
[85] H. Hefaidh, M. Djebabra, S. Lila, T. Mouna, Contribution to the evaluation of safety barriers performance, World Journal of Science, Technology and Sustainable Development, (2019).
[86] M. Rausand, Reliability of safety-critical systems: theory and applications, John Wiley & Sons, 2014.
[87] N.J. Duijm, Safety-barrier diagrams as a safety management tool, Reliability Engineering & System Safety, 94 (2009) 332-341.
[88] R. Pitblado, M. Fisher, B. Nelson, H. Fløtaker, K. Molazemi, A. Stokke, Dynamic barrier management-Managing safety barrier degradation, in: Institution of Chemical Engineers Symposium Series, 2016-Janua, 2016, pp. 1-8.
[89] A. Moshnikov, V. Bogatyrev, Risk Reduction Optimization of Process Systems under Cost Constraint Applying Instrumented Safety Measures, Computers, 9 (2020) 50.
[90] A. Zhang, Y. Liu, Performance evaluation of digitalized safety barriers, in: Methods in Chemical Process Safety, Elsevier, 2022, pp. 281-307.

[91] K. Øien, S. Hauge, M.G. Jaatun, L. Flå, L. Bodsberg, A survey on cybersecurity barrier management in process control environments, in: 2022 IEEE International Conference on Cloud Computing Technology and Science (CloudCom), IEEE, 2022, pp. 113-120.
[92] M. Battaglini, M. Andriescu, K. Spyridopoulos, N. Olausson, Smart digital monitoring systems for occupational safety and health: workplace resources for design, implementation and use. European Agency for Safety and Health at Work - EU-OSHA, 2022.
[93] Z. Nawaz, P. Jain, Barrier status panel: Tool for barrier management, in: 2017 2nd International Conference on System Reliability and Safety (ICSRS), IEEE, 2017, pp. 421-428.
[94] I.L. Johansen, M. Rausand, Barrier management in the offshore oil and gas industry, Journal of Loss Prevention in the Process Industries, 34 (2015) 49-55.
[95] I. Prashanth, G.J. Fernandez, R.G. Sunder, B. Boardman, Factors influencing safety barrier performance for onshore gas drilling operations, Journal of Loss Prevention in the Process Industries, 49 (2017) 291-298.
[96] H. Sun, H. Wang, M. Yang, G. Reniers, Resilience-based approach to safety barrier performance assessment in process facilities, Journal of Loss Prevention in the Process Industries, 73 (2021) 104599.
[97] Ø. Arild, E.P. Ford, H.P. Lohne, M.M. Majoumerd, V. Havlova, A comparison of FEP-analysis and barrier analysis for CO2 leakage risk assessment on an abandoned Czech oilfield, Energy Procedia, 114 (2017) 4237-4255.
[98] J. Ge, K. Xu, C. Wu, Q. Xu, X. Yao, L. Li, X. Xu, E. Sun, J. Li, X. Li, What is the object of safety science?, Safety science, 118 (2019) 907-914.
[99] M. Shahrokhi, A. Bernard, A development in energy flow/barrier analysis, Safety science, 48 (2010) 598-606.
[100] G. Landucci, F. Argenti, A. Tugnoli, V. Cozzani, Quantitative assessment of safety barrier performance in the prevention of domino scenarios triggered by fire, Reliability Engineering & System Safety, 143 (2015) 30-43.
[101] W. Røed, A. Mosleh, J.E. Vinnem, T. Aven, On the use of the hybrid causal logic method in offshore risk analysis, Reliability engineering & System safety, 94 (2009) 445-455.
[102] T. Aven, S. Sklet, J.E. Vinnem, Barrier and operational risk analysis of hydrocarbon releases (BORA-Release): Part I. Method description, Journal of hazardous Materials, 137 (2006) 681-691.
[103] C. Li, Y. Jin, Z. Guan, Z. Dang, J. Jin, B. Zhang, New quantitative risk prediction method of deepwater blowout: Case study of Macondo well accident, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, (2021) 1-20.
[104] S. Sultana, S. Haugen, An extended FRAM method to check the adequacy of safety barriers and to assess the safety of a socio-technical system, Safety science, 157 (2023) 105930.
[105] I. 62502, IEC 62502, 2010-06: Analysis techniques for dependability–Event tree analysis, in, Beuth Verlag GmbH, Berlin.
[106] I.E. Commission, IEC 61025: 2006, Fault tree analysis (FTA), (2006).
[107] A. de Ruijter, F. Guldenmund, The bowtie method: A review, Safety science, 88 (2016) 211-218.
[108] Q. Wang, S. Chen, J. Shi, F. Chen, J. Zhang, L. Chen, J. Li, Z. Dou, Assessment of safety barrier performance in complex chemical processes: bridging conventional semi-quantitative risk assessment techniques with systems-theoretic optimisation, Chemical Engineering Science, 316 (2025) 121927.
[109] R. Ouache, M.N. Kabir, Models of probability of failure on demand for safety instrumented system using atmospheric elements, Safety science, 87 (2016) 38-46.
[110] H. Srivastav, A. Barros, M.A. Lundteigen, Modelling framework for performance analysis of SIS subject to degradation due to proof tests, Reliability Engineering & System Safety, 195 (2020) 106702.
[111] W. Mechri, C. Simon, K. BenOthman, Switching Markov chains for a holistic modeling of SIS unavailability, Reliability Engineering & System Safety, 133 (2015) 212-222.
[112] R. Ferdous, F. Khan, R. Sadiq, P. Amyotte, B. Veitch, Fault and event tree analyses for process systems risk analysis: uncertainty handling formulations, Risk Analysis: An International Journal, 31 (2011) 86-107.
[113] H. Zerrouki, Risk assessment of a liquefied natural gas process facility using bow-tie and Bayesian networks, Process Safety Progress, 41 (2022) 480-491.
[114] A. McGill, R. McCloskey, D. Smith, V. Salehi, B. Veitch, Building a Functional Resonance Analysis Method Model: Practical Guidance on Qualitative Data Collection and Analysis, International Journal of Qualitative Methods, 22 (2023) 16094069231211145.

[115] R. Patriarca, M. Chatzimichailidou, N. Karanikas, G. Di Gravio, The past and present of System-Theoretic Accident Model And Processes (STAMP) and its associated techniques: A scoping review, Safety science, 146 (2022) 105566.
[116] H. Taibi, B. Hamaidi, H. Zerrouki, A. Chergui, Modeling safety barriers and risk analysis in cement firing systems: A BORA-based approach incorporating risk influencing factors, Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, (2025) 1748006X251325579.
[117] R. McLeod, I. Randle, The CIEHF White Paper on Human Factors in Barrier Management: Recommendations for good practice, 2017.
[118] R. Pitblado, W.R. Nelson, Advanced safety barrier management with inclusion of human and organizational aspects, Chemical engineering transactions, 31 (2013) 331-336.
[119] N. Tamascelli, A. Dal Pozzo, G.E. Scarponi, N. Paltrinieri, V. Cozzani, Assessment of safety barrier performance in environmentally critical facilities: bridging conventional risk assessment techniques with data-driven modelling, Process Safety and Environmental Protection, 181 (2024) 294-311.
[120] M. Bucelli, N. Paltrinieri, G. Landucci, V. Cozzani, Safety barrier management and risk assessment: integration for safer operations in the Oil&Gas industry, Proceedings of the HAZARDS, 27 (2017).
[121] F. Khan, S.J. Hashemi, N. Paltrinieri, P. Amyotte, V. Cozzani, G. Reniers, Dynamic risk management: a contemporary approach to process safety management, Current Opinion in Chemical Engineering, 14 (2016) 9-17.
[122] H. Hadef, W. Boulagouas, M. Djebabra, Adjustment of generic frequencies for major accident hazards: Case of SEVESO establishments, Journal of Loss Prevention in the Process Industries, 96 (2025) 105610.
[123] Y. Wang, S.H. Chung, Artificial intelligence in safety-critical systems: a systematic review, Industrial Management & Data Systems, 122 (2022) 442-470.
[124] D.J. Provan, D.D. Woods, S.W.A. Dekker, A.J. Rae, Safety II professionals: How resilience engineering can transform safety practice, Reliability Engineering & System Safety, 195 (2020) 106740.
[125] A. Rachman, R.C. Ratnayake, Implementation of system-based hazard Analysis on physical safety barrier: A case study in subsea HIPPS, in: 2015 IEEE international conference on industrial engineering and engineering management (IEEM), IEEE, 2015, pp. 11-15.
[126] C. Pilbeam, N. Doherty, R. Davidson, D. Denyer, Safety leadership practices for organizational safety compliance: Developing a research agenda from a review of the literature, Safety Science, 86 (2016) 110-121.
[127] L. Niu, Y. Liu, The Relationship Between Leadership Safety Commitment and Resilience Safety Participation Behavior, Psychology Research and Behavior Management, 15 (2022) 517-531.
[128] B.C.P. Jansen, F.L. Firing, A Holistic Approach to Safety Barrier Management, (2016).
[129] K.B. Karolius, G. Psarros, O.C. Astrup, L. Qin, C.V. Welter, D. Vassalos, Maritime Operational Risk Management Using Dynamic Barriers, Ships and Offshore Structures, (2021) 1-15.
[130] A. Zhang, Y. Liu, A. Barros, Y. Wang, Prognostic and Health Management for Safety Barriers in Infrastructures: Opportunities and Challenges, (2018) 1035-1042.
[131] A. Waqar, I. Othman, R.A. Gonzalez-Lezcano, Challenges to the implementation of BIM for the risk management of oil and gas construction projects: structural equation modeling approach, Sustainability, 15 (2023) 8019.
[132] M.M. Zadeh, A. Shamisa, R. Heibati, S.M.T. Bathaee, The Solution of Digital Transformation Challenges with The Future of Operations in The field of IoT & AI for Smart Grids, in: 2024 14th Smart Grid Conference (SGC), 2024, pp. 1-7.
[133] T. Mazhar, D.B. Talpur, T.A. Shloul, Y.Y. Ghadi, I. Haq, I. Ullah, K. Ouahada, H. Hamam, Analysis of IoT security challenges and its solutions using artificial intelligence, Brain sciences, 13 (2023) 683.
[134] M. Ahmed, I. Bashar, S.T. Alam, A.I. Wasi, I. Jerin, S. Khatun, M. Rahman, An overview of Asian cement industry: Environmental impacts, research methodologies and mitigation measures, Sustainable Production and Consumption, 28 (2021) 1018-1039.
[135] M. Schneider, M. Romer, M. Tschudin, H. Bolio, Sustainable cement production—present and future, Cement and concrete research, 41 (2011) 642-650.

[136] A. da Costa, R.F. Martins, A.Ć. Soares, Failure analysis of a rotary satellite kiln located in a cement production line, Engineering Failure Analysis, 148 (2023) 107212.
[137] N.A. Madlool, R. Saidur, M.S. Hossain, N. Rahim, A critical review on energy use and savings in the cement industries, Renewable and sustainable energy reviews, 15 (2011) 2042-2060.
[138] Y. Xiao, Y. Xue, A review on application of microwave in cement life cycle, Renewable and Sustainable Energy Reviews, 199 (2024) 114498.
[139] S.J. Deery, A. Dougherty, Best safe practices in cement plants, in: IEEE-IAS/PCA 2001 Cement Industry Technical Conference. Conference Record (Cat. No. 01CH37150), IEEE, 2001, pp. 313-331.
[140] B. Afkhami, B. Akbarian, N. Beheshti, A. Kakaee, B. Shabani, Energy consumption assessment in a cement production plant, Sustainable Energy Technologies and Assessments, 10 (2015) 84-89.
[141] V. Sousa, J.A. Bogas, Comparison of energy consumption and carbon emissions from clinker and recycled cement production, Journal of cleaner production, 306 (2021) 127277.
[142] M.L. Nehdi, A. Marani, L. Zhang, Is net-zero feasible: Systematic review of cement and concrete decarbonization technologies, Renewable and Sustainable Energy Reviews, 191 (2024) 114169.
[143] V.I. Efimov, S.M. Popov, O.S. Korobova, N.V. Efimova, Improvement of the Environmental Safety in the Light of Climate Agenda in the Production of Cement, Bezopasnost' Truda v Promyshlennosti, 2022 (2022) 55-60.
[144] J. Kline, Can Safety be the Master Measure?, in: 2019 IEEE-IAS/PCA Cement Industry Conference (IAS/PCA), IEEE, 2019, pp. 1-8.
[145] H. Borgheipour, D. Eskandari, A. Barkhordari, M. Mavaji, G.M. Tehrani, Predicting the relationship between safety climate and safety performance in cement industry, Work, 66 (2020) 109-117.
[146] R. Manikandan, Pradeep Kannan, P., Rajpradeesh, T., Rajesh, S., Risk Assessment Using Bow-Tie Tool in Cement Industry, ICAMR 2019. Springer Proceedings in Materials, vol 5. Springer, Singapore. https://doi.org/10.1007/978-981-15-8319-3_44, (2021).
[147] E. Code, Official Journal of the French Republic: Classification and Nomenclature of Installations for Environmental Protection (ICPE), in, (2024), https://www.legifrance.gouv.fr.
[148] ISO 9001: 2015 Quality Management Systems-Requirements, Guidance Document, (2015).
[149] ISO 45001, Occupational Health and Safety Management Systems: Requirements with Guidance for Use, ISO, 2018.
[150] ISO 14001: 2015 Environmental management systems: A practical guide for SMEs, ISO, 2017.
[151] ISO 50001: 2018 Energy management, ISO, 2018.
[152] A.K. Chatterjee, Chemistry and engineering of the clinkerization process—Incremental advances and lack of breakthroughs, Cement and Concrete research, 41 (2011) 624-641.
[153] A.A. Usón, A.M. López-Sabirón, G. Ferreira, E.L. Sastresa, Uses of alternative fuels and raw materials in the cement industry as sustainable waste management options, Renewable and Sustainable Energy Reviews, 23 (2013) 242-260.
[154] R. Chaudhury, U. Sharma, P. Thapliyal, L. Singh, Low-CO2 emission strategies to achieve net zero target in cement sector, Journal of Cleaner Production, (2023) 137466.
[155] S. Barbhuiya, B.B. Das, D. Adak, Roadmap to a net-zero carbon cement sector: Strategies, innovations and policy imperatives, Journal of Environmental Management, 359 (2024) 121052.
[156] K.S. Devi, V.V. Lakshmi, A. Alakanandana, Impacts of cement industry on environment-an overview, Asia Pac. J. Res, 1 (2017) 156-161.
[157] Q. Xiang, H. Pan, X. Ma, M. Yang, Y. Lyu, X. Zhang, W. Shui, W. Liao, Y. Xiao, J. Wu, Impacts of energy-saving and emission-reduction on sustainability of cement production, Renewable and Sustainable Energy Reviews, 191 (2024) 114089.
[158] N. Mohamad, K. Muthusamy, R. Embong, A. Kusbiantoro, M.H. Hashim, Environmental impact of cement production and Solutions: A review, Materials Today: Proceedings, 48 (2022) 741-746.
[159] E. Benhelal, G. Zahedi, E. Shamsaei, A. Bahadori, Global strategies and potentials to curb CO2 emissions in cement industry, Journal of cleaner production, 51 (2013) 142-161.
[160] O.E. Ige, D.V. Von Kallon, D. Desai, Carbon emissions mitigation methods for cement industry using a systems dynamics model, Clean Technologies and Environmental Policy, 26 (2024) 579-597.
[161] Y. Guo, L. Luo, T. Liu, L. Hao, Y. Li, P. Liu, T. Zhu, A review of low-carbon technologies and projects for the global cement industry, Journal of Environmental Sciences, 136 (2024) 682-697.

[162] X. Hao, X. Wang, J. Liu, X. Wang, Z. Zhang, Y. Ji, A multi-indicator prediction method for NOx emission concentration and ammonia escape value for cement calciner system, Journal of Computational Science, 76 (2024) 102212.
[163] X. Zhang, J. Tian, X. Wang, Y. Zhu, T. Hu, P. Hu, Multiphase flow simulation and industrial application of an in-line gasifier for NOx emissions control from cement kiln, Journal of Industrial and Engineering Chemistry, (2024).
[164] B.A. dos Santos, A. de Souza Silva, E.S. Junior, L.P.C. Monteiro, F.B. Mainier, Proposal for Reducing Emissions of SOx in Cement Plants, American Journal of Environmental Engineering, 4 (2014) 143-146.
[165] C. Ciobanu, I.A. Istrate, P. Tudor, G. Voicu, Dust emission monitoring in cement plant mills: a case study in Romania, International Journal of Environmental Research and Public Health, 18 (2021) 9096.
[166] E.M. Metwally, A.A. Zahran, M.K. Fattah, Uses of Alternative Fuels in Cement Industrial Sectors as Sustainable Development Option: Case Study Cement Company in Egypt, International Journal of Environmental Studies and Researches, 3 (2024) 66-73.
[167] S. Eshkoraev, ALTERNATIVE RAW MATERIALS AND FUELS IN CEMENT PRODUCTION: SHAPING SUSTAINABLE PRACTICES, Multidisciplinary Journal of Science and Technology, 4 (2024) 193-206.
[168] S. Barbhuiya, F. Kanavaris, B.B. Das, M. Idrees, Decarbonising cement and concrete production: Strategies, challenges and pathways for sustainable development, Journal of Building Engineering, (2024) 108861.
[169] E. Putri, M. Lestari, N. Novrikasari, D. Andarini, A. Camelia, P. Fujianti, T. Nurhaliza, Bowtie Method: Study of Occupational Health and Safety Risks in Cement Production Process, Media Kesehatan Masyarakat Indonesia, 17 (2021) 124-133.
[170] I. Alimohammadi, F. Mirzaei, A. Farshad, Assessment of hazard kiln cement factory with Failure Mode Effects and Criticality Analysis (FMECA), Iran Occupational Health, 9 (2013).
[171] A.F. Rosyidiin, M.L. Singgih, P. Suwignjo, HAZARD IDENTIFICATION AND RISK CONTROL IN ROTARY KILN WITHIN THE CEMENT MANUFACTURING COMPANY.
[172] V. Karahan, C. Akosman, Occupational health risk analysis and assessment in cement production processes, Turkish Journal of Science and Technology, 13 (2018) 29-37.
[173] A.H. Rahmani, A. Almatroudi, A.Y. Babiker, A.A. Khan, M.A. Alsahly, Effect of exposure to cement dust among the workers: an evaluation of health related complications, Open access Macedonian journal of medical sciences, 6 (2018) 1159.
[174] R. Manjula, R. Praveena, R.R. Clevin, C. Ghattargi, A. Dorle, D. Lalitha, Effects of occupational dust exposure on the health status of portland cement factory workers, International Journal of Medicine & Public Health, 3 (2013).
[175] N. Hamidi, M. Omidvari, M. Meftahi, The effect of integrated management system on safety and productivity indices: Case study; Iranian cement industries, Safety science, 50 (2012) 1180-1189.
[176] C. Rachid, V. Ion, C. Irina, B. Mohamed, Preserving and improving the safety and health at work: Case of Hamma Bouziane cement plant (Algeria), Safety Science, 76 (2015) 145-150.
[177] M.K. Tomar, Study of occupational health, safety and environmental aspects in major cement manufacturing industry (Ultratech Cement Limited.), Journal of Environment and Earth Science, 4 (2014) 117-120.
[178] F. Ficici, V. Ari, Optimization of the preheater cyclone separators used in the cement industry, International journal of green energy, 10 (2013) 12-27.
[179] A. Yunusa-Kaltungo, M.M. Kermani, A. Labib, Investigation of critical failures using root cause analysis methods: Case study of ASH cement PLC, Engineering Failure Analysis, 73 (2017) 25-45.
[180] H. Chen, X. Zhang, P. Hong, H. Hu, X. Yin, Recognition of the temperature condition of a rotary kiln using dynamic features of a series of blurry flame images, IEEE Transactions on Industrial Informatics, 12 (2015) 148-157.
[181] A. Atmaca, R. Yumrutaş, Analysis of the parameters affecting energy consumption of a rotary kiln in cement industry, Applied Thermal Engineering, 66 (2014) 435-444.
[182] T. Liu, Q. Zhang, G. Li, Z. Ma, M. Zhang, Design and implementation of the temperature monitoring system of infrared rotary kiln shell, in: 2017 12th IEEE Conference on Industrial Electronics and Applications (ICIEA), IEEE, 2017, pp. 253-257.

[183] I. Makaremi, A. Fatehi, B.N. Araabi, M. Azizi, A. Cheloeian, Abnormal condition detection in a cement rotary kiln with system identification methods, Journal of process control, 19 (2009) 1538-1545.
[184] M. Fallahpour, A. Fatehi, B.N. Araabi, M. Azizi, A supervisory fuzzy control of back-end temperature of rotary cement kilns, in: 2007 International Conference on Control, Automation and Systems, IEEE, 2007, pp. 429-434.
[185] H. Chen, T. Yan, X. Zhang, Burning condition recognition of rotary kiln based on spatiotemporal features of flame video, Energy, 211 (2020) 118656.
[186] T. Matias, D. Gabriel, F. Souza, R. Araújo, J.C. Pereira, Fault detection and replacement of a temperature sensor in a cement rotary kiln, in: 2013 IEEE 18th Conference on Emerging Technologies & Factory Automation (ETFA), IEEE, 2013, pp. 1-8.
[187] V. Gomathi, S. Srinivasan, K. Ramkumar, G. Muralidharan, Structural analysis based sensor measurement fault diagnosis in cement industries, Control Engineering Practice, 64 (2017) 148-159.
[188] K.D. Stephan, J.A. Pearce, L. Wang, E. Ryza, Cement kiln temperature measurements using microwave radiometry, in: IEEE MTT-S International Microwave Symposium Digest, 2005., IEEE, 2005, pp. 151-154.
[189] S. Shankar, L. Thomas, H. Pratheesh, K. Suresh, Burning Zone Temperature Estimation of Rotary Kiln Using Flame Image Analysis in Cement Plants, in: 2018 International CET Conference on Control, Communication, and Computing (IC4), IEEE, 2018, pp. 255-259.
[190] A. Rahman, M. Rasul, M.M.K. Khan, S. Sharma, Impact of alternative fuels on the cement manufacturing plant performance: an overview, Procedia Engineering, 56 (2013) 393-400.
[191] F. Bartknecht, M. Siegfried, H. Weber, Sensors solutions and predictive maintenance tools to decrease kiln and conveyor belt downtime, in: 2019 IEEE-IAS/PCA Cement Industry Conference (IAS/PCA), IEEE, 2019, pp. 1-9.
[192] H. Knopfel, D. Schmidt, Optimized kiln operation by keeping kiln shell temperatures at set point with controlled water cooling, in: 2018 IEEE-IAS/PCA Cement Industry Conference (IAS/PCA), IEEE, 2018, pp. 1-11.
[193] W.-N. Wu, X.-Y. Liu, Z. Hu, R. Zhang, X.-Y. Lu, Improving the sustainability of cement clinker calcination process by assessing the heat loss through kiln shell and its influencing factors: A case study in China, Journal of Cleaner Production, 224 (2019) 132-141.
[194] E. Worrell, L. Price, N. Martin, C. Hendriks, L.O. Meida, Carbon dioxide emissions from the global cement industry, Annual review of energy and the environment, 26 (2001) 303-329.
[195] M. Onifade, B. Genc, Spontaneous combustion of coals and coal-shales, International Journal of Mining Science and Technology, 28 (2018) 933-940.
[196] S. Sklet, J.E. Vinnem, T. Aven, Barrier and operational risk analysis of hydrocarbon releases (BORA-Release): Part II: Results from a case study, Journal of hazardous materials, 137 (2006) 692-708.
[197] M. Bourareche, R. Nait-Said, N. Ouazraoui, Implementing BORA in oil and gas process case study: Algerian industry, in: 2015 International Conference on Industrial Engineering and Operations Management (IEOM), IEEE, 2015, pp. 1-8.
[198] X. Zhen, J.E. Vinnem, Prioritization of critical risk influencing factors in quantitative risk analyses for offshore petroleum installations, Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 235 (2021) 63-79.
[199] M.J. Akhtar, I.B. Utne, Modelling the impact of human fatigue on the risk of shipping accidents, in: Transport Research Arena (TRA) 5th Conference: Transport Solutions from Research to DeploymentEuropean CommissionConference of European Directors of Roads (CEDR) European Road Transport Research Advisory Council (ERTRAC) WATERBORNE^{TP}European Rail Research Advisory Council (ERRAC) Institut Francais des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR) Ministère de l'Écologie, du Développement Durable et de l'Énergie, 2014.
[200] X. Zhen, J.E. Vinnem, C. Peng, Y. Huang, Quantitative Risk Modelling of Maintenance Work on Major Offshore Process Equipment, Journal of Loss Prevention in the Process Industries, 56 (2018) 430-443.
[201] Y. Huang, G. Ma, J. Li, H. Hao, Confidence-based quantitative risk analysis for offshore accidental hydrocarbon release events, Journal of Loss Prevention in the Process Industries, 35 (2015) 117-124.
[202] J.E. Vinnem, J. Seljelid, S. Haugen, S. Sklet, T. Aven, Generalised methodology for operational risk analysis, in: Proceedings of ESREL, 2007, pp. 61-68.

[203] T. Aven, S. Hauge, S. Sklet, J.E. Vinnem, Methodology for incorporating human and organizational factors in risk analysis for offshore installations, International Journal of Materials & Structural Reliability, 4 (2006) 1-14.
[204] I.A. Okaro, L. Tao, Reliability Analysis and Optimisation of Subsea Compression System Facing Operational Covariate Stresses, Reliability Engineering & System Safety, 156 (2016) 159-174.
[205] M. Bourareche, R. Nait Said, F. Zidani, N. Ouazraoui, Improving barrier and operational risk analysis (BORA) using criticality importance analysis case study: oil and gas separator, World Journal of Engineering, 17 (2020) 267-282.
[206] K. Gould, A.J. Ringstad, K.v.d. Merwe, Human Reliability Analysis in Major Accident Risk Analyses in the Norwegian Petroleum Industry, Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 56 (2012) 2016-2020.
[207] T. Binninger, The virtual cement plant-the benefits and technology of simulators, in: IEEE-IAS/PCA 2004 Cement Industry Technical Conference (IEEE Cat. No04CH37518), IEEE, 2004, pp. 235-244.
[208] N. Shabana, Cement Rotary Kiln, Qatar Natl. Cem. Company, (2013) 1-2.

Appendices

Appendix A

Table 0.1: HAZOP Table for pre-heating tower (Deviation=Parameter+Guideword)

Guideword	Deviation	Possible causes	Consequences	Safety controls	Risk	Recommendations
Parameter: Pressure						
None of	No pressure	Kiln OFF.	Loss of production.	SOP.	2D	Regular inspection and maintenance.
More of	High pressure	1. Blockages in Cyclones/Ducts, smoke chamber/precalciner (e.g., coating, raw meal buildup).	Restricted material/gas flow. Hot material release. Process shutdowns. Equipment rupture.	Pressure Transmitter. Emergency Response. Routine inspections, Alarm. air cannons.	5B	Use air cannons to avoid excessive manual cleaning. Optimization of the kiln combustion. Proper training for emergency scenarios. Optimize raw mix chemistry.
		2. Excess exhaust gas (low ID fan speed or insufficient suction, damper closed, clogging of filter bags).	Overloading system capacity, duct erosion, fan failure.	Fan speed controllers, damper position indicators, filter differential pressure alarms.	4B	Simulation training for operators to practice responding to high pressure scenarios. Pressure relief valve “smoke chamber”.
		3. Excessive feed rate of raw meal.	Meal surge.	Feed rate controllers. Interlock System.	3C	Regular inspection and maintenance.
		4. Sticking flap valve closed.	Cyclone blockage.	Routine maintenance.	5C	Add position sensors or indicators to critical flap valves.
		5. High false air ingress (leaks in ducts/seals).	Increased gas volume, fan overload, thermal imbalance.	Gas Analyzer Seal inspections.	3B	Regular inspection and maintenance.
Less of	Low pressure	1. High ID fan speed / excessive suction.	Potential for process disturbances or shutdowns.	Fan speed controllers (Proximity sensor + Variable Frequency Drive (VFD).	2C	Optimization of the kiln combustion.
		2. Excessive false air.	Unstable operating conditions	Gas Analyzer	2B	Regular inspection and maintenance.
		3. Low raw meal feed rate	Process upset, operational delays Overheating the kiln.	Feed rate controllers Interlock System.	3C	Regular inspection and maintenance.
Parameter: temperature						
None of	No temperature	kiln OFF.	Loss of production.	Thermocouples.	2D	Regular inspection and maintenance.
More of	Higher temperature	1. Combustion imbalance (improper fuel-air ratio).	Sticky material buildup (coating and concretion). Hot material spillage. Damage to refractory lining. Possible wear & tear due to thermal expansion and contraction.	Thermocouples. Fuel flow control valves with alarms. Gas Analyzer Emergency Shutdown.	4B	Optimization of the kiln combustion. Proper training for emergency scenarios. Access control and security. Add redundancy in critical sensors. Avoid cooling hot materials with water.
		2. False air ingress.	Increased energy consumption. Increased emissions.	Gas Analyzer	2B	Regular inspection and maintenance.
		3. ID Fan speed too high.	Accumulation of exhaust gases (risk of backpressure or CO buildup).	Fan speed controllers (Proximity sensor + Variable Frequency Drive (VFD).	3C	Optimization of the kiln combustion. Regular inspection and maintenance.
		4. Loss of kiln feed.	Loss of production.	Feed rate controllers	2C	Add position sensors or indicators to critical flap valves.

Table 0.1 (continued)

Less of	Lower temperatu-re	1. Inefficient combustion (due to incorrect fuel-air ratio, burner malfunction…).	Increased CO emissions (due to incomplete combustion) Explosion risk from unburned fuel accumulation (T<650°C). Environmental non-compliance (high VOC emissions).	Preheater gas analyzer.	4B	Regular maintenance & calibration. Optimize Heat Recovery/Upgrade **[137]**.
		2. Damaged or degraded refractory lining due to thermal cycling (frequent kiln start-ups/shutdowns).	Heat loss. wear and tear, chemical attack. Cyclone blockage (refractory collapse).	SOP based operation.	4C	Regular inspection and maintenance. Schedule refractory repair during shutdowns (Refractory replacement). Use of high-quality, cycling-resistant refractory materials.
		3. Refer to High Pressure Cause 1&3.	Explosion risk if unburnt fuel accumulates in blocked zones. kiln flame instability (risk of explosion from unburned fuel).	Emergency shutdown. SOP based operation.	5D	
		4. Insufficient ID Fan speed/performance.	Potential for process disturbances or shutdowns.	Fan speed controllers (Proximity sensor + Variable Frequency Drive (VFD).	2C	Install redundant fan system. Regular inspection and maintenance.
Parameter: Hot meal flow						
None of	No flow	1. Air lift failure/ air slide (loss of conveying air, mechanical failure or power loss).	Back-up of hot meal. Overheating.	Emergency shutdown (interlocks for air slide fans).	3C	LADAR (Laser Detection and Ranging) sensors [191]. Regular inspection and maintenance. Limit alkali/chloride inputs.
		2. Raw meal silo empty.	Loss of production.	Low-level alarms.	2D	Regular inspection and maintenance.
		3. Human errors (incorrect settings).	Loss of production.	SOP based operation.	2B	Proper training.
More of	High flow	1. Human errors (incorrect setpoint).	Meal Surges (Hot meal avalanches). Incomplete calcination.	Operator monitoring.	3B	Review process alarm thresholds. Implement digital twin simulations for process optimization.
		2. Flap valve stuck open.	Poor quality clinker.	Flow sensor.	3C	Alert the control room prior to any inspection operation. Regular maintenance & calibration.
Less of	Low flow	1. Poor material distribution on one or more cyclone preheater stages.	Production disturbances. Poor quality clinker.	Flow sensor.	2C	Optimize raw mix chemistry. Regular inspection and maintenance.
		2. Build-up or partial blockage in riser, meal ducts or flap valve.			3B	Regular inspection and maintenance. Use CFD modeling to optimize flow paths.
Intermitte-nt	Intermittent Flow	1. Air supply interruption.	Meal surges. Increased thermal stress on refractory bricks.	SOP based operation.	3C	Proper training for emergency scenarios.
		2. Sticking flap valve (fails to open/close reliably due to buildup or mechanical wear).	Overpressure or clogging downstream.	Routine inspection.	4C	Add position sensors or indicators to critical flap valves. Replace unreliable flap valves.

Table 0.2: HAZOP Table for kiln (Deviation=Parameter+Guideword)

Guideword	Deviation	Possible causes	Consequences	Safety controls	Risk	Recommendations
Parameter: Pressure						
None of	No pressure	1. kiln OFF.	Loss of production.	SOP.	2D	Inspection and maintenance.
		2. ID Fan complete failure.	Loss of flame (risk of explosion). Backdraft (Backflow of hot gases).	Emergency shutdown. Flame detector Kiln camera. Pressure Transmitter (Kiln Hood).	5D	Install redundant ID fans. Proper training for emergency scenarios. SOP should empower kiln operator to stop the furnace in case of emergency.
More of	High pressure	1. The turbulence generated by the gas and air through the kiln / dust	Flame instability. Hot dust exhaust gas.	SOP based operation.	3C	Regular inspection and maintenance. Optimization of the kiln combustion.
		2. Excessive combustion (improper Fuel-Air ratio).	Production disturbances. Process instability.	Kiln inlet / Hood temperature sensors. Kiln inlet Gas Analyzer.	2B	Ensure homogeneous combustion through proper burner design/position and air/fuel ratios.
		3. Loss of flame.	Explosion in case of ignition / auto-ignition.	Flame detector. Kiln camera / operator. Gas analyzer.	5C	Install an explosion vent in the smoke chamber. Review SOP.
		4. Refer to preheater High Pressure cause 1,2&3.	Backdrafts. Overloading of the kiln.	Pressure Transmitter (Kiln Hood).	5C	Redundant pressure sensors.
		5. Ring formation.	Production interruption. Mechanical stress and damage.	Vibration monitoring. Kiln amps monitoring.	4B	Optimize and stabilize the burning zone temperature and feed chemistry.
Less of	Low pressure	1. Refer to Low Temperature Cause 1&4.	CO formation, increased emissions. Off-spec clinker.	Kiln inlet gas analyzer. Fan speed controllers (Proximity sensor + Variable Frequency Drive (VFD).	3B	Optimization of the kiln combustion. Regular inspection and maintenance.
		2. Human error (inspection port left open, poorly maintained sealings / false air ingress).	Hot material spillage.	Frequent inspection. Spill collection area.	4B	Regular inspection, replacement of seals / maintenance.
Parameter: temperature						
None of	No temperature	kiln OFF.	Loss of production.	SOP.	2D	Regular inspection and maintenance.
More of	Higher temperature	1. Excessive combustion (improper Fuel-Air ratio).	Super-heated [180]. The appearance of hot spots or red spots. Increased consumption of bricks.	Kiln inlet gas analyzer. Kiln scanner.	3B	Reduce primary airflow to control the temperature of the flame. The furnace operator must closely monitor combustion conditions, fuel rates, flame shape and stability, kiln feed flow, kiln speed, furnace inlet temperature, and induced-draft fan speed.
		2. Failure of shell cooling fan.	Localized hot spots on kiln shell. Increased liquid phase (red river). Erosion and corrosion or mechanical damage.	Inspection.	4C	Controlled Water Cooling [192]. Review settings and interlocks procedures for Kiln.
		3. Kiln feed lower LSF (Lime Saturation Factor).	Thermal stress. Overconsumption of heat and electricity.	Laboratory analysis.	2C	Optimize raw mix chemistry.
		4. Loss of coatings. Falling of refractory bricks.	Shell deformation. Ring formation. Formation of Snowman.	Fans cooling shell. Kiln amps monitoring.	4C	Regular inspection and maintenance.
		5. Burner misalignment/position	Rhino horn will be made on the burner tip.	Kiln camera (flame distortion, fuel blockage).	2B	Ensure proper alignment/position of the burner to achieve a uniform flame profile.

Table 0.2 (continued)

Less of	Lower temperature	1. Inefficient combustion (due to incorrect fuel-air ratio, burner malfunction…).	Super-chilled **[180]**. Intermittent flame ejection. Delayed ignition (fuel accumulates, risking explosion in the calciner and smoke chamber). Environmental non-compliance (high CO, VOC emissions).	Gas analyzer. Flame detector.	5B	Microwave radiometry **[188]**. Optimization of the kiln combustion.
		2. Heat loss (conduction, convection, and radiation): fumes at the kiln outlet, kiln walls, heat loss through the clinker at the outlet.	Reduce the heat recovery of the cooler. Loss of energy efficiency.	Thermocouples. Gas analyzer.	2B	New refractories. Optimization of the kiln combustion.
		3. Flame instability. Loss of burner flame.	Formation of an explosive atmosphere. Explosion in case of ignition.	Flame detector. Kiln camera + operator Gas analyzer.	5C	Optimization of the kiln parameters/ combustion. Maintain uniform flame shape.
		4. Burner misalignment/position (neglecting proper maintenance and lack of proper kiln alignment/ position).	Poor clinker quality. Increased emissions.	Kiln camera	2B	
		5. Excessive kiln feed / Short retention time.	Frequent production stops. Ring formation. Clinker out of spec (under-burnt).	Kiln scanner. Kiln amps monitoring.	3C	Maintain optimal feed composition/flow. Optimization of the kiln parameters.
Parameter: Hot meal flow						
None of	No flow	1. Blockages in the preheater.	Loss of production. Hot meal avalanche. Increased refractory consumption. Hot spot.	Kiln scanner. Monitoring power consumption of the kiln's electric motor.	4C	Optimize raw mix chemistry. Optimal monitoring of power consumption of the kiln's electric motor.
		2. Same as no flow in the preheater.	Kiln shutdown Increased maintenance costs.	Emergency shutdown.	4C	Regular inspection and maintenance.
More of	High flow	1. Sudden release after blockage removal.	Formation of snowman. Spillage of hot meals. Red river [208].	Interlocks on feed. Secondary containment. SOP bases operation.	4C	Resize the retention container to capture all the hot meals surge.
		2. Human errors (incorrect setpoint: high kiln feed speed).	Poor clinker quality. Overload of the kiln. Flame instability.		3C	Review settings. Implement fuel/kiln speed interlock. Training and awareness.
Less of	Low flow	1. Kiln build-up (Rhino horn formation, ring formation, formation of Snowman, Boulder formation) [208].	Production disturbances. Loss of production.	Kiln scanner. Monitoring power consumption of the kiln's electric motor.	4C	Optimization of the kiln combustion. Optimize raw mix chemistry. Regular inspection and cleaning.
		2. Leakage from a damaged kiln upstream seal.	Production disturbances. False air ingress. Kiln draft/ combustion instability.	Upstream and downstream joint alarm.	3C	Maintenance and periodic inspection of upstream and downstream seals / Seal replacement.
		3. Partial preheater blockage.	Process instability. Hot spots in the kiln.	Emergency Response.	4C	Optimize chemical composition of the raw meal and the hot exhaust gases.
		4. Misalignment, unsteady kiln rotation, or speed variations can disturb material flow.	Poor clinker quality. Overload of the kiln.	Kiln shell scanner. Shell ovality measurements. Operator & CCR Response.	3D	Training and awareness. The feed-to-speed ratio should remain consistent during normal operations, and any adjustments to kiln speed or feed should be made gradually to avoid sudden changes in material behavior.

Table 0.2 (continued)

Reverse	Reverse flow	1. Slope < 3% in the direction of flow.	Increased retention time Material buildup and ring formation. Thermal and mechanical stress (shell / refractory).	Kiln scanner.	4D	Verify slope during shutdown/ annual geometric audit. Regular inspection and cleaning.
		2. Big ring in the kiln.	Overload of the kiln. Kiln shutdown. Backdraft.	Monitoring of power consumption of the kiln's electric motor.	4C	Optimization of the chemical raw mix and combustion.
Intermitte-nt	Intermittent flow	1. Formation of rings or snowman / Fluctuating rotational speed	Increased retention time Material buildup and ring formation. Thermal and mechanical stress (shell / refractory).	Kiln scanner. Monitoring of power consumption of the kiln's electric motor.	4C	Optimization of the chemical raw mix and combustion. Regular inspection and maintenance.

Table 0.3: HAZOP Table for cooler (Deviation=Parameter+Guideword)

Guideword	Deviation	Possible causes	Consequences	Safety controls	Risk	Recommendations
Parameter: Pressure						
None of	No pressure	Kiln OFF.	Loss of production.	SOP based operation.	2D	Regular inspection and maintenance.
More of	High pressure	1. High exhaust gas emissions from the kiln (ID Fan or baghouse underperformance).	Instability in kiln draft and burning zone.	Pressure Transmitter at kiln Hood. ID fan current and speed monitoring.	4C	Implement redundant ID fan performance alarms (speed, current, and draft pressure) for early detection of underperformance. Ensure operators are regularly trained on updated SOP.
		2. Tertiary air duct blockage or TAD damper closed.	High pressure in cooler hood. Incomplete combustion in the precalciner. Explosion risk (increased CO and NOx emissions and unburnt fuel).	Differential pressure transmitters across TAD. Position feedback on tertiary damper Scheduled inspection/cleaning routines	5D	Optimize chemical composition of the raw meal and the hot exhaust gases to reduce risks of coating/build-up. Refractory coating inspection/ replacement. Include damper position feedback in the control system with alarms for abnormal closure or jamming.
		3. Cooling fans speed too high (excess cooling air).	Dust recirculation. Process disturbances.	Pressure transmitters. Interlock with ID fan draft.	2C	Review settings and calibrate the cooling air control logic.
Less of	Low pressure	1. Excessive suction from the ID fan.	High clinker outlet temperature due to poor clinker cooling. Draft imbalance affecting kiln combustion and heat distribution.	Fan speed control via VFD. Pressure transmitters.	3C	Review and optimize ID fan setpoints. Regular inspection and maintenance.
		2. False air ingress through cooler casing, grate seals, or duct joints.	Kiln shutdown.	Maintenance procedures.	4D	Inspect and seal false air entry points (cooler casing, joints, grate seals). Regular training for operators on draft balance management.
Parameter: temperature						
None of	No temperature	Kiln OFF.	Loss of production.	Thermocouples.	2D	Regular inspection and maintenance.
More of	Higher temperature	1. Hot meal avalanches.	Uncontrolled spillage. Ejection of hot clinker from the conveyor.	Thermocouples. Emergency stoppage. Secondary containment.	4C	Train operators for early blockage detection.
		2. Insufficient cooling air (poorly performing fans).	Poor quality clinker (off-spec).	Redundant cooling fans.	3C	Efficient fans with variable speed drives [137].
		3. Clinker overburning (in upstream kiln).	Red river. Thermal stress/ refractory damage.	shell scanners	4D	Optimize kiln combustion (fuel/air ratio, rotation speed, kiln feed, burner alignment….) Install infrared cameras at cooler discharge with alarm.
		4. Poor heat recovery for combustion air.	Inefficient combustion in the precalciner.	Thermocouples.	3D	Regular inspection and maintenance.
		5. ESP-fan speed too low (reduced draft through cooler and heat recovery).	Poor gas evacuation (Risk of buildup and fire). Dust accumulation.	Operational SOPs. VFD (Variable Frequency Drive) control on cooler fans.	5D	Set minimum speed limits and add ESP-fan performance monitoring (current, vibration, differential pressure) to predictive maintenance program.
Less of	Lower temperature	1. Cooling fans speed too high (excess cooling air).	/	Operational SOPs. VFD (Variable Frequency Drive) control on cooler fans.	3C	Regular inspection and maintenance. Implement interlock to reduce fan speed on low clinker temperature.
		2. low kiln temperature (underburned clinker)	Tertiary air temperature too low. Reduced precalciner efficiency.	Flame detector. Kiln shell scanner. Thermocouples.	4D	Optimization of the kiln combustion.

Table 0.3 (continued)

Parameter: Hot meal flow						
None of	No flow	Kiln OFF.	Loss of production.	SOPs.	2D	Regular inspection and maintenance.
More of	High flow	1. Post-cyclone blockage surge/ snowman or ring collapse at kiln outlet (hot meal avalanches).	Overloading cooler grate. Hot material spillage.	Operational SOPs. Secondary containment.	4C	Optimization of the chemical raw mix and combustion. Regular maintenance and clearance to reduce build-up and blockage.
		2. Post-crusher blockage surge (sudden flow surge after crusher blockage clearance).	Thermal and mechanical stress on grate and conveying systems. Hot material spillage.	Operational SOPs. Secondary containment.	4C	Proper training for emergency scenarios. Prevent direct contact.
		3. Human errors (incorrect setpoint: high kiln feed speed).	Hot material spillage. Poor quality clinker (off-spec).	Interlocks on feed. Secondary containment.	3B	Flowmeter installation (non-contact level measurement by radar). Operator training and emergency SOPs.
Less of	Low flow	1. Ring/ Snowman formation.	Hot material spillage.	Thermal camera. Air blasters.	4C	Flowmeter installation (non-contact level measurement by radar). Install multiple adequate air blasters in a strategic pattern
		2. Cyclone blockages.	Hot material spillage.	Operational SOPs. Secondary containment.	4C	Optimization of the chemical raw mix and combustion. Train operators on early signs and manual intervention procedures.
		3. Spillage in the upstream and/or downstream seals.	Potential for process disturbances or shutdowns. Fire/explosion risk. Uncontrolled false air ingress.	Operational SOPs. Secondary containment. Gas analyzer.	5B	Regular inspection and maintenance.
Reverse	Reverse flow	1. Grate plate reversal.	Thermal and mechanical stress on grate/equipment wear. Overheating in cooler inlet zone.	Operator & CCR Response. Thermocouples.	4C	Regular inspection and maintenance.
		2. Crusher blockage.	Thermal and mechanical stress on grate and conveying systems. Buildup (snowman formation). Hot material spillage.	Crusher motor torque monitoring.	4B	Install flow sensors/camera to detect reverse movement. Train operators on safe blockage clearance and early warning signs.

Appendix B

Script OCTAVE

```
clear all;
close all;
clc;
% Fonction inline pour convertir 'A'..'F' en index 1..6
getRow = @(letter, S) S(find("ABCDEF" == letter), :);
% ----- paramètres -----
PIE = 0.33;
PFDIPL1 = 0.025;
PFDIPL2 = 0.06;
WRif = [0.454 0.091 0.091 0.364 0.091 0.227 0.227 0.182 0.227 0.046 0.25 0.1 0.25 0.25 0.15];
SIE = [
0.5   0.33    0.2   0.1     0.5
0.75  0.67    0.6   0.55    0.75
1     1       1     1       1
1.33  1.67    2.33  4       1.33
1.67  2.33    3.67  7       1.67
2     3       5     10      2
];
SIPL1 = [
0.5   0.33    0.2   0.1     0.1
0.75  0.67    0.6   0.55    0.55
1     1       1     1       1
1.33  1.67    2.33  4       4
1.67  2.33    3.67  7       7
2     3       5     10      10
];
SIPL2 = [
0.5   0.33    0.2   0.1     0.33
0.75  0.67    0.6   0.55    0.67
1     1       1     1       1
1.33  1.67    2.33  4       1.67
1.67  2.33    3.67  7       2.33
2     3       5     10      3
];
RIF = ['A' 'B' 'C' 'D' 'E' 'F'];
states = {'A','B','C','D','E','F'};
% ---
fid = fopen('resultatsIE.txt', 'w');
if fid == -1
   error('Impossible d''ouvrir le fichier resultatsIE.txt');
end
% --- matrices de sommes (6 lignes: A..F ; 10 colonnes: 5 PIERev + 5 RRev)
somme1 = zeros(6,10);
somme2 = zeros(6,10);
somme3 = zeros(6,10);
somme4 = zeros(6,10);
id1 = zeros(1,6);
id2 = id1; id3 = id1; id4 = id1;
% --- Boucles : on fait varier RIF1..RIF4 (IE)
for i = 1:6
  for j = 1:6
    for k = 1:6
      for m = 1:6
          RIF1IE = RIF(i);
          RIF2IE = RIF(j);
          RIF3IE = RIF(k);
```

```
RIF4IE = RIF(m);
RIFIE = [RIF1IE RIF2IE RIF3IE RIF4IE];
strRIFIE = strjoin(cellstr(RIFIE.'), ' ');
% --- RIF fixes pour IPL1
RIF5IPL1 = 'C';
RIF6IPL1 = 'B';
RIF7IPL1 = 'D';
RIF8IPL1 = 'D';
RIF9IPL1 = 'C';
RIF10IPL1 = 'C';
% --- RIF fixes pour IPL2
RIF11IPL2 = 'C';
RIF12IPL2 = 'C';
RIF13IPL2 = 'B';
RIF14IPL2 = 'D';
RIF15IPL2 = 'D';
% ---- sélection des lignes (chaque getRow renvoie 1x5)
S1 = getRow(RIF1IE, SIE);
S2 = getRow(RIF2IE, SIE);
S3 = getRow(RIF3IE, SIE);
S4 = getRow(RIF4IE, SIE);
S5 = getRow(RIF5IPL1, SIPL1);
S6 = getRow(RIF6IPL1, SIPL1);
S7 = getRow(RIF7IPL1, SIPL1);
S8 = getRow(RIF8IPL1, SIPL1);
S9 = getRow(RIF9IPL1, SIPL1);
S10 = getRow(RIF10IPL1, SIPL1);
S11 = getRow(RIF11IPL2, SIPL2);
S12 = getRow(RIF12IPL2, SIPL2);
S13 = getRow(RIF13IPL2, SIPL2);
S14 = getRow(RIF14IPL2, SIPL2);
S15 = getRow(RIF15IPL2, SIPL2);
% ---- calculs pondérés (1x5 each)
MF1IE = WRif(1) * S1;
MF2IE = WRif(2) * S2;
MF3IE = WRif(3) * S3;
MF4IE = WRif(4) * S4;
MFIE = sum([MF1IE; MF2IE; MF3IE; MF4IE]);   % -> 1x5
MF5IPL1 = WRif(5) * S5;
MF6IPL1 = WRif(6) * S6;
MF7IPL1 = WRif(7) * S7;
MF8IPL1 = WRif(8) * S8;
MF9IPL1 = WRif(9) * S9;
MF10IPL1 = WRif(10) * S10;
MFIPL1 = sum([MF5IPL1; MF6IPL1; MF7IPL1; MF8IPL1; MF9IPL1; MF10IPL1]); % -> 1x5
MF11IPL2 = WRif(11) * S11;
MF12IPL2 = WRif(12) * S12;
MF13IPL2 = WRif(13) * S13;
MF14IPL2 = WRif(14) * S14;
MF15IPL2 = WRif(15) * S15;
MFIPL2 = sum([MF11IPL2; MF12IPL2; MF13IPL2; MF14IPL2; MF15IPL2]); % -> 1x5
% ---- résultats vectoriels (1x5)
PIERev = PIE * MFIE;                    % 1x5
PFDIPL1Rev = PFDIPL1 * MFIPL1;          % 1x5 (fixes)
PFDIPL2Rev = PFDIPL2 * MFIPL2;          % 1x5 (fixes)
RRev = PIERev .* PFDIPL1Rev .* PFDIPL2Rev;   % 1x5
% ---- concatène PIERev (5 cols) puis RRev (5 cols) => 1x10
somme = [PIERev, RRev];
% ---- accumulation (identique à IPL1/IPL2)
somme1(i,:) = somme1(i,:) + somme; id1(i) = id1(i) + 1;
```

```
          somme2(j,:) = somme2(j,:) + somme; id2(j) = id2(j) + 1;
          somme3(k,:) = somme3(k,:) + somme; id3(k) = id3(k) + 1;
          somme4(m,:) = somme4(m,:) + somme; id4(m) = id4(m) + 1;
          % ---- écriture détaillée (ligne par combinaison)
          fprintf(fid, '%s ',  strRIFIE);
          fprintf(fid, '%e ', PIERev);    % imprime les 5 valeurs PIERev
          fprintf(fid, '%e ', RRev);      % imprime les 5 valeurs RRev
          fprintf(fid, '\n');
      end
    end
  end
end
% --- Normalisation par le nombre d'occurrences (vérifie id>0)
for idx = 1:6
   if id1(idx)>0, somme1(idx,:) = somme1(idx,:) / id1(idx); end
   if id2(idx)>0, somme2(idx,:) = somme2(idx,:) / id2(idx); end
   if id3(idx)>0, somme3(idx,:) = somme3(idx,:) / id3(idx); end
   if id4(idx)>0, somme4(idx,:) = somme4(idx,:) / id4(idx); end
end
% --- Affichage rapide (optionnel)
disp('Somme1 (IE RIF1 - moyennes) :'); disp(somme1);
disp('Somme2 (IE RIF2 - moyennes) :'); disp(somme2);
disp('Somme3 (IE RIF3 - moyennes) :'); disp(somme3);
disp('Somme4 (IE RIF4 - moyennes) :'); disp(somme4);
% --- fermer le fichier détaillé
fclose(fid);
% --- écrire fichier compact des moyennes (une ligne par lettre A..F pour chaque somme)
fidavg = fopen('resultatsAVERAGEIE.txt', 'w');
if fidavg == -1
   error('Impossible d''ouvrir le fichier resultatsAVERAGEIE.txt');
end

% Somme1 (RIF1)
for r = 1:6
   fprintf(fidavg, 'Somme1 %s\t', RIF(r));
   fprintf(fidavg, '%0.2E\t', somme1(r,:));
   fprintf(fidavg, '\n');
end
% Somme2 (RIF2)
for r = 1:6
   fprintf(fidavg, 'Somme2 %s\t', RIF(r));
   fprintf(fidavg, '%0.2E\t', somme2(r,:));
   fprintf(fidavg, '\n');
end
% Somme3 (RIF3)
for r = 1:6
   fprintf(fidavg, 'Somme3 %s\t', RIF(r));
   fprintf(fidavg, '%0.2E\t', somme3(r,:));
   fprintf(fidavg, '\n');
end
% Somme4 (RIF4)
for r = 1:6
   fprintf(fidavg, 'Somme4 %s\t', RIF(r));
   fprintf(fidavg, '%0.2E\t', somme4(r,:));
   fprintf(fidavg, '\n');
end
fclose(fidavg);
disp(' Calcul IE terminé : resultatsIE.txt (détaillé) et resultatsAVERAGEIE.txt (moyennes) générés.');
```

Scientific Report

International Communications

- 5th International Conference on Energy, Materials, Applied Energetics and Pollution (CIEMEAP'19), held October 22–24, 2019, in Constantine, Algeria: Article title – Assessment of the performance of safety barriers
- 2nd International Conference on Advanced Engineering in Petrochemical Industry (ICAEPI), held November 26-28, 2019, in Skikda, Algeria Article title - Risk-based assessment of the effectiveness of safety barriers
- 2nd International Conference on Advanced Engineering in Petrochemical Industry (ICAEPI), held November 26-28, 2019, in Skikda, Algeria Article title - Assessment of chemical risks and their impacts on Health and the Environment

International Publications

Article 1

Modeling safety barriers and risk analysis in cement firing systems: A BORA-based approach incorporating risk influencing factors**, published in** ***Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*** **(International Journal).**

https://doi.org/10.1177/1748006X251325579

Article 2

From linear processes to resilient socio-technical systems: a hybrid HAZOP–Bowtie–FRAM framework for modeling operational risk in cement firing operations**, published in** ***Safety Science*** **(International Journal).**

https://doi.org/10.1016/j.ssci.2026.107432