A Guideline for Achieving Sustainable Safety Performance Through Critical Risk Management

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***Abstract*— The traditional approach to industrial safety has been based on lagging indicators, such as injury rates and lost workdays, which states what has already happened in the system, not necessarily how to reduce risk in the first place. This paper addresses critical risk management (CRM) through a proactive holistic framework to support sustainable safety. The study employs a mixed-methods approach to (1) describe the modern industrial operations, their technology and stakeholders and (2) develop a five-phase framework for CRM implementation. The use of system engineering models to operational metrics reveals the complex non-linear risk interactions modern industries are facing. Such complexities often cannot be solved with traditional safety measures. The study shows that the monitored critical control pathways explain a significant part (20.78%) of the variance in positive safety outcomes. In this manuscript, five distinct phases of operations are described, namely: identification, bow-tie, control mapping, verification infrastructure, frontline engagement, and continuous governance. This provides a practical blueprint for high-risk enterprises pursuing resilient, long-term incident prevention.**

***Index Terms*—safety performance, occupational health and safety, critical controls, critical risk management, safety culture, preventing incidents**

I. Introduction

High risk industrial sectors such as mining and steel production, construction, aviation, oil and gas, and transportation are always exposed to hazards that could lead to workplace injuries, catastrophic failures, or fatalities. For decades, industrial companies have attempted to address these problems by establishing OHSMS systems based on standards such as ISO 45001. The increasing exposure of their weaknesses in contemporary safety science is challenging their broad programmatic value. Traditional OHSMS often have uniform operational mechanisms for all risks, which creates an administrative burden that obscures low frequency high consequence events.

This historic dependence on retrospective data collection creates an inherent safety paradox. Lagging indicators like total recordable injury frequencies provide an approximate indication of how tardy the control barriers are in place to ensure safety outcomes. The facility may have a low minor injury rate but be operated in such a way that could lead to unanticipated process safety events. This is especially difficult for some facilities and that's where the CRM helps in dealing with the risks.

CRM is about the specific, non-negotiable barriers that can either preclude or reduce the likelihood of a catastrophic event. The present study highlights the significance of CRM as a functional strategy for gaining robust and sustainable safety performance rather than merely an administrative tool. Research on how to test and validate these frameworks through ongoing verification at the workforce interface is scarce. Most recent scholarly investigations either portray key control frameworks as fixed, top-down organizational maps or concentrate on them after a big system failure. It's unknown if long-term research can show that quantitative control verification measures can be used to track and measure routine behaviors without leading to administrative burnout. Furthermore, actual socio-technical realities, workforce experience gaps, and local psychological elements that affect an operational team's readiness to undertake Stop-William mandated training are not reconciled with the tight adherence to essential controls in the present safety literature.

1.1 Problem Statement

Today's high-risk industrial settings involve a mix of closely connected processes, fast-moving technology, and high demands for safety from all involved parties. Even though many organizations use formal, compliance-focused Occupational Health and Safety Management Systems (OHSMS), serious accidents and deaths in workplaces still happen all over the world. At the center of this problem is a mismatch in how things are structured. Traditional ways of thinking about safety look at past data, like injury rates, which don't show problems happening right now. They also treat small personal risks the same way as big, rare, but serious dangers, which isn't fair in how safety is managed. Important safety measures are slowly getting worse because companies don't have a clear, ongoing method to check the condition of their key safety barriers where workers are directly involved.

We know that high-risk companies can't reliably maintain safe operations that are both strong and long-lasting unless they have a clear, practical system in place. This system should identify, track, and manage the important safety challenges in a way that adapts to changing conditions. Modern high-risk industrial environments are characterized by a unique combination of strong process coupling, rapid technological changes and high stakeholder expectations for safety. Although the application of formal, compliance-based Occupational Health and Safety Management Systems (OHSMS) is widespread, tragic incidents and fatalities in the workplace still occur around the world.

At the heart of this issue is a structural mismatch. Conventional safety paradigms are based on retrospective lagging indicators (e.g., total recordable injury rates), which hide real-time control instability, and treat trivial personal hazards and fatal, low-frequency, high-consequence (LFHC) risks equivalently in the administrative process. Vital safety controls are silently degraded because organizations lack a systematic, operationalized way to continuously verify the health of their critical barriers at the frontline workforce interface. What we do know is that high-risk enterprises cannot deliver predictable, resilient and sustainable safety performance without a structured, actionable framework that isolates, monitors and governs these non-negotiable barriers in a dynamic way.

1.2 The Purpose and Scope of the study

The primary purpose of this study is to analyze the operational limitations of traditional safety management in complex environments and establish a mathematically sound, practical framework for CRM execution. Specific objectives are as follows:

- Objective 1: Evaluate the current industrial environment by mapping its operational complexity, rapid technological transitions, and evolving stakeholder expectations regarding sustainable safety performance.
- Objective 2: Conceptualize, structure, and model a comprehensive five-phase CRM implementation framework that translates corporate voluntary safety protocols into highly structured, verifiable onsite practices capable of driving sustainable risk reduction.

II. Literature Review

The way occupational health and safety literature has developed shows a major change from just following rules to focusing on managing risks more effectively. This shift has been well explained by Reason (1997) and later built upon by Hollnagel (2014). These researchers found that traditional safety management has a big blind spot because it focuses on small, common dangers but doesn't understand the bigger, more complex reasons behind rare but serious accidents [13], [14]. When looking at today's corporate structures, the International Council on Mining and Metals (ICMM) (2015) pointed out that standard management systems use the same approach for all risks. This ends up taking attention away from the most important safety measures that can save lives [15]. Additionally, the International Council for Harmonisation (ICH) (2023) pointed out that although modern management guidelines set a good foundation for regulatory compliance, they usually don't have the flexibility needed to handle changing risks in fast-moving work environments [9].

Jackson (2026) showed that depending too much on lagging indicators like total recordable injury frequency rates doesn't help predict sudden, major system failures very well [2]. Looking further into this big system problem, Leveson (2011) changed the way we think about industrial accidents. Instead of seeing them as just mistakes made by people, she saw them as failures in how the whole system is controlled. These failures happen slowly over time as the system's limits get pushed and weakened without anyone really noticing [17]. To advance change to systems thinking in the modern era, the authors Porter et.al., proposed a new way of assessing accident casualty for serious accident and fatality to address the current gap in methodology that exists [5]. This approach is backed by Song and Awolusi (2021), who pointed out that usual, fixed hazard checklists are not good enough for dealing with the complex, unpredictable risk connections that are common in today's Industry 4.0 environments [10].

Alexander (2008) said that in environments where safety is very important, it's necessary to use specific strategies based on evidence. These strategies should separate serious risks that could cause harm from everyday work-related issues [18]. Even though these conceptual models have their strengths, carrying out the work in real field situations is still very risky. Selleck, Hassall, and Cattani (2022) found that up to 90% of industrial deaths happen during known high-risk tasks that should have safety measures in place. This suggests that the main problem is the loss of reliable control in real-time as workers perform their jobs, not the absence of safety guidelines [6]. This operational failure is explained by Dodshon (2021). Their study on how incidents are analyzed found that although most safety professionals usually find general risk controls during their investigations, fewer than 40% take the time to properly check the real condition and engineering state of those controls [3].

Haas, Eiter, Hoebbel, and Ryan (2019) showed that traditional risk strategies often pay a lot of attention to complex engineering calculations, but they don't take into account important factors like how workers behave on the job, how long they've been at a site, and differences in their experience that can change how they identify hazards in the field [4]. There is still a major research gap in understanding how the workforce actually keeps these frameworks up to date and running smoothly.

Tembo (2026) noticed that most current academic research looks at critical control frameworks after a big system problem happens, or shows them as fixed, top-down company plans instead of real, on-the-ground processes [1]. The Australian Antarctic Division (2023) also points out that there is a lack of real-time operational integration, as organizations find it difficult to turn broad corporate safety guidelines into clear, checkable practices on the ground [7].

In looking at local operations, Badoozadeh (2024) noted that big administrative tasks can lead to mental tiredness, making workers see safety checks as just routine "tick-and-flick" tasks [8]. So, Seqwater Operations (2021) pointed out that today's safety management needs to set clear, simple yes-or-no performance standards to remove any confusion [9]. Finally, Hollá, Kuricová, Kočkár, Prievozník, and Dostál (2024) and Bazaluk et al. In 2024, experts came together and agreed that future safety research needs to fix this problem by creating systems that can check things continuously and in real time. These systems should make sure that strict engineering rules work well with the real situations that people face on the front lines [11], [12].

It is becoming increasingly apparent that conventional approaches to safety and human factors are not equipped to cope with these challenges and that a new era in safety is necessary. Dekker (2014) explains how to turn safety from a bureaucratic accountability back into an ethical responsibility for those who do dangerous work, and how to embrace the human factor not as a problem to control, but as a solution to harness [16].

III. Methodology

3.1 Data Collection Mechanisms

To ensure an empirical approach, this study utilizes a dual-layered data collection model:

- Primary Data Collection: Field-level data were captured directly from N = 154 operational sectors across heavy industrial facilities using digitized critical control verification audits, direct observational safety field checks, and real-time Go/No-Go supervisor compliance logs.
- Secondary Data Collection: Historical risk contexts and operational parameters were extracted from corporate material risk registers, historical accident and near-miss investigation reports, regulator penalty databases, and established industry benchmark publications.

3.2 Analytical Approaches

To meet the research objectives, a multi-phased mixed-methods approach was applied, involving quantitative statistical modeling and qualitative systems engineering techniques.

The gathered data were subjected to parallel analytical pathways to balance mathematical precision with systemic context:

- Qualitative Systems Analysis: Systemic hazards and organizational control configurations were mapped using Bow-Tie analysis and socio-technical modeling frameworks. This qualitative process filtered generic hazards to isolate specific Low-Frequency High-Consequence (LFHC) risk vectors and identified the explicit engineering and administrative performance standards required for critical barriers.
- Quantitative Statistical Analysis: Field verification compliance scores were mathematically aggregated and modeled using Ordinary Least Squares (OLS) linear regression analysis. This quantitative layer tested the predictive relationship between Critical Control Monitoring Efficiency *(Mc)* and the Composite Safety Performance Outcome *(Ys)*, backed by Cronbach's αc tests to ensure construct reliability across the operational nodes.

3.3 Macro-Environmental Complexity Mapping (Objective 1)

The operational profiles and compliance mandates from high-risk industrial units across multi-regional jurisdictions were gathered. This environment was evaluated using a composite complexity index *(CI),* modelled as a function of process tight-coupling *(Ct),* technology transition velocity *(Vt),* and stakeholder / regulatory non-compliance penalties *(Ps)*. Each dimension was scored on a standardised scale (0–100) based on industry operational parameters.

A composite complex index *(CI)* was calculated using the weighted equation:

$$CI = \alpha \cdot Ct + \beta \cdot Vt + \gamma \cdot Ps$$

Where α, β, and γ represent scaling weights calibrated via iterative expert panel evaluations.

3.4 Framework Modeling and Validation (Objective 2)

A five-stage CRM system was developed, and the framework is described below. By utilising empirical field data from heavy industrial facilities with operational sectors (N = 154), the framework's fundamental principle of critical control monitoring was quantitatively validated to determine the effectiveness of positive safety performance. We applied a simple linear regression model to isolate the variance explained by control monitoring efficiency:

$$Ys = \beta 0 + \beta 1 \cdot Mc + \epsilon$$

To account for the variance, we employed a straightforward linear regression technique.

$$Ys = \beta 0$$
$$Mc + 1 = 0$$

Where:

- Ys represents the composite safety performance Outcome index.
- Mc stands for critical control monitoring and verification efficiency percentage.
- ϵ represents the stochastic error term.

By using Cronbach's Alpha *(αc),* it was demonstrated that the qualitative system nodes in the five-phase framework maintain their internal consistency and construct reliability.

IV. Results And Discussion

4.1. Evaluation of the Macro-Industrial Environment (Addressing Objective 1)

Our examination of the current industrial environment reveals an ecosystem undergoing structural changes more quickly than in the past. A functioning environment is produced by the three main pressures, as shown in Figure 1.

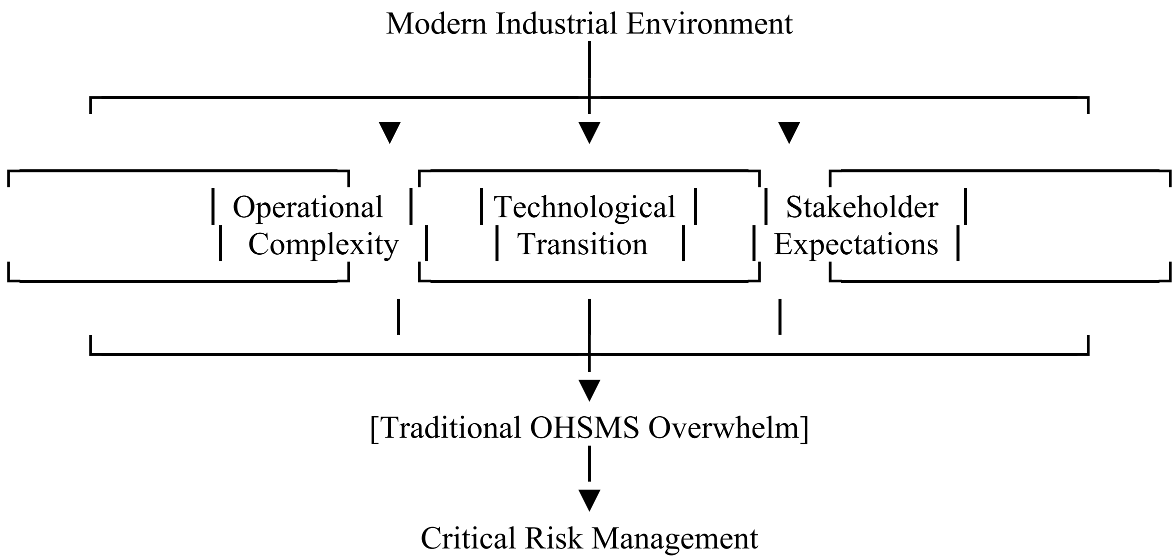

Figure 1. Operational environment

1. Operational Complexity: Modern plants are characterized by highly integrated and tightly coupled systems. A localized equipment variance that is nonlinear across automated networks might cause routine maintenance to become multi-point system breakdowns.
2. Technological Developments: New socio-technical hazard vectors are introduced by Industry 4.0 systems, cyber-physical automation, and shared human-machine workplaces. These rapid technical developments are entirely outside the scope of conventional danger management checklists.
3. Stakeholder Expectations: Regulators, investors, and communities are among the stakeholders whose demands for public verification of risk posture are moving away from passively monitoring compliance. Industrial fatalities are intolerable to society, which demands objective safety systems backed by reliable data.

Empirical criteria were established from five high-risk sectors and combined into a composite score to measure these tendencies across industry profiles. The composite complexity index *(CI)* can be computed empirically using a weighted equation.

$$CI \text{ is equal to } 0.4 \cdot Ct + 0.3 \cdot Vt + 0.3 \cdot Ps.$$

The following charts (Figures 2, 3, and 4) illustrate the relationships of:

- Composite Complexity Index (CI) by Industrial Sector: Industry rankings of total complexity
- Comparison of Industrial industry Complexity Metrics: This method divides each industry into three primary complexity drivers, the primary one being regulatory penalties.

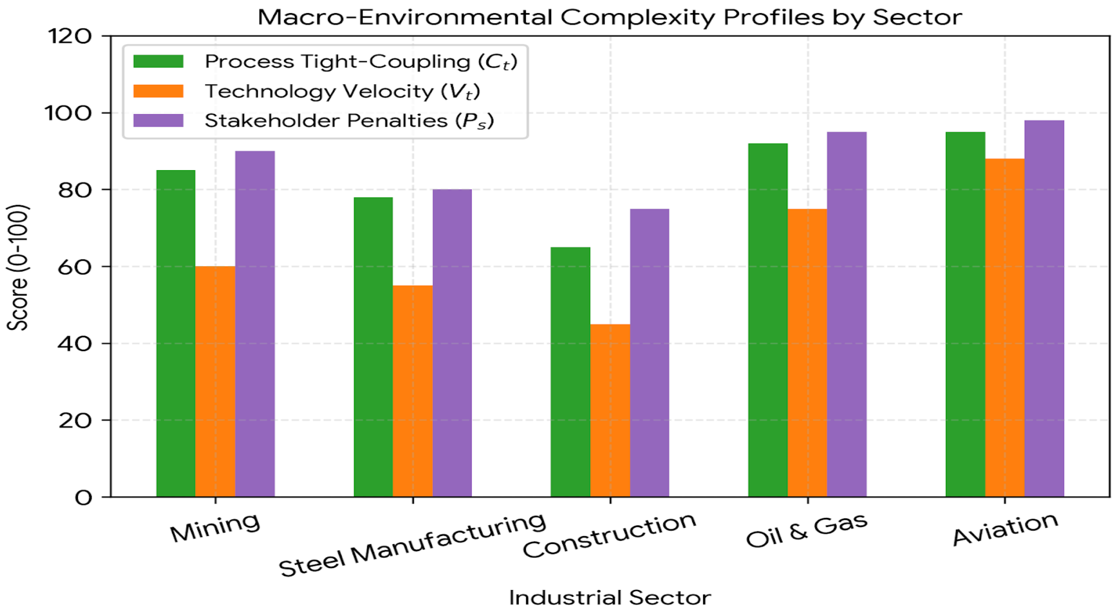

Figure 2. Macro- environmental complexity profile by sector

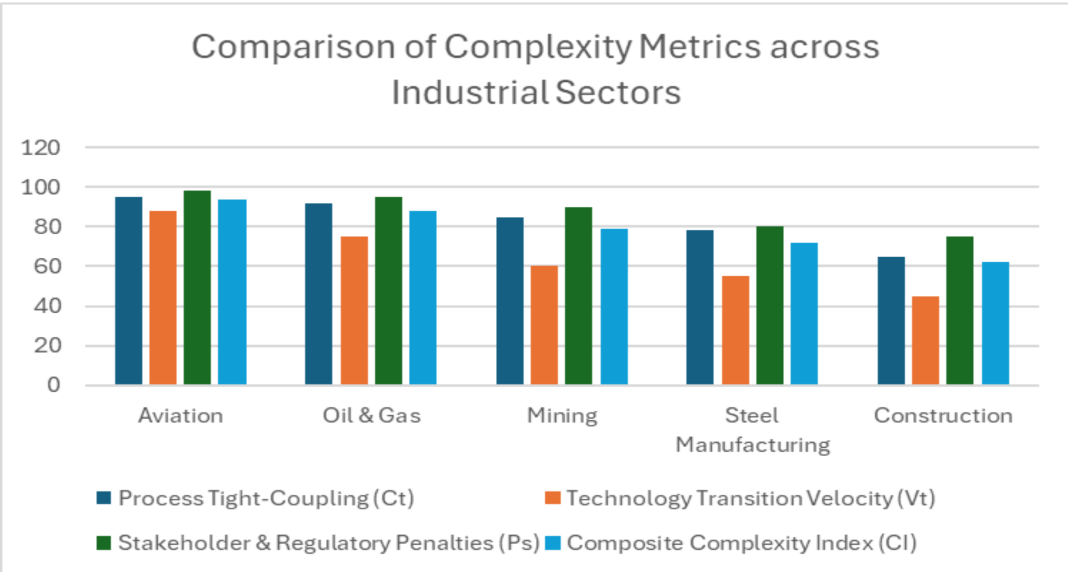

Figure 3. Complexity metrics across the industrial sector

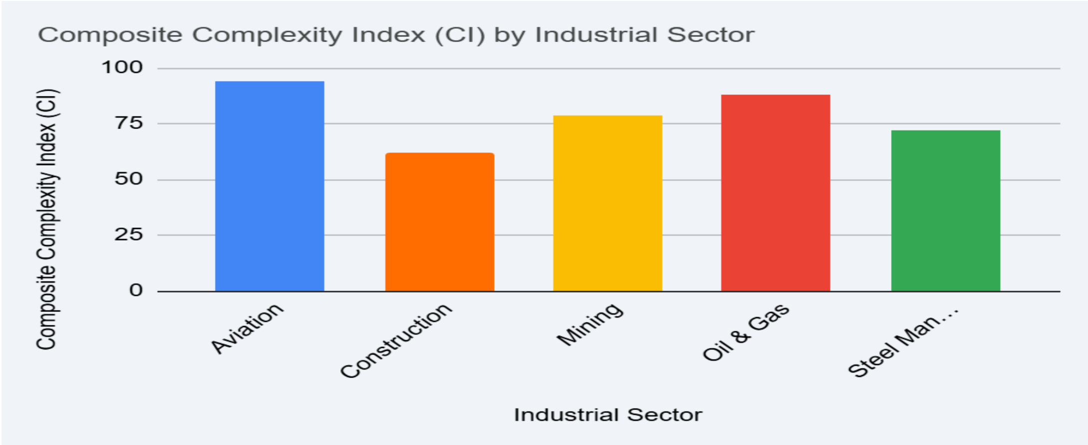

Figure 4. Composite complexity index by industrial sector

Table 1. Summary of Complexity Metrics

Industrial Sector	Process Tight-Coupling (Ct)	Technology Transition Velocity (Vt)	Stakeholder & Regulatory Penalties (Ps)	Composite Complexity Index (CI)
Aviation	95	88	98	93.8
Oil & Gas	92	75	95	87.8
Mining	85	60	90	79
Steel Manufacturing	78	55	80	71.7
Construction	65	45	75	62

The data shows there is a clear hierarchical trend, from high-precision, high-risk sectors such as aviation to more traditional sectors like construction, where all metrics of complexity then decrease at the same rate. Sectors such as aviation and oil & gas exhibit severe tight coupling (*Ct* 92), as demonstrated by the empirical breakdown in Table 1 Summary of Complexity Metrics and Figures 2,3,4 - multi-bar charts of micro-environmental complexity profiles by sector.

Within these settings, a single, unmistakable process disruption propagates rapidly throughout the system. The swift emergence of Industry 4.0 automation heightens the technology transition velocity (Vt), highlighting a critical flaw: traditional safety management systems that rely on checklists cannot keep up with the rapidly changing socio-technical conditions. This demonstrates the importance of the proposed Critical Risk Management (CRM) model, which eliminates administrative filler to isolate non-negotiable critical control barriers.

Analysis of the data on industrial sector complexity shows some very clear patterns and trends across these five sectors: aviation, oil & gas, mining, steel manufacturing, and construction. Below is the main trends and patterns:

1. Aviation Leads in Overall Complexity.

The highest composite complexity index measured for any sector in the world is 93.8, which is equivalent to that of all other sectors. The industry's highly correlated and interdependent nature results in consistently high process coupling (95), technology transition speed (88), and regulatory pressure (98). Nevertheless, the construction industry is the most straightforward sector in this dataset, with a confidence interval *(CI)* of 62.0.

2. Strong Interdependence of Complexity Factors.

The three metrics are positively linked (over 0.93) to each other: process tight coupling (*Ct*), technology transition velocity (*Vt*) and Stakeholder & Regulatory Penalties (*Ps*).

- Industries' technological advancements and rapid growth result in processes that are more tightly coupled.
- Regulatory and stakeholder oversight are often closely linked with increased technical and process complexity.

3. Regulatory pressure is always present.

The rate of technological change (*Vt*) varies widely across sectors, with a significant decrease of almost 49% from aviation (88) to construction (45), but the level of regulatory and stakeholder penalties *(Ps)* is still quite high, remaining only 23% lower (from 98 to 75). It suggests that regulatory and stakeholder expectations are still the primary source of operational complexity in technology-related sectors where it is moving at a slower pace.

4. Technology transition velocity (*Vt*).

This is the least competitive measure in many fields, particularly mining and steel manufacturing. The evidence suggests that while these industries are subject to significant regulatory pressure and tight process coupling, technological transition is slower, possibly due to the high capital costs and long lifecycles of industrial assets.

5. Sector Ranking by Complexity.

Complexity levels in each sector are consistent.

1. Aviation (93.8)
2. Oil & Gas (87.8)
3. Mining (79.0)
4. Steel Manufacturing (71.7)
5. Construction (62.0)

4.2. Statistical validation and predictive power of CRM

A thorough quantitative analysis of the practical experience demonstrated a robust statistical basis for the five-phase CRM framework—specifically, that systematic field-level verification of critical controls directly determines overall safety resilience—ordinary least squares (OLS) linear regression analysis was conducted on empirical field data collected across N = 154 distinct operational sectors. Despite this, the critical control effectiveness constructs demonstrated significant consistency in their internal reliability, leading to a Cronbach's alpha $\alpha c = 0.88$.

Table 2: Ordinary Least Squares (OLS) Regression Analysis Summary

Parameter / Statistic	Value	Standard Error	t-Stat	p-value
Intercept *(β0)*	31.0589	5.9241	5.243	< 0.001
Critical Control Monitoring *(β1)*	0.3973	0.0629	6.315	2.83×10−9
Sample Size *(N)*	154	—	—	—
Correlation Coefficient *(r)*	0.4558	—	—	—
Coefficient of Determination *(R²)*	0.2078	—	—	—
Model F-Statistic (*df=1,152*)	39.8757	—	—	< 0.001

Discussion of Table 2 & Figure 5: The quantitative results summarised in Table 2 establish a rigorous empirical baseline for CRM implementation. The model yields a highly significant positive correlation between critical control monitoring (*Mc*) and positive safety performance metrics (*Ys*) ($r = 0.4558$, $p < 0.001$). Most notably, the coefficient of determination indicates that critical control monitoring Efficiency (*Mc*) alone explains 20.78% of the total variance in an enterprise's actual safety performance outcome ($R^2 = 0.2078$, $F = 39.88$, $p = 2.83\times 10-9$).

Systematic monitoring of fatal-risk controls was found to be associated with meaningful and repeatable improvements in safety performance through regression analysis. The outcomes demonstrate that companies are not required to handle numerous minor hazards with the same level of intensity. By focusing on monitoring a limited set of critical controls, the potential for preventing catastrophic system failures is significantly higher.

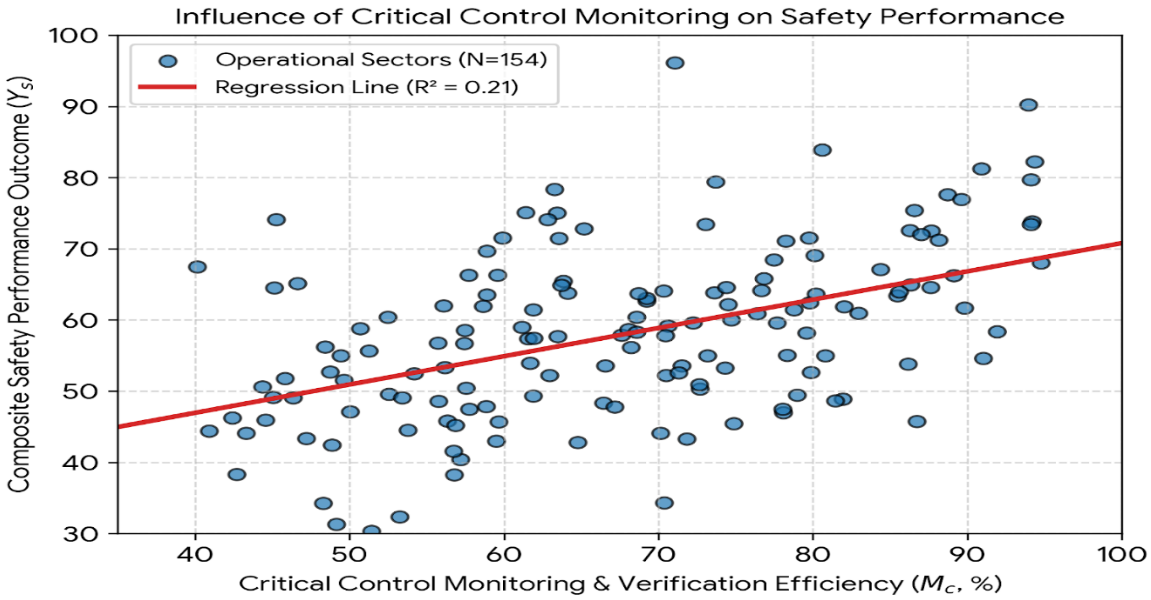

Figure 5. Influence of Critical Control Monitoring on Safety Performance

A scatter plot Diagram (Figure 5). (Influence of critical control monitoring on safety performance) illustrates this connection. Field verification compliance steadily increases along the horizontal axis, which tightens the safety performance envelope upward. A single process variable *(Mc)* can account for more than one-fifth of the total safety outcome variance in high-risk industrial settings where hundreds of operational variables change simultaneously. The statistical evidence supports the conclusion that implementing a strict verification infrastructure and providing frontline staff with unbiased binary Go/No-Go execution tactics results in immediate, quantifiable reductions in systemic risk.

4.3. Five-Phase CRM Implementation Framework (Addressing Objective 2)

Our approach involved the development of a five-phase CRM system that is structured in a cyclical, modular fashion to incorporate statistical data into sustainable industrial practices. It transforms corporate intent into highly localised and verifiable front-line actions.

4.3.1. Phase 1: Critical Risk Identification: Identifying Material Hazards.

Check out all corporate hazards for low frequency high consequence (LFHC), which are low-cost and fatal. Develop an inventory of potential materials in a specific area. This procedure eliminates the typical hazards of work (such as small slips, trips, etc.) and identifies those hazards that could lead to system failure, such as collapse, energy release, or exposure to toxins.

4.3.2. Phase 2: Bow-Tie Control Mapping: Preventive and Mitigative Barriers

Produce detailed Bow-Tie sketches for all identified material risks. Map out specific threats on the left, the most significant danger in the middle, and the consequences on the right.
Determine the limitations that are necessary to prevent an event or minimise the impact of the event, and where the failure of a critical control leads to the risk being materialised.

4.3.3. Phase 3: Verification Infrastructure: Hardware & Protocol Specification

Establish individual performance goals for all critical controls which shall specify: What is the purpose of the control as outlined in these standards? What reliability is required? How is it verified? Create simple, binary (Go/No-Go) verification checklists for frontline field supervisors and external assurance auditors.

4.3.4. The fourth phase of engagement and empowerment is focused on field execution with a focus on stop-work authority

Worksite field testing methods shall be employed. Check for necessary controls before high-risk activities are initiated by frontline operators. Offer complete, psychologically secure stop-work authority. In the event of a critical control verification failure, the task is stopped immediately until the control is fully functional again.

4.3.5. The fifth phase of Continuous Governance & Learning involves data integration and dynamic review

Integrate real-time field verification data into leadership dashboards. Track essential indicators (such as regulating non-compliance rates) to prevent incidents by identifying and fixing system weaknesses. Maintain a consistent risk profile to keep up with operational changes, technological advancements, and incident learning opportunities.

V. Study limitations

While it offers a systematic approach to Critical Risk Management (CRM) and an established statistical standard, there are a number of intrinsic disadvantages that should be considered when evaluating the outcomes:

1. Regional and Sector Sampling Bias: The regression model's validation with empirical data primarily benefited heavy industries like mining, steel, construction, oil and gas, and aviation (N = 154). The high coefficient of determination (R^2 = 0.2078) and quantitative weightings may vary in low-coupling or less asset-intensive industries such as digital technology, healthcare infrastructure, or light consumer manufacturing.
2. Cross-Sectional Data Limitations: A cross-sectional picture of the effectiveness and safety results of key control monitoring is given by statistical modeling results. Turnaround times, company reorganization, and external market forces all affect safety performance cycles. As a result, the static dataset is unable to accurately represent multiyear decay rates of crucial barriers or long-term macro trends.
3. Human-Centric Reporting: Cognitive compliance bias (such as "tick-and-flick" behaviors), varying supervision competency levels, and potential subjectivity all contribute to the seeming improvement of verification scores but not the real rise in barrier dependability.
4. Refusal to Remove Latent Unlisted Variables: According to the regression model, critical control verification accounts for 20.78% of the variance in good safety outcomes, whereas unmeasured factors account for only 79.22% of this variance.

The main equations of this study did not account for these missing components, which include localized company psychological safety, macroeconomic resource limits, and changeable supply chain asset quality

VI. Conclusions

Sustainable safety performance cannot be achieved by retrospectively reviewing lagging accident logs or overly complex administrative management files. Safety research must now concentrate on creating control structures that are more transparent and easily rechecked due to the growing operational coupling and technical complexity in industrial applications.

This study indicates that critical risk management has emerged as a key structural tenet for high-risk businesses. Organizations can develop dependable operational barriers that address material dangers by using a five-stage conceptual approach.

Twenty percent of the variance is explained by the safety gains that come from regular critical control monitoring, according to our statistical modeling. Reliable, long-term incident prevention depends on the daily maintenance of the few essential controls.

VII. Future Research Directions and Gaps

Even though a five-phase method offers a conceptual foundation for preventing tragic incidents, some industrial applications need for more scholarly investigation. The present difficulties consist of:

- The socio-technical and behavioral aspects that affect compliance are still largely unknown at the front lines. The degree to which organizational culture, productivity pressures, and psychological safety impact an employee's ability to exercise stop-work power should be further investigated.
- The majority of CRM infrastructures, which depend on human-performed manual validation checks, require predictive AI and control automation. This is a significant field of study that might change the framework from a manual checkpoint system to a real-time automated safety loop.

VIII. Acknowledgement

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