

Exploring Mandated Critical Control Management for Fatality Prevention in African Mines: Evidence from a Zambian Case Study

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Abstract

Critical Control Management (CCM) has become a central approach for preventing fatal and catastrophic events in mining by focusing attention on the few controls that matter most. However, in many African jurisdictions CCM remains largely voluntary, applied unevenly and not always embedded in regulatory or organisational governance. This paper uses a Zambian case study to explore how a more mandated CCM approach could strengthen fatality prevention in African mines while remaining sensitive to local regulatory capacity and operational realities. The analysis draws on a mixed methods study in the Zambian mining sector, combining a quantitative survey of mine employees (target N = 192, realised n = 154; 80 per cent response) with 16 key informant interviews and field observations. The study found a statistically significant, moderate positive correlation between monitoring and effectiveness of fatal risk controls and safety outcomes ($r = 0.45$, $p < 0.001$). Simple regression showed that control monitoring explained 20 per cent of the variance in safety outcomes ($R^2 = 0.20$, $F = 30.5$, $p < 0.001$), while reliability analysis indicated strong internal consistency for key constructs such as critical controls effectiveness (Cronbach's alpha = 0.88). Together, these findings suggest that more systematic management of fatal risk controls is associated with meaningful improvements in safety performance. Building on this evidence, the paper proposes a four layer CCM model for African mines that can be adopted or adapted by regulators and operators. The layers cover: (i) integrating CCM expectations into regulatory guidance and licence conditions; (ii) site specific bowtie linked CCM cycles; (iii) leadership accountability, worker protection and capability; and (iv) transparent monitoring, learning and benchmarking. Rather than prescribing a uniform solution, the framework is presented as a set of recommendations informed by the Zambian case study, showing how voluntary guidance can be progressively translated into more enforceable, context appropriate standards for safer, more resilient mining operations across the continent.

1. Introduction

Mining remains essential to national development and global supply chains, but it also exposes workers and communities to high-consequence risks that can lead to fatalities, occupational disease and major operational loss. The persistence of these outcomes demonstrates that the existence of safety procedures alone does not guarantee effective prevention. In high-risk industries such as mining, the decisive factor is often whether the controls that matter most are consistently defined, implemented, monitored and acted upon.

Critical Control Management has emerged as an important response to this problem. It is widely used to prioritise the controls that prevent material unwanted events or reduce their consequences, especially where the potential for fatal harm is high. International guidance has strengthened the conceptual basis for CCM, yet many mining organisations still struggle to convert the language of critical controls into a lived management system. In practice, mines may maintain risk registers, audits and standard operating procedures, while critical controls remain unevenly verified, weakly owned or poorly escalated when degraded.

This challenge is particularly significant in African mining contexts. Regulatory systems are often evolving, capacity is uneven, and mines may operate under contractor-heavy and resource-constrained conditions. These realities create a need for a mandated CCM approach that does not rely solely on voluntary adoption. This paper therefore argues that fatality prevention in African mines can be improved by mandating CCM through a layered framework that combines regulatory expectation, operational implementation, leadership accountability and transparent performance review.

The argument is supported by the findings of a thesis-based study on the role of critical controls in enhancing risk management practices in the mining industry in Zambia. The study provides empirical evidence that stronger monitoring and application of controls targeted at fatal risk are associated with better safety outcomes, even where a formal CCM system is not yet fully established. These findings offer a strong basis for extending the discussion from organisational practice to sector-wide mandate.

2 Literature and Context

2.1 CCM and fatality prevention

Critical Control Management is founded on the principle that not all controls require the same level of attention. In mining, some controls play a decisive role in preventing high-consequence events such as ground falls, vehicle interactions, fires, explosions, toxic exposures and energy releases. If those controls fail, the pathway to catastrophic harm can open rapidly. For this reason, CCM aims to identify the few controls that are critical, define the required standard for their performance, and verify whether they are present and effective in the field.

The literature reviewed in the thesis showed that jurisdictions with stronger implementation of critical controls have achieved meaningful improvements in safety performance. The review noted that Australian and Canadian experience has linked CCM implementation with substantial reductions in high-potential incidents and stronger control verification routines. At the same time, the literature also showed that the value of CCM depends heavily on enforcement quality, management commitment, worker engagement and supervisory practice. This reinforces the view that CCM is not merely a technical method, but a governance and behavioural system.

2.2 African and Zambian implementation realities

The Zambian context illustrates the broader challenge facing African mining systems. The thesis found that the implementation of CCM in Zambia remains uneven and constrained by inconsistent enforcement, irregular monitoring, workforce capability gaps, administrative system weaknesses and funding limitations. Mines often operate with controls intended to address major hazards, but these controls are not always formally identified and governed as critical controls under a structured framework.

The literature review also showed that cultural and behavioural factors strongly affect control reliability. A prior mixed-methods study cited in the thesis found that only 12 per cent of near misses were formally reported, while 43 per cent of respondents attributed under-reporting to fear of reprisal, 37 per cent to perceived futility and 20 per cent to lack of reporting mechanisms. The same review found that 67 per cent of workers viewed safety as primarily management's responsibility, and that safety compliance metrics dropped by 42 per cent during periods of intensified production targets. These findings illustrate how safety culture and production pressure can undermine critical control integrity if not actively managed.

2.3 Research gap addressed by the thesis

The thesis identified several important gaps in current CCM research relevant to African mines. These included the absence of localised frameworks, over-reliance on cross-sectional designs, insufficient attention to human factors, limited economic analysis of CCM, and minimal study of low-cost technologies suitable for resource-limited settings. These gaps justified a context-specific study capable of linking CCM concepts to operational realities in Zambia and, by extension, to wider African mining conditions.

3 Research Basis for the Paper

This paper draws on the empirical core of the Zambian study. The study adopted a mixed-methods design combining quantitative and qualitative approaches. The quantitative component used a structured questionnaire distributed to mine employees across selected sites, with a target sample of 192 and a realised sample of 154, giving an 80 per cent response rate. The qualitative component used semi-structured interviews and observation checklists with 16 key informants from a target of 20.

The questionnaire measured perceptions of risk identification, control implementation, training, management commitment, safety culture, regulatory support and safety outcomes using a five-point Likert scale. Composite indices were later developed to support descriptive, reliability and inferential analysis. Reliability was tested using Cronbach's alpha, and inferential analysis included Pearson correlation, simple linear regression and independent-samples t-tests. The analysis therefore provides both statistical evidence and contextual interpretation relevant to how critical controls function in practice.

A notable finding from the thesis is that many mines had controls aimed at mitigating fatal risk even where those controls were not formally designated within a mature CCM framework. This insight is important for African mines because it means the proposed framework does not start from a blank slate. Instead, it seeks to formalise, strengthen and standardise control disciplines that may already exist in fragmented or informal form.

4 Descriptive Findings from the Thesis

4.1 Training competence and safety culture

The thesis found that training competence received the highest average score of the major safety domains, with a mean of 4.4 on the five-point scale. About 90 per cent of respondents agreed or strongly agreed that they had received sufficient training on hazard recognition for their role, and similarly large majorities reported that training helped them apply control procedures with confidence. These results suggest that the sampled mines had made strong investments in training, providing a useful base for future CCM maturity.

Safety culture also scored relatively highly, with a mean of 3.9. Respondents broadly agreed that safety was a core value in their organisation, with a mean of 4.2, and that safety concerns were openly discussed and addressed, with a mean of 4.1. Around 85 per cent agreed that management showed a strong commitment to safety, while approximately 88 per cent reported active participation in safety meetings and programmes. At the same time, the thesis found that workers did not always feel entirely safe to speak up. The statement 'Workers feel comfortable reporting hazards without fear of reprisal' had a lower mean of 3.6, and nearly 20 per cent disagreed to some extent, indicating that psychological safety remained incomplete.

4.2 Regulatory environment and operational challenges

The regulatory environment support construct had a composite mean of around 3.1, showing more mixed perceptions than training or safety culture. Although respondents generally agreed that safety inspections occurred regularly and thoroughly, only about 20 per cent agreed that there were enough qualified safety inspectors to monitor mining sites effectively. More than half explicitly disagreed with that statement. Funding for safety audits was rated even lower, with a mean of 2.5, while only about 30 per cent agreed that regulatory bodies had the necessary equipment to conduct effective audits. These findings indicate that internal company systems were often viewed more positively than external regulatory capacity.

Operational challenges also remained significant. Roughly 35 per cent of respondents agreed that production targets sometimes took precedence over safety compliance, while around one-third agreed that there was pressure to complete tasks quickly in ways that could compromise safety. About 30 per cent believed budget limitations hindered safety measures, and 40 per cent agreed that staffing shortages reduced the effectiveness of safety oversight. These results suggest that even where positive safety systems exist, resource and production pressures can undermine control reliability.

4.3 Controls effectiveness and safety outcomes

The controls effectiveness and outcomes composite averaged about 3.94, indicating generally positive perceptions of the current controls used to manage fatal risks. Approximately 75 per cent of respondents agreed that the implementation of existing controls had reduced accidents at their sites, with a mean of 4.1 and a standard deviation of 0.9. Respondents also agreed that safety metrics had improved due to current control management, with a mean of 3.8, and that compliance with risk controls was regularly monitored and maintained, with a mean of 3.9.

Although the sampled mines did not uniformly operate under a formal CCM framework, these findings suggest that many controls were already serving a fatal-risk mitigation function. The thesis further noted that only 38 per cent of operations in the sample reported maintaining an up-to-date, comprehensive critical control register and conducting documented independent verification or audits beyond standard compliance checks. This confirms that positive outcomes were being achieved in part, but through uneven and incomplete systems.

4.4 Reliability and Statistical Evidence

Reliability analysis showed that the survey constructs were measured with acceptable to strong internal consistency. The safety culture and reporting scale, which contained eight items, achieved a Cronbach's alpha of 0.82. The training competence scale, with five items, achieved 0.74. The critical controls effectiveness scale, also with five items, achieved 0.88, which indicates very strong internal consistency. The regulatory environment support scale achieved 0.80, while the operational challenges construct was slightly lower at 0.69 but still close to the accepted 0.70 benchmark for exploratory work.

The strongest inferential finding was the moderate positive correlation between the monitoring and effectiveness of fatal risk controls and safety outcomes. The thesis reported a Pearson correlation coefficient of $r=0.45$ with $p<0.001$, indicating a meaningful and statistically significant linear association. In practical terms, sites where respondents perceived controls to be well monitored and effectively applied also reported better safety outcomes, including fewer accidents, stronger injury and fatality control, and improved occupational health metrics.

Simple linear regression reinforced this finding. The regression model was statistically significant with $F(1,152)=30.5$, $p<0.001$. The model explained about 20 per cent of the variance in safety outcomes, with $R^2=0.20$. The unstandardised coefficient was $B=0.50$, with a standard error of 0.09, meaning that for every one-point increase in the control effectiveness score on the five-point scale, the safety outcomes score increased by about 0.50 points. This provides empirical support for the argument that stronger control monitoring and application are associated with meaningful improvements in site safety performance.

Table 1. Reliability of Survey Constructs*

Construct theme	Number of items	Cronbach's alpha
Safety culture and reporting	8	0.82
Training and competence	5	0.74
Critical controls effectiveness	5	0.88
Regulatory environment support	Not stated in excerpt	0.80
Operational challenges	Not stated in excerpt	0.69

*Table 1 Summarizes the Cronbach's Alpha Coefficients for the Major Constructs.

Table 2. summary of key Quantitative Findings

Measure	Result	Interpretation
Survey target sample	192	Planned survey respondents
Survey realised sample	154	80 per cent response rate
Key informant target	20	Planned qualitative participants
Key informant realised	16	Completed interviews and observations
Correlation between fatal risk control monitoring and safety outcomes	$r=0.45$, $p<0.001$	Moderate positive relationship
Regression model fit	$R^2=0.20$, $F=30.5$, $p<0.001$	Fatal risk control monitoring predicts 20 per cent of variance in safety outcomes
Unstandardised regression coefficient	$B=0.50$, $SE = 0.09$	One-point increase in control score predicts 0.50 increase in safety outcome score
Operations with comprehensive register and independent verification	38 per cent	Formal CCM practice remains limited

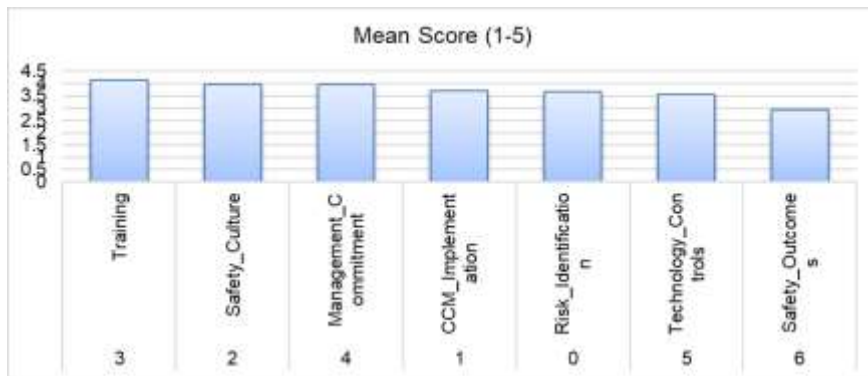


Figure 1 - Mean Likert Scores Across Major Safety Domains*

*Data based on survey of 154 respondents (n=154, 80 per cent response rate) from multiple Zambian mining operations; scores are on a five point scale where 1 indicates strong disagreement and 5 indicates strong agreement.

4.5 A Mandated Ccm Framework for African Mines

The thesis proposed a four-layer framework in response to the uneven application of critical controls in Zambia. This paper extends that model to African mines more broadly while preserving its contextual logic. The framework is designed to convert fragmented fatal-risk control practices into a consistent and enforceable system without ignoring differences in mine size, commodity, ownership structure or national regulatory capacity.

Layer 1: regulatory embedding and minimum standards

The first layer requires CCM to be embedded in mining licences, regulations, guidance notes or nationally recognised standards. The objective is to move critical controls from voluntary good practice into minimum safety expectation. Regulators should define requirements for identifying material unwanted events, maintaining site-specific critical control registers, assigning named control owners, and conducting verification at defined intervals. Inspectorates should be trained to audit control performance rather than only paper compliance.

This layer responds directly to the thesis finding that respondents doubted the capacity and resourcing of external oversight. If national systems are to support fatality prevention effectively, regulators must be able to recognise whether sites are applying CCM in substance rather than merely in language. A phased compliance model may be necessary in lower-capacity jurisdictions so that mines can build maturity while still meeting minimum requirements.

Layer 2: site-specific bowtie-linked CCM cycles

The second layer requires each mine to implement site-specific CCM processes linked to its principal hazards and material unwanted events. Bowtie analysis should be used to identify the threats, consequences, preventive controls and mitigating controls associated with each major hazard. From this analysis, sites should define which controls are critical and specify the required performance standard for each one.

The thesis found that leading mines were more likely to use advanced approaches such as bowtie analysis and digital monitoring, while the majority relied on simple risk assessments and compliance checklists. A mandated framework should retain flexibility in verification method, but it should require every site to identify and verify critical controls systematically rather than relying on generic or reactive practices.

Layer 3: organisational capability, leadership and worker protection

The third layer focuses on organisational capability. The thesis demonstrated that training and management commitment were among the strongest positive domains in the surveyed mines, with means of 4.4 and 3.9 respectively. This suggests that African mines may already have a base of training and leadership attention on which more mature CCM can be built. However, the same study also identified gaps in psychological safety, resource availability and production pressure.

A mandated CCM system should therefore include leadership key performance indicators linked to critical control integrity, routine refresher training, pre-task competence checks for high-risk work, and worker participation in identifying and reviewing controls. It should also protect workers who report control failures or stop work where critical controls are ineffective. These protections are particularly important in contexts where under-reporting and fear of reprisal remain barriers.

Layer 4: transparent monitoring, benchmarking and learning

The fourth layer is transparent performance monitoring and learning. Mines should report not only injury statistics but also leading indicators of control integrity, such as verification completion rates, percentage of controls found degraded, time to close high-risk actions, audit findings and trends in repeated deviations. These data should be reviewed internally and, where feasible, benchmarked across sites and jurisdictions.

The thesis highlighted that only 38 per cent of sampled operations had a comprehensive critical control register and documented independent verification. Transparent benchmarking would help reveal such gaps and encourage improvement. It would also support regulators and industry bodies in identifying where sector-wide support, training or intervention is needed.

Proposed CCM Framework: Four-Layer Model

Fig 2 - Proposed Ccm Framework

4.6 Discussion

The evidence from the thesis provides a strong rationale for moving beyond voluntary CCM guidance in African mines. The data show that better control monitoring and application are associated with better safety outcomes, even in a setting where formal CCM is only partially developed. This is an important finding because it demonstrates that the benefits of CCM are not limited to highly mature systems in well-resourced jurisdictions. They are also visible in African settings where fatal-risk controls are present but inconsistently governed.

The implication is that policy and industry should focus not only on introducing CCM terminology, but on mandating the organisational conditions that make CCM effective. These include a clear regulatory expectation, named accountability, verification discipline, leadership follow-through, worker engagement and transparent review of control performance. Without these features, mines may continue to achieve isolated improvements without building reliable fatality prevention systems.

The thesis also reinforces the importance of adapting CCM to local conditions. Resource constraints, staffing shortages, production pressure, limited inspectorate capacity and language diversity all affect implementation feasibility. A mandated system must therefore define safety minimums while allowing mines to tailor their verification tools, training methods and monitoring technology to practical realities. This balance between enforceability and adaptability is central to the framework proposed in this paper.

5 Conclusions

This paper has argued that African mines need a mandated Critical Control Management framework if fatality prevention is to improve consistently across diverse operating environments. The empirical findings from the Zambian mining study show that stronger monitoring and application of fatal risk controls are associated with better safety outcomes, with a statistically significant moderate correlation of $r=0.45$ and regression evidence showing that control monitoring explains 20 per cent of the variance in safety outcomes.

The thesis also shows that many mines already use controls aimed at fatal-risk mitigation, but often without a formal CCM structure. This creates an opportunity for improvement through standardisation and mandate rather than wholesale reinvention. The proposed four-layer model therefore embeds CCM in regulation, links it to site-specific bowtie analysis, strengthens organisational capability and worker protection, and requires transparent monitoring and benchmarking.

Mandating CCM in this way does not remove the need for local adaptation. Instead, it establishes safety minimums while supporting phased maturity and contextual flexibility. For African mines seeking to reduce fatalities and improve resilience, a mandated CCM model offers a practical bridge between global best practice and local operational reality.

Declaration of Competing Interests

The authors declare that they do not have any known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethical considerations

The article followed all ethical standards appropriate for this kind of research.

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