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A critical control approach to preventing fatalities in construction

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A Critical Control Approach to Preventing Fatalities in Construction

This thesis is presented for the degree of

Doctor of Philosophy

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ABSTRACT

Workplace fatalities continue to occur within the Australian construction industry at an unacceptably high rate. Most fatalities can be attributed to worker exposure to fatal energies while conducting high risk tasks in a dynamic work environment. Construction fatalities are usually single fatality events related to occupational safety hazards which are either not recognised by workers or not consistently controlled through existing safety practices. By comparison other resources industries have lower fatality rates because of their focus on identifying the controls and verification activities needed to address Major Accident Events (MAEs) and Principal Hazards in a manner that prevents fatalities.

The primary aim of this thesis research was to investigate and validate an alternative fatal risk management strategy to reduce construction single fatal events. The research developed a novel Critical Control Risk Management (CCRM) program which addressed the dynamic and variable factors which impact construction projects and compared CCRM safety performance together with safety climate data to identify organisational, leadership and supervisory attributes which impacted safety outcomes.

The research involved 5 studies to identify an alternative construction risk control strategy (1st study), validate the reliability and effectiveness of CCs (2nd study), develop a novel CCRM methodology) to address the dynamic construction environment (3rd study), investigate cultural and leadership effects on construction risk management practices (4th study) and finally (5th study) explore effect of CCRM on construction project safety and safety climate performance.

The design and validation of a CCRM program was developed to address the dynamic construction project life cycle, factors affecting critical control reliability together with behaviour elements affecting project critical risk and safety performance. The process of defining CCs for each MAE hazard, together with the specificity of CCs, reduced the overall number and complexity of controls front line leaders needed to focus their attention on. The analysis identified multiple MAE incidents were due to an erosion of control integrity or changes in barrier functionality tolerated by the work team and supervision. CCRM directly improved construction safety performance by increasing the frequency of hazard reporting by 8% ($p=0.05$) and in safety mature organisations it reduced high potential incidents by 80% ($p=0.005$). CCRM applied on a construction project consistently improves hazard reporting frequency through CC verification and assurance processes or indirectly from improved critical risk awareness and competency.

The studies expanded CCRM as a methodology to manage construction projects by applying dynamic risk profiling to support CCRM, but also quantified CC reliability for major hazards and determined factors affecting CC reliability. The longitudinal study of CCRM established the inter-relatedness of leading risk management activities, safety climate factors, risk maturity of organisations and lagging measures of incident performance. The studies highlighted the benefits of CCRM are optimised when senior leaders fully support project management and workers in the effective implementation of CCs. Construction organisations would benefit from a deeper understanding of how to improve CC reliability, the barriers which prevent ‘stop - work’ decisions being supported and factors which impact critical risk maturity within the organisation and across project stakeholder organisations.

Submitted in fulfilment of the requirements of the degree of Doctor of Philosophy.

Date of submission: 12 March 2023

DECLARATION

I certify that this thesis does not, to the best of my knowledge and belief:

i. Incorporate without acknowledgement any material previously submitted for a degree or diploma in any institution of higher education.
ii. Contain any material previously published or written by another person except where due reference is made in the text of this thesis; or
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Roberta Selleck

Date: 12 March 2023

STATEMENT OF CONTRIBUTION OF OTHERS

Paper 1 – Preventing fatalities in the construction industry – learnings from other industry critical risk management strategies.

My contribution to this paper included the identification of the research question, development of the literature search criteria, conducting the preliminary literature search, article review and the synthesis of the literature. All these activities were undertaken under the standard PhD supervision of Dr Marcus Cattani. I developed the first draft of this paper and incorporated comments raised by the supervisory panel (Dr Marcus Cattani, Prof. Jacques Oosthuizen) in all subsequent drafts until the final one.

Paper 2 – Proposal for and validation of novel risk-based process to reduce the risk of construction site fatalities (Major Accident Prevention (MAP) program).

My contribution to this paper included the identification of the research question, development of the methodology, sourcing the research panel, conducting infield action research, consolidation of data and conducting the statistical analysis. All these activities were undertaken under the standard PhD supervision of Dr Marcus Cattani with technical risk input from Dr Maureen Hassall. I developed the first draft of this paper and incorporated comments raised by the supervisory panel (Dr Marcus Cattani, Dr Maureen Hassall) in all subsequent drafts until the final one.

Paper 3 – Determining the Reliability of Critical Controls in Construction Projects.

My contribution to this paper included the identification of the research question, methodology (in consultation with Dr Maureen Hassall), sourcing the research panel, coordinating the research input, consolidation of data and conducting the statistical analysis. All these activities were undertaken under the standard PhD supervision of Dr Marcus Cattani with technical risk input from Dr Maureen Hassall. I developed the first draft of this paper and incorporated comments raised by the supervisory panel (Dr Marcus Cattani, Dr Maureen Hassall) in all subsequent drafts until the final one.

Paper 4 – How did COVID-19 pandemic impact safety on a Construction Project? A case study comparing pre and post COVID-19 influence on safety at an Australian construction site.

My contribution to this paper included the identification of the research question, development of the methodology, conducting the surveys, consolidation of data and conducting the statistical analysis. All these activities were undertaken under the standard PhD supervision of Dr Marcus Cattani. I developed the first draft of this paper and incorporated comments raised by the supervisory panel (Dr Marcus Cattani, Dr Maureen Hassall) in all subsequent *drafts until the final one.*

Paper 5 – Critical Control Risk Management (CCRM) – Does it impact construction safety performance.

My contribution to this paper included identification of the research question, development of the methodology, conducting the surveys, consolidation of data and statistical analysis. All these activities were undertaken under the standard PhD supervision of Dr Marcus Cattani. I developed the first draft of this paper and incorporated comments raised by the supervisory panel (Dr Marcus Cattani, Dr Maureen Hassall) in all subsequent drafts until the final one.

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I also want to acknowledge the construction companies who were generous in providing access to projects and resources over a five-year period to conduct the various studies. The companies elected not to be specifically identified here, but each has made significant contribution and in particularly provided the experts and data required. The acknowledgement seems under-stated; however, each company has learned through the research and each organisation has taken the knowledge to improve their organisations safety risk management.

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1. Selleck, R., and Cattani, M., (2019). *Preventing Fatalities in the Construction Industry - A Review of Critical Risk Management Strategies*. Journal of Health, Safety and Environment, 2019. 35(3): p. 193-211. https://ro.ecu.edu.au/ecuworkspost2013/7176/
2. Selleck R. J., Hassall M., Cattani M. (2023) Proposal for and validation of novel risk-based process to reduce the risk of construction site fatalities (Major Accident Prevention (MAP) program). *Safety Science* **158**, 105986. https://doi.org/10.1016/j.ssci.2022.105986
3. Selleck R. J., Hassall M., Cattani M. (2022) Determining the Reliability of Critical Controls in Construction Projects. *Safety* **2022**, 8, 64. https://doi.org/10.3390/safety8030064
4. Selleck R. J., Cattani M., Hassall M. (2022). How did COVID-19 pandemic impact safety on a Construction Project? A case study comparing pre and post COVID-19 influence on safety at an Australian construction site. *Safety* **2022**, 8(4), 77. https://doi.org/10.3390/safety8040077
5. Selleck R.J., Cattani M., Hassall M. (2023) Critical Control Risk Management (CCRM) – Does it impact construction safety performance? *Submitted.*

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DEFINITIONS AND ABBREVIATIONS

Term	Definition
Activities	Work scopes undertaken during construction projects
Consequence	Unplanned outcomes from escalation of event (post energy release) – specifically single or multiple fatality or disabling injury
Controls	Human action, system or object which prevents unplanned event or mitigates escalation of consequences
Critical Control	(as per ICMM (International Council on Mining and Metals (ICMM), 2015) definition) Is the control a human act, object, or system? and Does it directly prevent the release of hazardous energy or mitigate the consequences? or Is the control performance, specifiable, observable, measurable and auditable?
Major Accident Event (MAE)	The release of energy through an unplanned event which has the potential to result in a single or multiple fatality or disabling injury from *foreseeable events with known controls*.
Major Accident Event Hazard (Threat)	The mechanism by which the hazardous energy is released causing an MAE. (Importantly, a threat is not a failed control). e.g., Platform failure
Major Accident Event Category	Grouping of common MAE Scenarios – e.g., Working at Height

THESIS OVERVIEW

This thesis is presented in seven chapters that combine to make a coherent body of research. The structure of the thesis, illustrating how the various studies come together as coherent body of research is shown in Figure 1.

Chapter 1: Introduction

The chapter is an introduction as it describes the inadequacy of the current construction risk management programs to prevent recurring fatalities where the controls are known and positions the research in the consideration of alternative risk management strategies. The chapter discusses the theoretical framework supporting the research, the research questions investigated in chapters three to six, and the research methodology underpinning each of the published studies.

Chapter 2: Literature Review

Chapter 2 presents the literature review findings which outlines alternative risk management strategies including the oil and gas 'safety case' and the Critical Control Risk Management (CCRM) strategies which are considered in the context of the dynamic construction organisation and work environment. The literature review evaluates and critiques the existing construction risk management practices, then compares attributes of both the safety case and CCRM strategies to determine the 'best fit' to address current construction fatal risk limitations. The review also highlighted factors which need to be considered when developing a construction specific fatal risk management strategy. The review achieved the following objective one of the research projects:

Research Objective: Evaluate current risk practices to identify an alternative risk management strategy to prevent construction fatalities (Part I – Literature Review).

The findings from this review helped inform subsequent research activities described in Chapters 3 to 6. The literature review was peer reviewed and published in the *Journal of Health, Safety and Environment*.

Chapter 3: Developing the CCRM methodology for Construction Projects.

Chapter 3 describes the development through action research of a construction specific Major Accident Prevention (MAP) program aligned to CCRM strategy. The research included validation of the MAP program (pilot program) on a construction project over a twelve-month period. The findings helped answer the following research question:

Research Question 1: Can a CCRM strategy, when applied to known fatality risks, reduce the likelihood and severity of potentially fatal events in the construction industry?

The safety performance results during the pilot program confirmed the novel MAP processes were provided the adaptability required for Critical Control (CC) management on a construction project. Analysis of the safety performance from the pilot program was inconclusive in respect to potential fatality events due to data limitations. The safety analysis was able to identify two key findings:

i. the MAP program does not operate in isolation to existing construction risk management processes, and

ii. organisational factors, including a shift in decision making authority, occurred and had a potential to affect the CC performance.

The insight gained from the study was used in the subsequent studies in developing a measure to assess CC performance (Chapter 4) and explore the organisational factors which influence CC performance (Chapter 5). The study into the development and validation of MAP was peer reviewed and published in the *Safety Science* journal.

Chapter 4: Evaluating Factors impacting CC Reliability

Chapter 4 discusses the analysis of CC performance factors through analysis of historical fatality and serious injury events across four construction companies over a ten-year period. The study validated the CCs developed from study 3 and identified factors affecting the reliability of CCs due to gaps in implementation or effectiveness of the CC. The study achieved the following objective of the research projects:

Research Objective: Develop a measure to assess the contribution of an alternative risk management strategy in managing field level fatality risks (Part 11 - Critical Control Reliability).

The study considered the following specific research questions:

i. Do known critical controls, as documented within existing high-risk activity performance standards and organizational specifications, address known construction safety risks?

ii. What performance factors that affect the reliability of critical controls to assist in the implementation of safety barrier programs within construction organizations?

The statistical analysis identified CC reliability was primarily impacted by organisational or leadership factors resulting in tolerance of sub-standard CC effectiveness and / or ineffective implementation. The findings were applied in subsequent studies (Chapter 5 and 6). The study into measuring of Critical Controls was peer reviewed and published in *Safety* journal.

Chapter 5: The relationship between leading and lagging indicators and Construction Safety Performance during a disruptive event.

Chapter 5 discusses the effects of a major disruption event (COVID-19) on a construction safety performance, including CCs, and the factors influencing workforce safety perceptions. The study used leading and lagging safety indicators combined with pre and post COVID-19 safety surveys to assess organisation and leadership factors. The findings helped to answer the following research question:

Research Question 2: What effect will implementation of a CCRM strategy in the construction industry have on existing risk management processes, safety performance and human factors which influence safety performance?

The findings from the study highlighted the role of effective leadership and safety communication improved safety performance including MAP. However, as an individual case study of a project experiencing an abnormal event (COVID-19) the results were limited and should not be extrapolated as representing typical construction projects. The study did achieve the research objective:

Research objective (Part V): Explore the relationship of CCRM on safety climate and organisational risk management through case studies, safety climate and risk maturity surveys to enable comparative analysis of the impact of CCM on different attributes of organisation risk (Part V).

The findings did establish a valid statistical method of comparing lead and lag safety indicators with safety climate surveys which was applied in the longitudinal MAP study (Chapter 6). The case study was peer reviewed and published in *Safety* journal.

Chapter 6 – Construction Safety Performance Impact of CCRM and relationship to leading / lagging indicators and safety climate.

Chapter 6 discusses the culmination of the previous studies which were incorporated into a longitudinal research study to evaluate MAP contribution in preventing construction fatality events. The study was conducted over 5 years comprised 31 international construction projects, from 9 countries and 2 companies. The findings support research question 2 and helped to answer research question 3:

Research Question 2: What effect will implementation of a CCRM strategy in the construction industry have on existing risk management processes, safety performance and human factors which influence safety performance?

Research Question 3: Are there inter-country cultural variations that impact the effectiveness of a construction CCRM strategy?

Findings confirmed MAP has direct and indirect effect on construction safety performance as measured through leading and lagging safety measures and safety climate perceptions. Variance occurred between companies and between projects within each company with management commitment, safety communication and competency key factors which influence MAP effectiveness and safety performance. The study has been submitted as a paper to *Safety Science* for peer review and publishing.

Chapter 7 - Conclusions

Chapter 7 discusses the research findings and assesses the extent to which they support the research questions and how they relate to existing research into construction fatality prevention strategies. The chapter critically reflects on the impact of the research, insights, and limitations of the research. The chapter brings together all the research findings and presents the conclusions with recommendations for construction organisations considering the use of a CCRM strategy like MAP and identifies areas for future research.

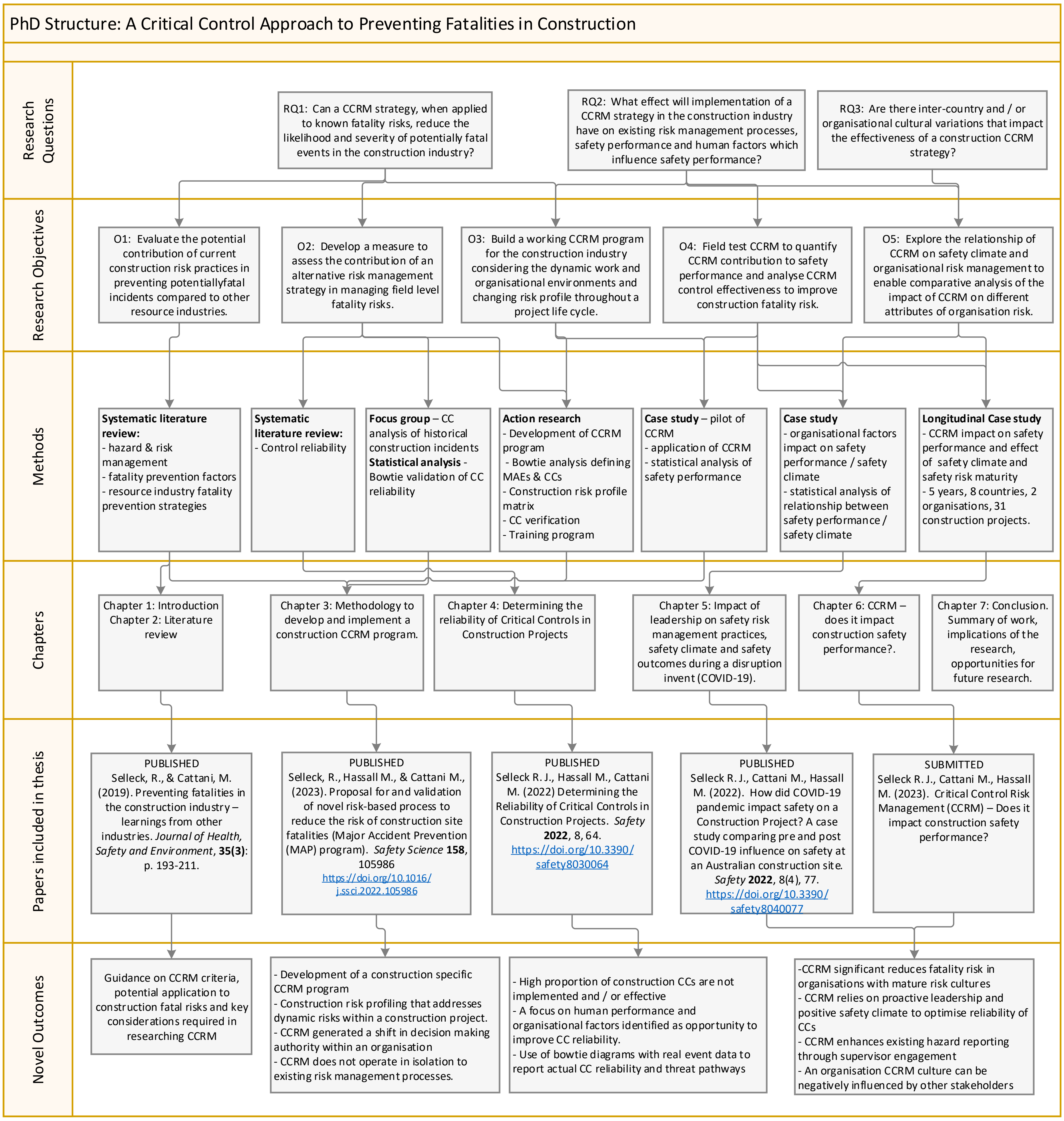

Figure 1: Structure of Thesis and Research

CHAPTER 1. INTRODUCTION

Workplace fatalities continue to occur within the construction industry arising from multiple work environments and scenarios, most fatalities can be attributed to worker exposure to fatal energies while conducting high risk tasks in a dynamic work environment. Construction fatalities are usually single fatality events related to occupational safety hazards which are either not recognised by workers or not consistently controlled through existing safety practices. By comparison the oil and gas industry have low fatality and serious injury rates following the introduction of 'safety case' legislation. The oil and gas safety case provides detailed analysis of technical process related safety risks (NOPSEMA, 2013) and the layers of controls required to prevent and mitigate the risks. The focus on engineering controls that are less reliant on human decision-making contribute to the lower frequency of serious incident events (NOPSEMA, 2019).

The principles of a safety case include the identification of workplace Major Accident Events (MAEs), risk analysis to identify controls which prevent fatality and significant events, critical controls, and the verification of critical controls to ensure they are implemented, and effective. The mining industry has developed Critical Control Risk Management (CCRM) to prevent catastrophic events including fatalities. Like the safety case, CCRM required identification of workplace Material Unwanted Events (MUEs) including fatalities, then differs from the safety case by shifting the focus onto risk treatment. The rigor of CCRM ensures critical controls have detailed specification of operating parameters, a regime of inspection and monitoring which includes indicators of potential CC failure modes (Hassall et al., 2015).

The construction industry safety risk management strategies (defence in depth through layers of cascading risk assessment processes (Carter & Smith, 2006; Hallowell & Gambates, 2009; Perlman et al., 2014b)) have been inadequate in preventing foreseeable MAEs with known controls. CCRM is proposed as an alternative risk management strategy for the construction industry. The research will develop and test a Critical Control Risk Management (CCRM) program for a series of high-risk construction tasks, through case studies. The research aims to provide construction site Supervisors with a series of tools to minimise distraction from non-essential controls, improve cognitive awareness of fatal hazards and provide transactional guidance on how to identify, monitor and apply the standards which prevent MAE's, including fatalities in the construction industry.

1.1 Research Problem

Construction fatalities which currently occur within the industry are caused by the same mechanisms as fatalities historically over the last thirty years (Lander et al., 2016). The construction industry ranks in the top three highest fatal incidence rates in Australia, Great Britain, and USA (Figures 2,3 & 4) with fatal incidence rates plateauing over the last five years.

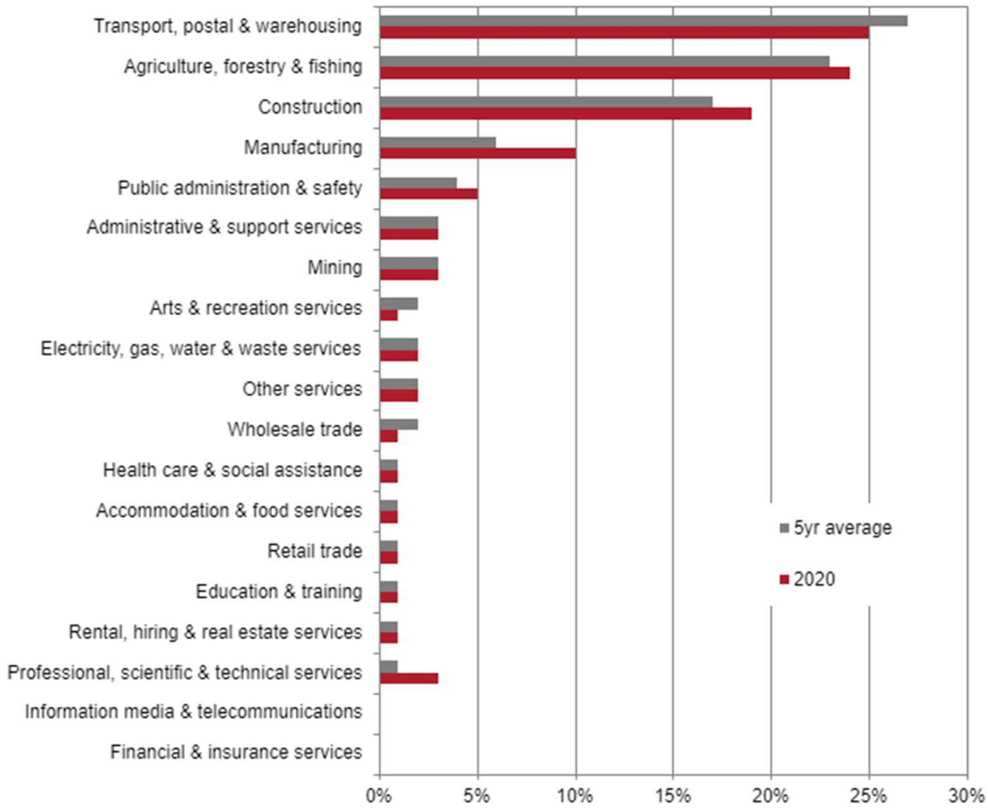

Figure 2: Australian Worker fatalities: proportion by industry of employer, 2020 and 5 year average (2016 - 2020).(Safe Work Australia, 2020)

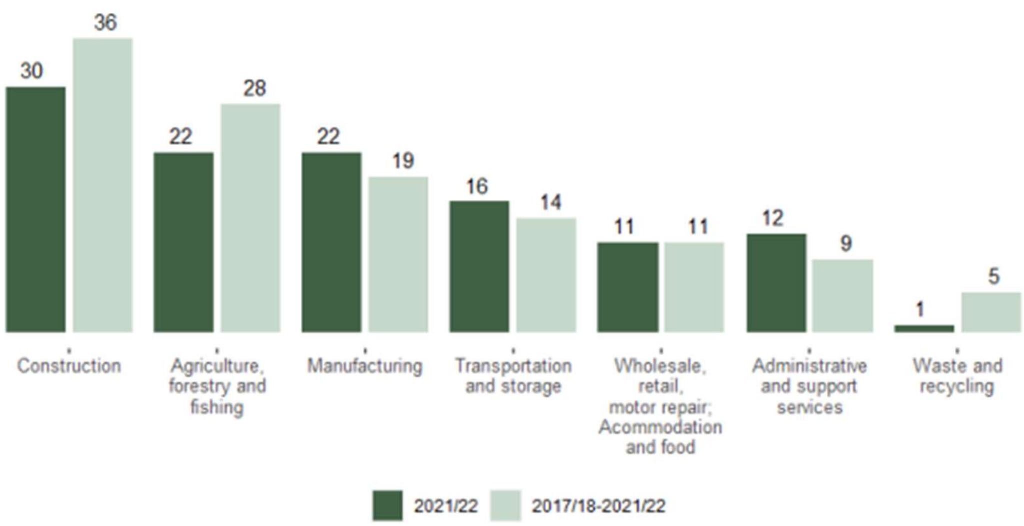

Figure 3: Great Britain – Number of fatal injuries by selected main industry group, 2021/22p and annual average for 2017/18 – 2021-22. (Health and Safety Executive (UK), 2022)

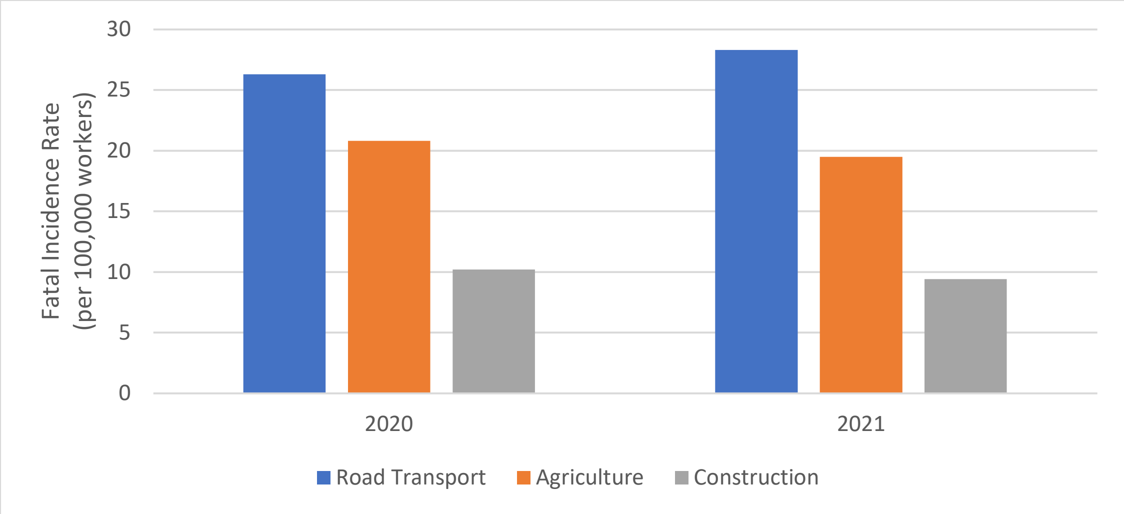

Figure 4: USA Fatal incidence rate by industry of employer - 2020 and 2021. (U.S. Bureau of Labor Statistics, 2022)

The fatalities arise due to the common high-risk tasks undertaken by workers where the risks are known, however the controls are not reliable (e.g., failure to hook up when working at height). The industry and statutory regulators have developed comprehensive safety standards and codes of practice on how to execute high risk tasks safety (Safe Work Australia, 2018b).

Table 1: Worker fatalities: Construction industry sub-divisions by mechanism of incident, 2016 to 2020 (combined) (Safe Work Australia, 2020).

Construction sub-division and mechanism	No. of fatalities	% of fatalities
Construction services	**89**	**58%**
Falls from a height	28	18%
Vehicle collision	16	10%
Contact with electricity	12	8%
Being hit by falling objects	12	8%
Being hit by moving objects	9	6%
Being trapped between stationary and moving objects	4	3%
Slide or cave-in	2	1%
Being trapped by moving machinery	2	1%
Other mechanisms	4	3%
Building construction	**46**	**30%**
Falls from a height	19	12%

Construction sub-division and mechanism	No. of fatalities	% of fatalities
Being hit by falling objects	10	6%
Vehicle collision	4	3%
Being hit by moving objects	4	3%
Contact with electricity	4	3%
Being trapped by moving machinery	2	1%
Other mechanisms	3	2%
Heavy & civil engineering construction	**19**	**12%**
Being hit by moving objects	9	6%
Vehicle collision	4	3%
Slide or cave-in	2	1%
Being hit by falling objects	2	1%
Other mechanisms	2	1%
Construction 5 year total	154	100%

Despite the knowledge available to project management, supervisors and workers, and the construction experience on site, fatality events continue to occur where controls have not been implemented or were not effective. Control reliability is an underlying assumption of the current construction industry 'defence in depth' risk management strategy, raising the question on how the construction industry can ensure controls are reliable every time they are challenged. The construction industry will benefit from an understanding of why controls are failing, what organisational and individual factors influence control reliability and how to detect control deviations.

The second part of fatality prevention within the construction industry problem is the dynamic construction work environment with constant organisational changes, and highly mobile workforce (Woolley et al., 2020). When considered together with significant changes in the safety risk profile throughout a project lifecycle, each construction project presents a unique safety climate requiring an alternative safety risk strategy to be highly adaptable to the changing risks.

1.2 Theoretical Framework

Research into accident prevention has identified multiple factors and safety controls required to prevent incidents from occurring (Bellamy, 2015; Mohammadi et al., 2018; Zhang et al., 2019). Construction specific studies have analysed incidents to identify causation factors (Betsis et al., 2019; Chi et al., 2015; Winge, et al., 2019), the mechanisms of energy release

(Chi et al., 2009) and factors influencing fatality prevention including leadership, risk management, and safety climate (Alarcón et al., 2016). However, construction fatalities from foreseeable events with known controls still occur across the industry. Risk management strategies currently practiced within the construction industry have not been effective in preventing MAEs or fatalities from causes with known controls.

The Critical Control Risk Management (CCRM) risk management strategy (International Council on Mining and Metals (ICMM), 2015), together with the Oil and gas industry, or operators of hazardous facilities safety case regime (NOPSEMA, 2013; Safe Work Australia, 2012) apply a similar methodology to prevent major accident events (MAEs) from occurring. The safety case regime focuses on process safety to identify MAEs with catastrophic (multiple fatalities) consequences, on a production facility with well-defined process and control systems, then defines the safety management system. Critical Control Risk Management (CCRM) also requires the identification of MAEs (defined as major unwanted events) and the threats which give rise to MAEs, however differs from the safety case by focussing on risk treatment and specifying critical controls. CCRM explicitly links the management of MAEs risks to critical controls and reliability of the critical controls through verification processes (International Council on Mining and Metals (ICMM), 2015).

The ICMM (International Council on Mining and Metals (ICMM), 2015) release of a comprehensive CCRM guideline expanded the International Standard Organisation Risk Management Guideline (ISO 31000) (International Organization for Standardization, 2018) by expanding the ‘risk treatment’ guidance, defining critical controls and the method to assess controls. Complimenting the ICMM guideline Hassall et. al., 2015 provided detailed concepts to improve control design, management, and contingency for control failure modes. The emergence of CCRM created a base to consider construction MAE hazards differently.

The structure of the safety case regime applied in the oil and gas and / or hazardous facilities was problematic for the construction industry as the safety case required detailed description of a facility as the basis for risk analysis (NOPSEMA, 2013). When undertaking a construction project, the facility is in the process of being built. Every day sees a change in the facility. The construction project risk profile is in constant change as work progresses, new work scopes commence or are completed. The workforce is in constant flux as new trades or specialists undertake specific work scopes. The complexity of construction management and control is equally dynamic with multiple stakeholders influencing decision making (Woolley et al., 2020). CCRM as a risk management strategy enables construction MAE hazards to be assessed independent of the facility being constructed. The question of how to account for the continuous changing work scopes, risk profile and workforce still needs to be resolved.

The oil and gas safety has predominantly been applied in operational contexts where MAEs are multiple fatalities derived from process safety events. The mining industry has applied CCRM to both process safety (multiple fatality) and personal safety (single fatality) MAE risks. Construction industry fatalities result from high-risk work activities (e.g., working at height (Betsis et al., 2019), lifting using cranes,) where the interaction between human factors and the activity give rise to personal safety related fatalities. CCRM has been implemented in the mining operations internationally with varying levels of success (Hassall, 2017), it remains uncertain if CCRM can be effectively applied to the construction environment.

Underpinning CCRM is the ability operators and / or workers being able to i) identify the MAE hazards, ii) interpret the situation being observed in the field, iii) be motivated to apply the controls and iv) be empowered to stop work if the controls are not implemented or sub-standard. These social constructs are inter-dependent and related to human knowledge, risk perception, personal motivation and organisational decision making and are subject to human error. In considering a CCRM strategy to prevent construction fatalities the social context which influences safety within the construction industry and / or on a project site needed to be considered in the research design.

1.3 Research Questions and Objectives

CCRM provides an alternative risk management strategy to the construction industry, however the industry has unique operating conditions, with projects undergoing continuous change under complex management structures. CCRM implementation in other industries (e.g., mining) has identified complexities in implementation methodology and integrity of CC verifications (Dodshon & Hassall, 2017). For construction organizations to invest in the development and implementation of CCRM, organisational leaders who are accountable for fatality prevention will need assurance that the controls being defined will prevent fatalities (are they the ‘right’ controls?), how will CCRM provide reliable control of fatal risks and what organisational factors will influence the effectiveness of a CCRM program.

The thesis considers the following 3 research questions:

1. Can a CCRM strategy, when applied to known fatality risks, reduce the likelihood and severity of potentially fatal events in the construction industry?

2. What effect will implementation of a CCRM strategy in the construction industry have on existing risk management processes, safety performance and human factors which influence safety performance?

3. Are there inter-country and / or organisational cultural variations that impact the effectiveness of a construction CCRM strategy?

In undertaking the research to explore the research questions the following objectives were proposed:

1. Evaluate the potential contribution of current construction risk practices in preventing potentially fatal incidents compared to other resource industries, (Part I – Literature Review).

2. Develop a measure to assess the contribution of an alternative risk management strategy in managing field level fatality risks (Part 11 - Critical Control Reliability).

3. Build a working CCRM program for the construction industry (Part III) considering the dynamic work and organisational environments and changing fatality risk profile through a project lifecycle.

4. Field test CCRM using action research and case studies to quantify CCRM contribution to safety performance and analyse CCRM control effectiveness to improve construction projects fatality risk (Part IV); and

5. Explore the relationship of CCRM on safety climate and organisational risk management through case studies, safety climate and risk maturity surveys to enable comparative analysis of the impact of CCM on different attributes of organisation risk (Part V).

In summary, this research developed a novel construction industry CCRM program (Major Accident Prevention), through a combination of construction focus groups and action research which was validated over twelve months on a construction project. Two complimentary studies considered the factors affecting the reliability of CCs and the social constructs influencing construction safety performance highlighted during a disruption event (COVID-19 pandemic). The findings from the three preliminary studies were used to refine the MAP program for five-year international longitudinal research across 31 projects, 8 countries, 6 resource sectors and two organisations to improve statistical power of the research and consider the social constructs which may influence MAP safety outcomes.

The research aimed to provide construction site Supervisors with a series of tools to minimise distraction from non-essential controls, improve cognitive awareness of fatal hazards and provide transactional guidance on how to identify, monitor and apply the standards which prevent MAEs. Construction management implementing a CCRM strategy will benefit from an understanding of organisational factors which optimise CC effectiveness and the risk competency required to support the CCRM program.

1.4 Research Methodology

A pragmatic methodology underpins and is applied to the research to better understand why fatality events continue to occur from construction high-risk activities where controls are known, and the events are preventable. A pragmatic philosophical view focusses on situations, actions, and consequences in respect to application of solutions within the societal environment which the research problem is observed (Cresswell & Cresswwell, 2018). The pragmatic philosophy underpins mixed method research where the research problem exists in a social context and knowledge about the problem is explored using different and many approaches (Tashakkori & Teddlie, 2010).

To effect improved safety performance in the construction industry (i.e., reduction in fatal incidents) the research uses mixed methods to better understand why fatalities continue to occur and apply potential solutions which are analysed for effectiveness. The research applies quantitative analysis of historical incident data to identify risk control failures and the social constructs which affect the reliability of the risk controls. The results are used to inform the action-research (Coghlan & Shani, 2014) in the development of an 'intervention' program which is tested through a case study. Social factors impacting the effectiveness of a construction project safety performance are identified through qualitative safety climate surveys. Using convergent mixed methods (Cresswell & Cresswwell, 2018), qualitative survey results are analysed together with safety performance quantitative analysis to identify correlations and provide insight as to the effectiveness of the 'intervention' program when applied in different social contexts (e.g., companies, countries, and projects). The pluralistic mixed method approach to investigating the research problem improves the knowledge and understanding of 'why' fatalities are occurring and 'what' human actions can be taken to improve the safety performance, the essence of a pragmatic research philosophy (Cresswell & Cresswwell, 2018).

1.4.1 Preventing fatalities in the construction industry – learnings from other industries.

In Chapter 2 a realist review summarises the similarities and differences of risk management strategies used in other industries in comparison with existing construction risk management programs and results. The review outlines the factors affecting construction risk management effectiveness including hazard identification (Carter & Smith, 2006), risk perception and tolerance (Hopkins, 2011b), rule-based decision making (Hayes, 2012) and the impact of safety culture and safety climate (Hale & Swuste, 1998). The review identified five social constructs which needed to be considered in the design and implementation of CCRM strategy for construction projects which forms the basis for further research.

The social construction included:

i. How the CCs were developed to ensure the practical application in the field.

ii. Provide criteria to support effective frontline decision making that is directly relevant to the fatal hazards.

iii. Adaptability of controls to multiple high-risk work activities.

iv. Managing human factors which contribute to failure of critical controls.

v. Different cultural factors between projects in developing countries (e.g., Hong Kong) and developed countries (e.g., Australia).

The chapter concludes with the observation that in the absence of a paradigm shift is risk management and the existing 'failure to learn' risk culture construction fatality events will continue to occur from the same causes (Graham, 2011; Hopkins, 2011a).

1.4.2 Developing the Major Accident Prevention program (a CCRM approach) for construction.

In Chapter 3 action research applies a critical realism ontology to identify construction MAEs and conduct bow-tie analysis to determine construction CCs. Action research enabled the creation of knowledge through focus group participation, testing within existing construction projects with feedback validation of the new tools as practical for use in the field. The pilot program conducted over twelve months on an Australian construction project identified the MAP program contributed to improvements in existing risk management processes. The study also raised questions on the social constructs influencing the relationship between existing risk manage practices, MAP activities and the human factors influencing decision making in the field, particularly are the CCs the "right controls" to prevent fatalities in practice.

1.4.3 Determining the reliability of CCs in construction projects.

In Chapter 4 a critical realism ontology is applied through objective evaluation of MAP CCs against ten years of historic construction events to assess the CC reliability and identification of the human factors which affect CC reliability. Measuring reliability of risk controls can apply quantitative (Safe Work Australia, 2012; Kang et al., 2016), semi-quantitative (Casson Moreno et al., 2018; Grattan, 2018; Roelen et al., 2018; Winge & Albrechtsen, 2018) and qualitative processes (Hassall et al., 2015) depending upon the control to be measured, if the events where a control is challenged in the normal environment can be tracked or if the control can be tested under controlled conditions. The study applied a semi-qualitative assessment (Hassall et al., 2015) where the relative effectiveness of the control together with the adequacy of the control was considered by a panel of international construction safety professionals. Focus group members independently evaluated fatal, serious disabling injuries and high potential MAE events with the assessments subsequently reviewed by the panel to improve objectivity of the assessments. The chapter concludes with reliability scores mapped onto the relevant MAE bow ties revealing reliability gaps in CCs including sub-standard implementation of CCs, errors due to individual decision making and substandard actions or lapses. The findings whilst validating CCs performance specifications highlighted social constructs influencing the decision making to apply the CCs needed further investigation.

1.4.4 Case study comparing pre /post COVID-19 influence on safety.

In Chapter 5 the critical realism is applied through mixed research method using objective evidence in the form of safety statistics to interpret the social constructs generated from safety climate perception surveys. The research evaluated the differing effects of a disruptive event on a construction project safety performance (in this instance COVID-19 pandemic) and the influence of safety leadership. Workplaces with more positive safety climate have a better safety performance as workers hazard recognition and safety risk perception increase (Pandit et al., 2019), improve safety compliance as a function of supervisor safety leadership (Kapp, 2012; Petitta et al., 2017a) and participation in safety practices (Zhang et al., 2020). Safety climate surveys measure individual safety perceptions at a point in time and can be used to monitor shifts in safety climate and associated safety performance in response to changing events . The chapter concludes by confirming the significant influence of project leaders on worker motivation, participation in risk management processes and compliance to safety requirements and highlights difference between organizations working on the same project.

1.4.5 CCRM – Does it contribute to construction safety performance?

In Chapter 6 a five-year longitudinal study of MAP, as a CCRM program, was undertaken using the MAP methodology validated in the pilot study and improvements in CCs identified from the fatal risk analysis. The longitudinal study comprised 31 international construction projects, across multiple countries and different companies to consider the social constructs and risk management practices which influence safety performance including MAP. The mixed method research used in the COVID-19 study was adapted to assess difference between organisations, countries, roles and other demographics and the social network influencing safety risk management. The longitudinal study applied objective evidence from a broad spectrum of construction projects by limiting bias derived from individual organisations, companies, or national cultures. The duration and breadth the study comparing MAP and control projects improved the statistical power of the study and provided deeper insight into the influence of non-safety related factors.

CHAPTER 2. PREVENTING FATALITIES IN THE CONSTRUCTION INDUSTRY – A REVIEW OF CRITICAL RISK MANAGEMENT STRATEGIES.

Chapter 2 has been published as:

Selleck, R., and Cattani M. (2019) Preventing fatalities in the construction industry – a review of critical risk management strategies. *Journal of Health, Safety and Environment*, **35(3)**: 193-211.

2.1 Introduction

The Australian construction industry comprises 330,000 businesses, directly employs over 1m people or 9% of the total employment market and contributes 8% of the nation's GDP (Reserve Bank of Australia, 2018). Construction projects occur throughout Australia including capital cities, regional centres, and remote offshore and onshore sites.

In 2012 (updated in 2018), Safe Work Australia (Safe Work Australia, 2018a) identified the construction industry as a priority in its ten-year Work Health and Safety (WHS) improvement strategy due to relatively high fatality and occupational injury rates and proposed that to achieve better outcomes both concerted management support together with a systematic risk management process were required.

The construction industry ranked second in the comparison of the proportion of fatality rates by industry (Figure 1), with a five-year average (2012 to 2017) of 15.8% of worker fatalities (per 100,000 workers), (Safe Work Australia, 2018d). Proportionally the construction industry fatality rate is over-represented based on the number of workers employed by the industry. When fatalities including transport are re-distributed by industry of employer the construction industry is ranked second behind agriculture, forestry, and fishing (Safe Work Australia, 2018d).

Notably, other high-risk industries such as mining demonstrate a better fatality rate performance of 3.9% as a five-year average and are proportionally ranked tenth (Figure 5). The mining industry data is inclusive of fatality events within coal mining, metalliferous mining and the onshore oil and gas industry sectors.

In addition to the Safe Work Australia data3 the offshore oil and gas industry performance reported by NOPSEMA (NOPSEMA, 2019) the industry had a fatality rate of 0.01 (per million-man hours worked) between 2010 and 2019. Collectively these high-risk industries have a higher performance than the construction industry. An understanding of how these industries approach fatality prevention and why they have been more successful has the potential to assist in developing improvements in the construction industry.

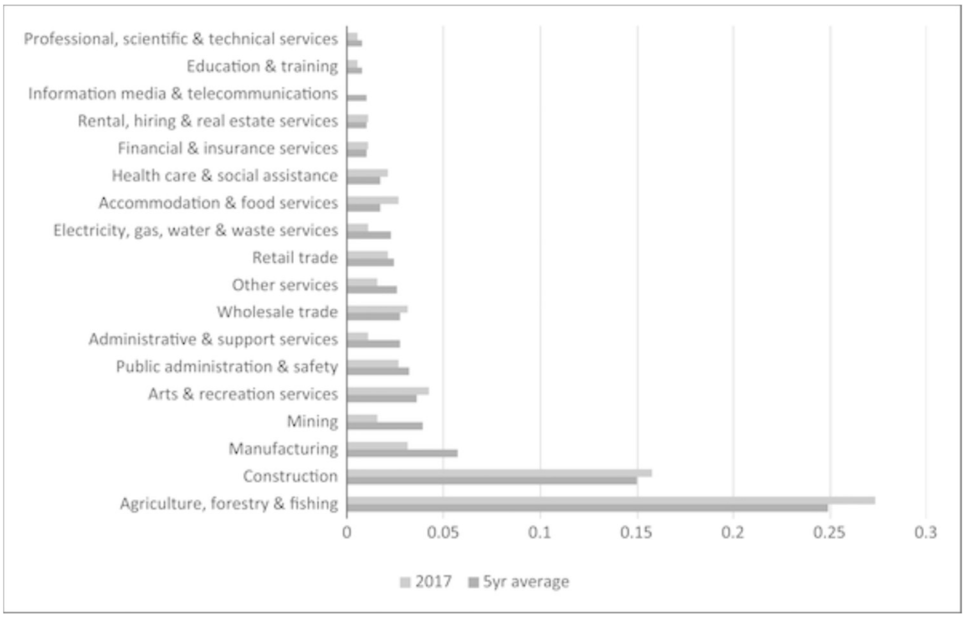

Figure 5 Worker fatalities: proportion by industry of employer, 2017 and five-year average (2013 to 2017)[1]

The coal mining, metalliferous mining and oil and gas industries have historically experienced catastrophic multiple fatality events in Australia[1] and internationally[2] A response from regulators has been the development of major hazard standards and major hazard facility (MHF) regulations or in the offshore oil and gas industry in the form of "safety case" regulations. The MHF and safety case regulations require organisations owning or operating an MHF or offshore hydrocarbon facility to apply a risk-based approach to identify major accident events and develop a safe system of work to prevent the occurrence of the major accident events and mitigate consequences. The development of MHF or safety case safe systems of work is focussed on addressing potential failure modes inherent in the operation of the facility and the interfaces between process systems, control measures, control measure performance standards, emergency planning and how to involve the workforce (NOPSEMA, 2013). The development and implementation of MHF and safety case standards are often referred to as Process Safety defined as — *"a disciplined framework for managing the integrity of operating systems and processes that handle hazardous substances" (International Association of Oil and Gas Producers (IOGP), 2013a)*.

[1] Source: Safe Work Australia (2018) — Work-related traumatic injury fatalities report 2017
[2] IOGP, (2013) – OGP Life Saving Rules, Report No. 459

In contrast, fatalities in the construction industry historically result in one- or two-person events which occur on a regular frequency in Australia from repeat causes (Safe Work Australia, 2018d). Construction fatalities are generally the result of high-risk activities (e.g. working at height, entering confined spaces, operating heavy plant and machinery) where the activity and human factors (i.e. personal safety) which gives rise to fatalities occurring, rather than the inherent risk.

Ninety-three per cent of construction fatalities in Australia (n = 195) reported between 2012 and 2018 were single fatality events. There were no fatalities reported in the oil and gas industry in Australia and 52 reported in the mining industry in the same period (NOPSEMA, 2019).

Single fatality events across all three industries are commonly caused through exposure to personal safety hazards. For example, in 2017, the percentage attributable to personal safety for the respective industries: construction (75%, n = 30); oil and gas (85%, n = 333) and mining (NA, n = 3), (Table 2). The fatality events across all three industries in recent years are dominated by single fatality events arising from hazardous energies, where the controls are adequately defined, but not adequately applied, through existing risk management practices (Hull et al., 2002; International Association of Oil and Gas Producers (IOGP), 2013a; Quinlan, 2014). Therefore, it appears the primary focus for the improvement of fatality rates in construction is improved by better management of single fatality events, arising from exposure to personal safety hazards.

Table 2: Industry Comparison - Fatality by Type in 2017 (% of total annual fatality events)

Fatality Causation	O&G[1]	Construction[2]
Explosion/burns	15.2	0
Caught in, under, between	27.3	9
Confined Space	12.1	0
Contact with electricity	3.0	10
Fall from height	3.0	30
Struck by moving objects	36.4	11
Struck by falling objects	-	15

[1]IOGP (2013).
[2]Safe Work Australia (2018).

However, Jørgensen (2016) proposes the principles which apply to major hazards resulting in catastrophic events should also be applied to “simple events” of low consequence (single fatality) and higher frequency (recurring) arising from occupational high-risk hazards.

The Australian legislative framework for construction requires a risk-based approach to manage high-risk activities, however, does not apply the same rigour on controls as required by the MHF and safety case requirements. The construction industry relies on a rules-based approach (e.g., life-saving rules), described by the national Codes of Practice (Safe Work Australia, 2018b), with reference to Australian Standards (e.g., AS 2865-2009 Confined Spaces, AS/NZS 1891.1:2007 Industrial fall-arrest systems and devices) and implemented through WHS safe work procedures.

The construction industry will benefit by considering the fatality prevention tools from other industries which could be adapted to managing construction high-risk activities.

This paper is a review of risk management tools and management practices used in the construction industry and considers the factors needed to adapt them to improve fatality rates.

2.2 Methodology

A literature review was conducted using keywords search inclusive of combinations of “fatality prevention”, “fatality risk”, “major accident event”, “safety”, “hazard management” and “critical control” combined with the three industries of construction, mining and oil and gas. Searches were conducted using World Wide Web, Scopus, ASCE and Science Direct which yielded 12,748 articles for review. The literature was then screened for duplicates, by currency (last ten years) and industry resulting in 138 for further review. Upon reading a total of 42 papers were relevant to the strategies used to prevent fatalities across industrial resources sector. Separate literature reviews were conducted for each study conducted as part of the thesis and presented as part of the study.

The search results were reviewed and filtered to compile studies (Table 2) which assessed the application or effectiveness of safety management practices and tools used in construction, mining and oil and gas industries.

The filtered search results (Table 3) have been applied the following two criteria:

a. How does the tool or practice contribute to fatality prevention?

b. Can the tool or practice be adapted to prevent fatalities in the construction industry?

NOTE: In the absence of oil and gas fatality events in Australia in the last five years international data was considered in the review.

Table 3: Summary of SMS Practices Evaluated by Research

SMS Practice	Factor	Data Collection Method	References
Pre-project/pre-task planning		Survey & empirical data	(20, 70, 71)
Safety inductions/training		Survey & empirical data	(70, 72–74)
Evaluation and reward		Survey & empirical data	(70, 75)
Fit for Work testing		Survey & empirical data	(70, 75)
Accident/incident investigation **Near miss reporting**	F1	Survey & empirical data	(13, 20, 24, 26, 70)
Management commitment	F2	Survey & empirical data	(70, 72, 74)
Safety staffing		Survey & Case Study	(20, 75)
Worker engagement/involvement	F1, F2	Survey, empirical data	(13, 19, 22, 72, 75, 76)
Contractor management	F2	Survey & empirical data	(70, 75)
Safety equipment/PPE		Survey	(76, 77)
Safety audits	F1, F2	Survey & empirical data	(13, 19, 70, 77)
Management training		Survey & Case Study	(75, 77)
Risk Management Tools Hazard Identification (HZID) workshops, Job safety analysis (JSA), Safe Work Method Statements (SWMS), pre-task risk assessment	F1	Empirical data, survey, case study	(13, 19, 20)
Safety observations	F2	Empirical data	(13, 19, 22)
Stop Work Authority	F3	Empirical data	(13)
Barrier Control Risk Management - Safety Case/Critical control management/Safety Case	F1, F3	Empirical data, case study	(9, 14, 25, 28, 78, 79)

The objective of safety risk management systems (practices and tools) is to “control the effects of human errors in the actual, physical work activity as well as management and design errors” (Safe Work Australia, 2018b). Two inherent principles are embodied within fatality risk management: all high-risk work activities are subject to inherent human error or violations; and the risk management practice or tool needs to prevent critical events and/or mitigate consequences through control processes, actions, or systems (Li & Guldenmund, 2018). To meet the fatality prevention criteria the safety practice or tool needs to either (i) directly control or mitigate human error, or (ii) define how high-risk activities will be controlled.

Salas and Hallowell (2016) identified three factors (Table 4) comprising of groups of safety practices which predict injuries and severity of injuries the objective of a fatality risk management program. The three factors are described as “work in progress risk management” (F1), “workforce engagement and monitoring” (F2) and “non-routine safety actions” (F3) (Salas & Hallowell, 2016). The “work in progress risk management” (F1) highlights the tools which identify, and control workplace risks and audit compliance to the controls (discussed in Section 3.1) whereas the other two factors focus on engagement (F2, discussed in Section 3.3) and interventions (F3, discussed in Section 3.2) which contribute to injury prevention.

Table 4: Workplace SMS Factors which Predict Injuries on a Project.

Factor Name	**Safety Practices**	**Predictive Value**	**Transformed Factor (OLS co-efficient/P-value)**
Work in progress risk management (F1)	Near miss reporting JSA development JSA engagement Contractor safety audits	TRIR* (R2: 0.5258)	-0.486 >0.01
		SR⁺ (R2:0.2850)	-0.113 <0.01
Workforce engagements and monitoring (F2)	Contractor PM engagements Contractor safety rep engagements Client safety engagements	TRIR	-0.116 >0.01
		SR	-0.0518 <0.01
Non-routine safety actions (F3)	Stop work authority Subcontractor safety audits	TRIR	-0.226 0.003

* TRIR – Total Recordable Incidence Rate (per 200,000 work hours)

⁺SR – Severity rate

2.3 Results

Assessment of Work in Progress Risk Management (F1) Tools Layered Risk Management The Australian construction industry uses a series of qualitative risk assessment tools, known as layered risk management, which define a system of barriers or “defences in depth”, to evaluate task risk, specify the controls and verify their effectiveness (Li et al., 2020, Li & Guldenmund, 2018; Safe Work Australia, 2018c). Construction risk (Saleh & Cummings, 2011) management practices used as part of the “defence in depth” process include Hazard Identification (HAZID) workshops to assess construction packages (Li & Guldenmund, 2018), engineered safe work method statements (SWMS) (Safe Work Australia, 2018c) for high risk work, job hazard analysis (JHA) for task-based activities (Safe Work Australia, 2018c; Salas & Hallowell, 2016) and personal risk assessments (e.g., Stepback, Take 5) to assess specific localized hazards just prior to commencing a task. The underlying premise of layered risk management is, by managing risk through an increasing level of detail from project level to the task level, all activities whether high or low risk, are managed to an acceptable level (Hallowell & Gambates, 2009).

Whilst layered risk management aims to increase the performance of risk management, as Reason (2016), observes no defence is perfect, and latent conditions or active failures may occur unexpectedly, resulting in events. Dekker (2014) suggests that layered risk management is overly bureaucratic, as the process has become more important than the relationship between the hazard and its control. The disconnect between a hazard and its control may be compounded by the metrics used to measure safety performance, such as the number of risk assessments, observations or inspections conducted (Dekker, 2014). Smith (2018) describes this as inherently misleading as counting "pieces of paper" does not inform the effectiveness of the controls. The arguments of Dekker (2014) and Smith (2018) identify there is a disconnect between the monitoring of hazard and risk management control implementation and common leading indicators which measure participation in the risk management programs, and not directly measure the application or effectiveness of controls. Management is at risk of making decisions based on participation data without a full understanding of the status of risk controls.

Table 5: Construction Risk Assessment Structure (example[5])

Purpose of HSE Hazard Assessment Tool/Program	Responsibility	
	Line Management/Supervisors	All Personnel
Task-Based Hazard Identification, Assessment & Control	Project Risk Assessment (HAZID) Construction Risk Assessments (HAZID) Safe Work Method Statement Job Hazard Analysis	STAART Card Take 5
Monitoring Work Environment Hazards	HSSE Workplace Inspections	Hazard Reports
Verify HSSE Hazard Programs	Supervisor Observation and Intervention Loss Preventions Inspections (LPIs)	

[5]Adapted from Clough Pty. Ltd. (80) HSSE Risk Management Procedure.

2.3.1 Safe Work Method Statements/Job Safety Analysis

The Australian WHS regulations require all construction high-risk activities to have documented risk management plan in the form of a Safe Work Method Statement (SWMS) (Safe Work Australia, 2018c). The objective of the SWMS is to assist business owners, supervisors and workers implement control measures to ensure high-risk work is conducted safely. The WHS regulations permit the use of “generic” SWMS on condition they are reviewed to include local hazards (Safe Work Australia, 2018c). A Job Safety Analysis (JSA) is undertaken for other routine tasks, they are generated by the teams undertaking the work and are used by supervisors to highlight the risk of the work being undertaken (Lingard et al., 2017; Safe Work Australia, 2018a; Salas & Hallowell, 2016).

Assessment of the effectiveness of SWMS and JSA’s to predict Total Recordable Incidence Rate (TRIR) identified the risk assessment and controls process were not significant (Hinze et al., 2013; Lingard et al., 2017). However, the development of SWMS and JSA’s together with the workforce engagement by supervisors was significant (Salas & Hallowell, 2016). SWMS and JSA’s increase the hazard awareness of work teams through the development and engagement process (Bahn, 2013; Pereira et al., 2017); however, may be subject to the human errors associated with the personal perception of risk (Carter & Smith, 2006).

2.3.2 Near Miss Reporting

Near miss reporting provides an opportunity for organisations to analyse events, even though the full consequence of the event has not occurred. Near miss reporting is useful to understand incident causal factors and the reason controls and barriers failed (Gnoni & Saleh, 2017). The investigation of near miss events can expose failures in the hierarchy of controls and failures in the multiple lines of defences and integrity of the control systems, inspections and monitoring of the controls designed to prevent the event (Gnoni & Saleh, 2017; Saleh et al., 2014). Near miss investigations can be predictors of TRIR and Serious Injury Rate (Salas & Hallowell, 2016). Near miss investigations rely on the findings of failures after the release of the hazardous energy rather than predictions.

The construction industry continues to experience recurring fatalities through a “failure to learn” from major hazard and near miss events, a common issue which has also occurred in the mining and oil and gas industries (Hopkins, 2014; Stemn et al., 2018). Near miss reporting may vary due to “blame” or negative connotations being associated with the process as it is linked to incident reporting (Hinze et al., 2013) resulting in the process being unreliable. Alternative pro-active methods to identify, monitor and maintain the effectiveness of controls need to be considered as near miss reporting is not a pro-active or reliable source of information.

2.3.3 Defence in Depth Risk Management

Risk assessment of major hazards is conducted to identify, assess, and mitigate potentially catastrophic hazards before they could cause an accident (Hassall et al., 2015; Hull et al., 2002; Lord Cullen, 1990). The catastrophic events can be rare occurrences resulting from complex design or control system failures (e.g., well blow-out) or from frequently recurring events (e.g., falling from heights) where controls are simple and able to be implemented by workers, supervisors, and site management (Hull et al., 2002).

Regulatory frameworks for the construction industry impose a duty of care for employers to provide a safe working environment through the provision of safe systems of work. How each organisation addresses these requirements is determined by the organisation itself (Alarcón et al., 2016). Construction organisations have responded to managing the risk of fatality events using “major hazard” risk management programs. These programs include rules-based standards applied through hazard identification techniques and risk control training programs reinforced with ongoing supervisor led communication processes (Albert et al., 2014; Kines et al., 2013).

The construction industry emphasis on the development of the “safe system of work” has resulted in a series of “defence in depth” methods to identify, assess and manage process safety. Methods such as Process Hazard Analysis (PHA) and Layers of Protection Analysis (LOPA) define the barriers [controls] which stop an accident sequence. The LOPA ensures critical controls for each barrier are defined, together with the verification monitoring required to maintain the integrity of the barrier. One form of LOPA, the bowtie method, is a semi-quantitative risk assessment which systematically defines the hazards which give rise to an event and potential consequences using a barrier approach (Delvosalle et al., 2006; Jacinto & Silva, 2010). The bow-tie analysis is used primarily in hydrocarbon, chemical or other MHF facilities where the operation and control systems are well defined and predictable (Delvosalle et al., 2006). In the dynamic construction environment where change is continuous, and the activities introduce inherent risks, application of bow-tie analysis has been limited (Jacinto & Silva, 2010).

2.3.4 Safety Case and Critical Control Management (CCM)

The oil and gas industry “safety case” regulation requires that prior to construction, all facilities have a documented management system covering design and operation of the installation, based on formal risk assessments, a comprehensive safety management system, and adequate provision for emergency protection of personnel and evacuation (Lord Cullen, 1990). Regulator acceptance of the “safety case” is a critical process in the life cycle of the oil and gas installation or Major Hazardous Facility (MHF) which is not the case in the construction industry.

The risk analysis of a safety-case provides the opportunity to identify design and other factors which can give rise to a catastrophic event. However, as Haddon-Cave (Haddon-Cave, 2009) found in an investigation of the Nimrod MR2 aircraft disaster, the risk assessment process was a “paper-based” exercise where design flaws were not identified, risks ignored or under-estimated and inspections were not applied. The safety-case risk analysis provides a method to identify critical risks and controls, however, has similar flaws to the layered risk management approach currently applied in the construction industry if there is not a focus on control implementation. Grattan (2018) similarly observes the effectiveness of barriers relies on both hardware and human/organizational factors. Current process industry formal safety assessment methods can be improved by better validating the human and organizational factors affecting the integrity of the barriers (Jørgensen, 2016).

A major change brought about by implementation of the oil and gas “safety case” was the shift in focus from measuring performance based on lag indicators of safety, such as injury rates, to leading indicators, such as direct inspection of controls which directly applied to the integrity of the safety case barriers (Vinnem, 2010). To this point, Graham (2011) observed major oil and gas accidents events were more likely — for example the Texas City explosion in 2005, where lag indicators were used.

The International Council on Mining and Metals (ICMM), (2015) coordinated the development of the CCM process to define, manage and verify the effectiveness of controls, informed by the safety case methodology. Although this process results in a “concise set of controls”, Hassall (2017) notes there has been significant variance between mining companies adopting it. The CCM methodology is a process like the safety case promotes a shift to perceive controls as human or device actions, and which verify the controls implementation and effectiveness. Given the variability in CCM implementation observed (Hassall, 2017), the desired improvements in fatality prevention offered by CCM can only be achieved if management and employees support the shift to control effectiveness.

Data collated from Safe Work Australia comparing the mining (Figure 6) and the construction industry (Figure 7) indicates that since the implementation of CCM by the major mining companies in Australia there has been an improving trend in the frequency of fatal incidents.

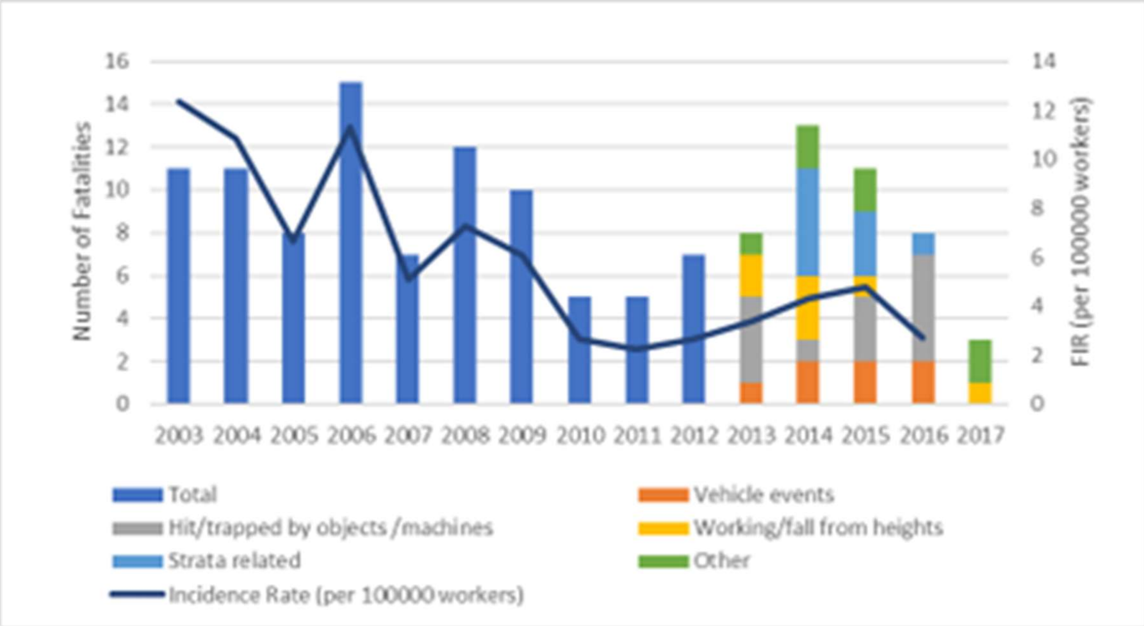

Figure 6: Mining Fatalities in Australia[2]

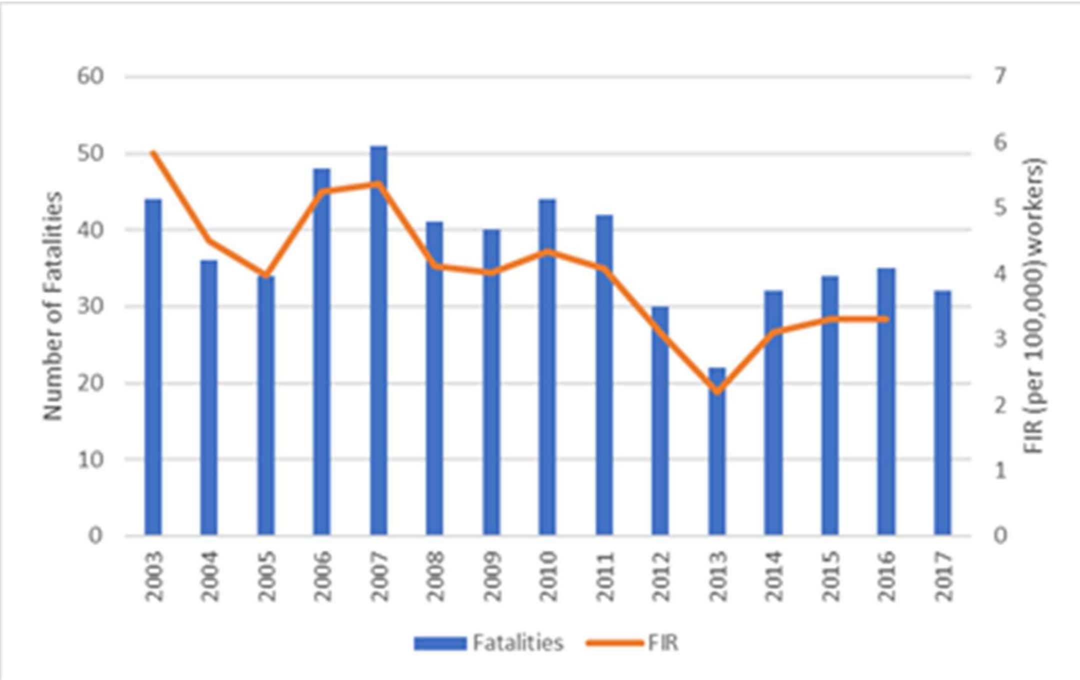

Figure 7: Construction Fatalities in Australia

Both the oil and gas industry safety case risk assessment and the mining CCM approach focus on clearly defining the critical controls which prevent major accident events and specify field verification to ensure the controls are effectively implemented.

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[2] Data sourced from Safe Work Australia, 2013 & 2018b

Assessment of Intervention Tools (F3)

An analysis of 22 common safety practices identified three factors (ie group of risk management practices) which predict injury rate (TRIR) and severity rate of injuries (Table 3) and have the potential to be used as “leading indicators” of safety risk management system. The use of “intervention” processes and tools (hazard reporting, stop work authority, inspections, audits) which interrupt or correct at-risk behaviours or substandard processes correlated with the occurrence of serious injuries (Salas & Hallowell, 2016). The effective implementation of the risk practices and tools may be impacted through poor hazard identification (Perlman et al., 2014b), high-risk tolerance by the line management (Kapp, 2012), decision making based on rules and inadequate use of stop-work (Dekker, 2014) and construction project safety leadership and barriers to effective engagement (Wu et al., 2016).

Hazard identification

The safety risk management process relies on the effectiveness of the hazard identification process. Carter and Smith (Carter & Smith, 2006) demonstrated workers on construction sites have varying ability to identify hazards and overall hazard identification is poor, with more experienced workers having better hazard identification skills. Bahn (Bahn, 2013) showed the effectiveness of hazard identification training is temporary, with improved hazard identification observed following training using visual simulations of real workplaces to improve hazard identification, however, this deteriorated and returned to pre-training levels within four weeks (Bahn, 2013; Perlman et al., 2014b). Hazard identification research identified workers are unlikely to consistently identify hazards in a dynamic construction environment where the risk profile changes daily and will put themselves or others at risk (Bahn, 2013; Neitzel et al., 2013). Hazard reporting systems are relied upon in the construction environment to identify and manage the constant change in risks which occur within a project. However, the hazard reporting process is based on human error and unreliable as workers are unable to consistently identify workplace hazards.

Supervisor Risk Tolerance and Rule-Based Decision Making

Supervisors are critical to the effectiveness of controls, as it is their perception of the task risk which triggers actions to adjust controls when required. It is the Supervisor’s judgement as to when additional action or control needs to be applied (Hopkins, 2011b). The point on the risk continuum at which a frontline supervisor chooses to act to implement controls is based on their perception of risk, experience and “gut feel”. Clear guidance is essential to ensure the Supervisor understands the organisation’s perception of risk, when additional controls are required, and when work should be stopped if the integrity of the control is compromised. Life-Saving Rules are used to provide standards for supervisors and employees to manage fatal risks and as a means to reduce human-error inherent in hazard identification and risk perceptions and tolerance.

Safety rules (e.g., life-saving rules, golden rules) are used to communicate the controls required to manage known safety hazards and have been used as part of safety management systems (IOGP, 2013a). The oil and gas industry has also used Life-Saving Rules which aim to prescribe a series of strict behavioural standards, derived from analysis of fatal events, and were first published in 2012 (IOGP, 2016). Over time the Life-Saving Rules have become standardised, general statements which are reinforced through hazard training, inductions, and audits. In 2017 the IOGP attributed 87% the industry fatalities to human factor causes (i.e., personal safety) which ironically are directly related to the known controls documented in the IOGP Life Saving Rules. The same rigour of hazard management applied to process safety has not been applied to personal safety events reinforcing Grattan's (2018) argument further work is required to understand the human factors which affect barrier [rule] implementation.

Hale and Swuste (1998) describe three types of rules; those describing a goal; a method to reach an outcome or an action. Whilst the objective of safety rules is to define actions to be taken when specific hazards are identified in the field, the safety rule is generalized and does not provide specific standards or scope for the application of the rule leaving it up to the individual to interpret how and when the rule is to be applied. Hayes (Hayes, 2012) found supervisors were less likely to take action to stop work or mitigate compromised barriers where the "rules" being referenced were not specific and therefore the pressure to minimise costs or maintain schedule will erode the decision maker's [supervisor] commitment to safety over time (Hopkins, 2011b).

In Hopkins's argument where major accident events (MAE's) are identified, two factors need to be considered to prevent MAE's from occurring; rules (controls) need to be specific (i.e., Type 3) and compliance to the rules need to be monitored to ensure they are implemented and effective.

How rules [controls] are developed and applied also needs to be considered to ensure ownership by the frontline personnel (Hale et al., 2015). Engagement with frontline personnel will be a key to the development of the controls, enabling, frontline supervision and workers to apply the controls and adapt when exceptions occur (Hale et al., 2015).

Assessment of Factors Influencing Workplace Engagement (F2)

Site leadership is critical to an effective fatality prevention program as site leadership (construction management, supervisors) establish the organisation tolerance and acceptance of risk influencing the safety climate on a project site (Guo et al., 2016; Kapp, 2012; Zohar & Luria, 2010). Construction site leaders are influenced by complex external cultural relationships (client, company, contractor) which may have competing values and core belief systems (Choudhry et al., 2007). Importantly, site leaders can influence the construction site "safety climate" through encouraging work team safety motivation and compliance to agreed safety standards (Guo et al., 2016; Probst et al., 2019).

2.3.5 Project Safety Climate (Within the Project)

"Safety climate" is an indicator of an individual's perception of their work environment, experiences, belief, and actions as related to safety in the organisation at a particular point in time (Bluff, 2011; Clarke, 2000; Guo et al., 2016; O'Neill et al., 2015). Safety climate is based on personal experiences related to the systems, practices, behaviours, and events workers observe in the workplace and what is being rewarded or supported by site leaders. It is widely recognised that leaders cannot directly create or change the culture, or as Hopkins (Hopkins, 2005) observes leaders see culture as a value, and when they set out to change the "hearts and minds" of an organisation, they do not succeed. In a review of the literature recognised a positive safety climate predicts a better safety performance through higher levels of safety participation and safety compliance (Guo et al., 2016; Kapp, 2012; Zohar & Luria, 2010), and has a direct and negative effect on "at risk" behaviours (Cavazza & Serpe, 2009). Proactive safety leadership together with the social support of team members directly affects the attitude and behaviours of the work teams (Bluff, 2011), including compliance to the standards required (Fernández-Muñiz et al., 2007). Where supervision enforce the safety standards and expected behaviours of work team members, holding individuals accountable to the standards, a higher level of workforce compliance is observed, and safety improves (Grill & Nielsen, 2019; Petitta et al., 2017a).

The CCRM program (ICMM, 2015) whilst risk-based and focused on critical controls requires a high level of compliance to the critical controls. Hence a positive shift in safety climate and risk maturity to have a safety motivated workforce is an underpinning requirement of CCRM (Hassall, 2017). Dekker (2014) points out that introducing a rules-based approach introduces more bureaucracy, complexity and confusion and is indicative of a less risk mature organisation. The point of difference between rule-based decision making and suggested bureaucracy is critical controls generated through CCRM bringing clarity and reducing the "noise" of multiple layers of standards and rules currently in use within the construction industry. The CCRM approach builds the critical control verification checklists which workers apply to high-risk tasks, analogous to a pilot undertaking a prefight check of the integrity of aircraft and critical flight systems. The risk maturity of the organisation is in recognising the integrity of CCRM is based on one rule “follow the critical controls”.

Safety Culture (External Factors to the Project)
The definition of “safety culture” is a subset of an organisations’ culture described as the underlying values, beliefs and assumptions held collectively in a group and shared in the behaviours, patterns and processes which affect safety (Choudhry et al., 2007; Clarke, 2000; Hopkins, 2005; O'Neill et al., 2022). Differences in safety culture within construction projects also arise due to the underlying safety maturity of the labour resource (Man et al., 2017), mistrust arising between nationalities (Korkmaz & Park, 2018), country or regional regulatory regimes (Chen et al., 2017) and underlying ethnic values which can include language barriers (Bust et al., 2008). Often described as “the way we do things around here”, the attributes of culture are not readily measured, not easily changed and subcultures (client, company, contractor) may exist across different work groups. The culture of safety on a construction project is known to be influenced by the company, client and subcontractor management with the project work groups usually reflecting the values and beliefs of the parent organisations, unless concerted effort to engage and align the work groups, through their supervision, to a common value set (Chen et al., 2017; Wu et al., 2016). In the absence of an aligned commitment to CCRM standards and integrated application of CCRM across all involved organisations within the project, variability based on sub-cultural differences is likely to impact CCRM implementation and effectiveness.

By understanding the underpinning safety culture of the construction workforce, the WHS management systems and practices can be adapted to improve workforce understanding and communication of risk management programs. Training, risk assessment, and communication tools need to be designed to ensure the MAE hazards and critical controls are known, understood, and implemented. The role of project leaders and line supervision need to ensure miscommunication or conflict between different working groups is also monitored and actively managed and therefore rely even more on engagement practices (Salas & Hallowell, 2016).

2.4 Discussion

The layered approach of risk management in the construction industry has contributed to reducing personal injury rates; however, management of fatal risks associated with high-risk construction activities has not significantly improved in the last decade, with the most recent results indicated a reversing trend (Safe Work Australia, 2018f).

The layered risk management practices applied across the construction industry rely on effective hazard identification by the teams and individuals involved in assessing the risk. This is inherently flawed given the high rate of hazards regularly not identified in the workplace (Bahn, 2013; Carter & Smith, 2006; Neitzel et al., 2013; Perlman et al., 2014b). The studies on hazard identification did not specifically focus on fatal risks. It would be expected a higher rate of hazard identification would be prevalent in the construction work force relative to fatal hazards, however, further work to understand the magnitude of the potential gap in hazard identification is required.

Combined with the variability in risk perception of workers (Hayes, 2012; Perlman et al., 2014b), often described as risk complacency (Dekker & Pitzer, 2016), the fatal hazards are often under-estimated, so the controls used to manage the risks may be missed or not effectively implemented. When controls are identified and implemented the line supervision is left to interpret the adequacy of the controls based on the "rules" [controls] which apply to the work being conducted. If the risk is a continuum, as proposed by Hopkins (Hopkins, 2011b), the decision making by supervision to 'stop work' based (Hale & Swuste, 1998; Hayes, 2012). The decision to stop work can be confronting when cost and/or schedule of the project is affected, particularly where the assessment to stop work is based on the individual worker, supervisor or line managers judgement and not backed by specific criteria (Hayes, 2012). By improving the specification of controls currently known and in use, which directly prevents the release of fatal energies construction workers, supervisors and line managers would be better equipped to make consistent assessments as to the integrity of the control and add surety to the decisions whether to continue or stop work.

For a major hazard program to be effective a construction organisation's safe system of work needs to reduce variability in the identification and assessment of major hazards (Carter & Smith, 2006; Perlman et al., 2014b) prevalent in the dynamic construction work environment. The safe system of work needs to reduce bureaucracy and complexity in the number of controls to be applied (Dekker, 2014) and improve the integrity of monitoring of control implementation and effectiveness (Smith, 2018). Factors affecting the risk maturity of the organisation including decision making (Hayes, 2012), risk tolerance (Guo et al., 2016; Hopkins, 2011b), compliance to critical controls (Petitta et al., 2017a) and safety climate at each project site (Petitta et al., 2017a; Zohar & Luria, 2010) need to be considered and managed to ensure work teams are engaged in the fatality prevention program.

Alternative risk-based strategies such as the adoption of the oil and gas safety case or critical control management potentially provide a new approach across construction organisations.

To ease the level of change, it would be appropriate to adapt existing construction tools and ensure:

i. effective identification of all major hazards in the workplace before the task starts during planning

ii. controls specified to provide clear guidance on stop work decisions

iii. a shift in the focus of the organisation to monitor and respond to critical controls, and

iv. risk maturity — discipline to consistently implement critical controls and/or stop work when they are not implemented or effectives.

A paradigm shift in construction risk management leadership is required to treat personal safety fatality risks using the techniques like process safety risks. This includes applying the discipline and rigour of monitoring and assurance required to maintain the integrity of the controls (Dekker, 2014).

Both the oil and gas industry safety case and the mining CCRM approach focus on clearly defining the critical controls which prevent major accident events and field verification to ensure the controls are implemented and effective.

These risk models have the potential to be applied to the construction industry as:

i. the mechanisms which currently cause fatalities in the construction industry are known, and

ii. the typical controls to prevent the fatal energies involved being released are also known.

Current insights into the development and application of the Critical Control Management approach being applied in the coal mining industry (Hassall et al., 2015; Hassall & Joy, 2016) provide a method which could be adapted to the construction industry such as bow-tie analysis of fatal personal safety risks to identify critical controls with a field-based verification process.

2.5 Literature Review Summary

The construction industry, like the oil and gas industry previously, would benefit by adopting a shift in focus from risk assessment and the associated bureaucracy to risk treatment and control to prevent the ongoing occurrence of fatality events across the industry. The design and implementation of a CCM approach would need to consider:

i. how the controls were developed to ensure the controls are practical.

ii. provide criteria to support effective frontline decision making that is directly relevant to the fatal hazards.

iii. the adaptability of controls to multiple high-risk work activities.

iv. managing human factors which contribute to the failure of critical controls, and

v. different cultural factors are external and internal to a project site and between project teams.

Undertaking a paradigm shift in risk management will require concerted management effort and leadership to prevent ongoing recurrence of fatalities within the construction industry.

CHAPTER 3. PROPOSAL FOR AND VALIDATION OF NOVEL RISK-BASED PROCESS TO REDUCE THE RISK OF CONSTRUCTION SITE FATALITIES (MAJOR ACCIDENT PREVENTION (MAP) PROGRAM).

Chapter 3 has been published as:

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3.1 Introduction

The construction industry fatality incidence rate (fatalities per 100,000 workers) is the second highest in Australia after Agriculture, Fishing and Forestry (Safe Work Australia, 2020) and is similarly ranked in other developed nations including USA, UK, and Singapore[3]. Safe Work Australia (Safe Work Australia, 2020) reported over 90% of fatalities are one or two person events from common high-risk activities with known hazards and known controls Table 6.

Table 6: Risk Profile of Construction Fatal Event Causation.

Event Predictability **(Event Consequence)**	**Foreseeable events with known controls**
Catastrophic (multiple fatalities)	Natural events: cyclone, bushfire, flooding Design: engineering faults, design failures
Critical (single / two-person fatality events)	Task specific events: Fall from Working at Height Dropped Object Caught between objects Working in Confined Space Vehicle interactions
Non-fatal injury/illness events (less than fatal)	Slip, trip, fall at same level Muscle overuse / over exertion

Research into accident prevention has identified multiple factors and safety controls to prevent incidents from occurring (Bellamy, 2015; Mohammadi et al., 2018; Zhang et al., 2019).

[3] Health & Safety Executive-United Kingdom; Ministry of Manpower - Singapore; Occupational Safety & Health Administration -USA;

Construction specific studies have analysed incidents to identify causation factors (Betsis et al., 2019; Chi et al., 2015; Winge, et al., 2019), the mechanisms of energy release (Chi et al., 2009) and factors influencing fatality prevention including leadership, risk management, and safety climate (Alarcón et al., 2016). However, construction fatalities from foreseeable events with known controls still occur across the industry.

The identification of hazards with potential for a fatality (i.e., major hazards) arising from the foreseeable events are understood within the construction industry as evident in a variety of fatality prevention programs (e.g., Life Saving Rules which prescribe a series of behavioural expectations to minimise fatality risk from foreseeable events). For these events, preventative controls have also been defined in standards and codes of practice in Australia and internationally [4]. Regulators have published detailed safety standards on construction high-risk activities and defined the controls to be applied to prevent and mitigate consequences which lead to fatalities (Safe Work Australia, 2018c, 2020). Although the hazards and controls associated with the construction high risk activities are well-known, incident investigations continue to identify controls that were either not implemented or the performance of the control was inadequate (Bellamy, 2015; Dodshon & Hassall, 2017; Lingard et al., 2021). A better understanding of the reasons why the controls are unreliable is required when considering alternative risk control strategies.

Hopkins (2011b) suggests risk is a continuum and humans' perception of risk varies according to their experience, risk tolerance and other factors including perceived or real production pressure. In practice the fatality risk reduction action an individual takes following the identification of a hazard is based on their personal perception of risk, even if it differs from the expectation of their employer (Hayes, 2012).

In high-risk industries, the ambiguity of individual risk perceptions and required action is reduced through rules with detailed specifications which converts the risk into a dichotomy for the purpose of decision-making that is the risk is acceptable or not-acceptable (Hopkins 2011). It is the combination of risk management (i.e., to consistently identify major accident risks and controls) and rule compliance (implementation of controls) which should provide a more sustainable approach for preventing reoccurring major accident events. Hayes (2012) expanded this in an analysis of three organisations operating in rule-based, goal setting safety regulatory environments. Where controls [rules] had specified tolerance limits managers were

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[4] Health & Safety Executive-United Kingdom; Ministry of Manpower - Singapore; Occupational Safety & Health Administration -USA; Canadian Centre for Occupational Health and Safety - Canada, Department of Labour – South Africa

more likely to act and intervene when controls deviated from the limits even when under production pressure.

Our review, Selleck and Cattani (2019), concluded that the construction industry “would benefit by adopting a shift in focus from risk assessment, and the associated bureaucracyto risk treatment with a focus on control reliability and effectiveness to prevent the ongoing occurrence of fatality events across the industry”. We recommended exploring whether the Critical Control Risk Management (CCRM) process could be adapted to construction in a manner that improves the management of fatality risks. In this paper we explore whether CCRM can be adapted to a construction work environment and improve project safety performance.

3.1.1 CCRM and Potential Use in Construction

CCRM is a defence in depth risk management approach enhanced by High Reliability Organisation (HRO) theory to focus human effort in complex socio-technical systems on the critical elements that prevent fatalities. CCRM applies bow-tie analysis to identify the threat pathways and multiple controls (i.e., defence in depth) to prevent unwanted events and to mitigate their consequences (International Council on Mining and Metals (ICMM), 2015). CCRM shifts the focus from risk assessment to risk control. CCRM identifies the critical controls that are crucial in preventing fatalities and that need an enhanced level of attention to ensure they are implemented and effective. HRO theory is based on being sensitive to operations, preoccupied with failure, mindfulness, and where the premise is maintaining a constant state of mind that operations that are ‘safe’ or could go ‘unsafe’ (Weick & Sutcliffe, 2007) which describes how all organisation levels should focus on or attend to the critical controls.

In CCRM, rule-based criteria for Critical Controls are defined, enabling line management and their team members to consistently interpret and apply controls. This somewhat removes the subjectivity of individuals’ decision making regarding the expected controls (ICMM, 2015).

CCRM has been adopted by the mining industry where it has helped to reduce injuries and fatalities (Rio Tinto, 2021). However, there is no equivalent program in the construction industry. For a CCRM based program to be adopted by construction organizations, it needs to be capable of functioning in the dynamic work environment, including a constantly changing workforce, which is not generally seen in a mining environment.

3.1.2 Risk Management in Construction Currently

Risk management in construction, and all industries which use “ISO31000: 2018 Risk Management – Guidelines” rely on hazard assessment processes to manage safety risks. In brief, when hazards are identified, a risk assessment is conducted (i.e., the likelihood of a predicted consequence occurring) (ISO31000:2018). The risk assessment is used to inform an evaluation of the risk, either as subjective rating (I.e., low to very high) or as calculated rates of failure based on incident data, which is used predominantly for process safety applications (e.g., safety cases for major hazard facilities). The risk assessment rating provides relativity between risks and is relied upon by senior leaders to make decisions on the effort and resources required to manage the risk, a fundamental concept of the “risk management framework” (ISO31000:2018). The rating is used to determine if risk treatment is required and if so, then the controls to be implemented are identified.

The construction industry risk management process is applied as “layers” where hazard assessment and control are used at increasing levels of detail, from project wide to task level activities. The intent is that at each level, the risk of each activity is managed to an acceptable level (Hallowell & Gambates, 2009). An underlying assumption of the layered risk management process and hazard assessments is that defined controls, including human actions, are consistently implemented throughout the construction activities. Construction research has identified that reliance on these human factor practices in current risk management systems produces variable levels of control due to human factors. Human factors affect hazard identification, risk control implementation and the effectiveness of the layered risk management systems (Selleck & Cattani, 2019). Albert and Pandit (2020) demonstrated workers are more likely to identify hazards which impose greater safety risk, indicating workers have a heightened level of recognition of fatal risks, but there is work to do to enhance this process as fatal events are still occurring.

To address the risk of fatality events, the construction industry risk-based approach needs to:

- reduce human error associated with hazard identification.
- reduce complexity of the layered risk management process by focussing on risk treatment (I.e., controls).
- improve the specification of controls to enable consistent decision making on the implementation and effectiveness of controls; and
- be resilient to the dynamic construction environment as changes in the risk profile occur throughout the project lifecycle.

The ICMM CCRM concept provides a methodology to determine construction critical controls and outlines processes supporting implementation within an organisation (ICMM, 2015). The adaptation of the ICMM methodology within a construction organization potentially achieves point 1 to 3 above. However, it is unclear how to address consistent application in the dynamic construction work environment with the constantly changing risk profile through a project lifecycle (point 4). Whilst mining companies have been applying CCRM within the operations and cascaded down to subcontractors undertaking construction, no research literature could be found that explores the application of the CCRM approach to actual construction projects.

To address this gap, this paper presents the novel research that describes the development and validation of a fatality prevention model which combines the risk-based approach focussed on control effectiveness and principles of HRO to address the common mechanisms of construction fatality events.

3.2 Aim and Objectives

The project aim was to validate a novel risk-based process to reduce the risk of construction site fatalities by considering and answering the improvements identified from previous studies and reviews (Albert, et al., 2020; Selleck & Cattani, 2019).

With the working name the Major Accident Prevention (MAP) program the objectives of the project were:

- Define a risk-based model to assist the management of construction fatality risk reduction.
- Describe and validate the steps required to implement the model on a construction site consistently throughout the project lifecycle.
- Conduct a pilot study to evaluate the performance of the new model relative to existing risk management processes and the human factors which contribute to the failure of controls.
- Conduct statistical evaluation of the potential impact on incident performance.

3.3 Methodology

The research applied a multi-step methodology to develop the new risk-based program and to test the program on a construction project. The research was conducted in four phases:

- Section 3.1: Development of a construction critical control risk management model
- Section 3.2: Design and development of the MAP program with supporting risk-based tools
- Section 3:3: Pilot study to validate the MAP program on a construction project.

- Section 3.4: Statistical analysis of safety leading and lagging indicators to evaluate the impact of MAP on safety performance.

The structure and sequence of the research is outlined in Figure 8 and summarized in Table 7. The initial phase included the design and development of the risk-based processes and tools to support field execution of critical control risk management. This was iterative throughout the development of the bowties and alignment on controls. This phase also included the organisational and competency factors to implement MAP on a project. The pilot study tested the MAP processes, training, and use of field critical control verifications. The third phase was the post implementation statistical analysis to explore MAPs' contribution to safety performance.

Table 7: Summary of Research Methodology by Phase

Research Phase	Steps	Relevant Section
Design and development of MAP program	Bow-tie risk workshops	Section 3.2.1, Appendix B, C
	Organisational Principles	Section 3.2.2
	Project Risk Profile	Section 3.2.3, Appendix D
	Supervisor / Team Critical Control Verification & Competency	Section 3.2.4 and 3.2.5 Appendix E
	Measuring MAP Performance	Section 3.2.6
Pilot Study – validation of MAP processes	Trial of MAP on Pilot Project and feedback to improve MAP processes	Section 3.3.
Measuring MAP impact on safety performance	Statistical measurement and analysis of MAP contribution to Pilot Project safety performance.	Section 3.4

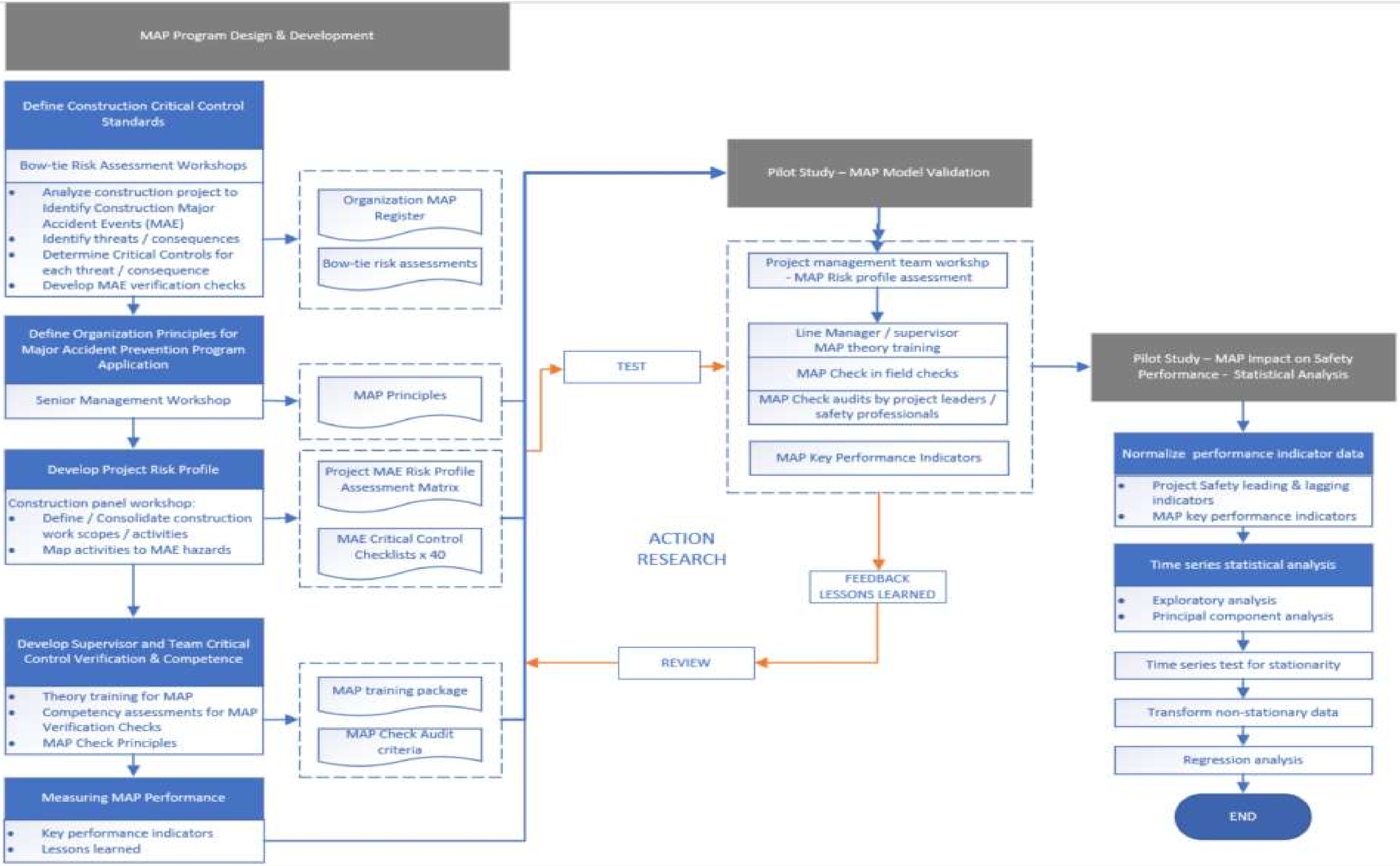

Figure 8: Research Framework by Phase

3.3.1 Major Accident Prevention Model

The Major Accident Prevention (MAP) program was developed by adapting the safety case and the ICMM (2015) CCRM models to manage known personal safety fatalities experienced in the construction industry. The MAP program builds on the process outlined in the ICMM (2015) bow-tie methodology to produce a system design which addresses both the dynamic risks experienced throughout the construction project lifecycle and the critical control standards. The MAP program (Figure 9) is a cyclic system which identifies and applies Critical Control (CC) verification, monitors CC performance and provides feedback on improvements to the CCs throughout a project.

The MAP program was designed to be applied on any construction project. The first two steps define the Critical Control standards and determine the verification checks required as part of the monthly project schedule. Steps 3 and 4 are supervisor-based verification of controls in the field ensuring the competency to conduct verifications is maintained through Step 5 monitoring. Any gaps in Critical Controls either not being implemented or not up to standard are reviewed in Step 6 and action taken to address the gaps.

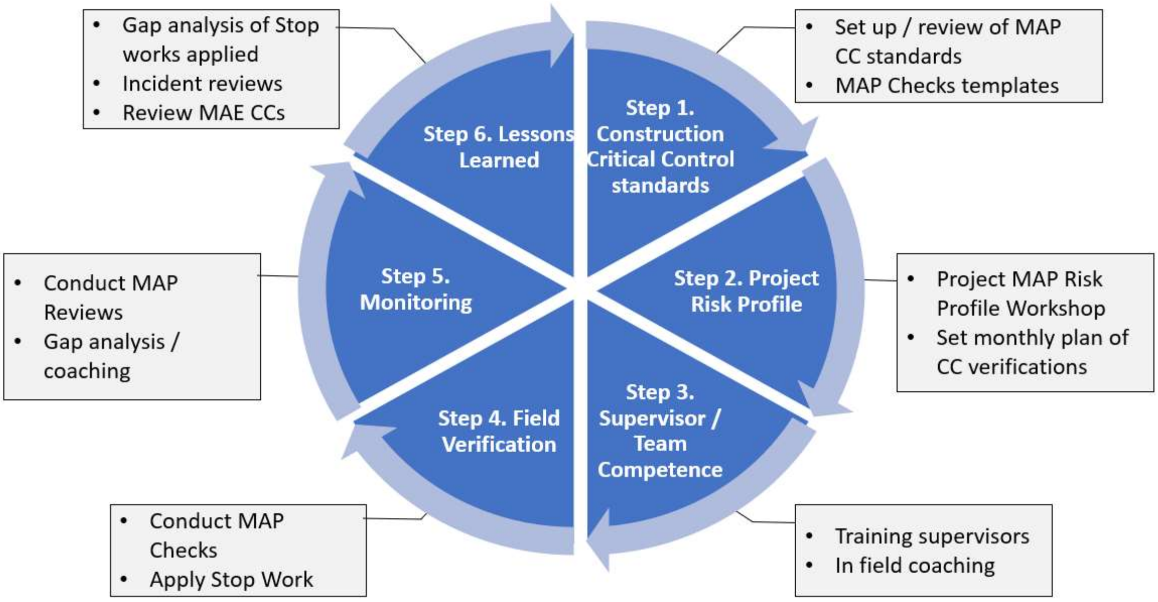

Figure 9: Construction Industry - Major Accident Prevention Model

The development of MAP involved a high level of engagement with construction industry personnel to ensure Critical Controls (i.e., those controls designed to prevent fatalities or 'CCs') are practical, provide specific criteria to enable consistent decision making and can be adapted to multiple high-risk work activities (Selleck & Cattani, 2019).

To support the practical application, and engage construction management and front-line leaders, an action research methodology was applied to both the design of the Major Accident Prevention (MAP) program and facilitating the case study implementation. Action research method was chosen because as Coghlan and Shani (Coghlan & Shani, 2014) observed an insider action research capability can be used to: *"1) study and shape new opportunities and threats, 2) to empower decision-makers to seize opportunities and 3) to sustain the organization's success….".* Action research enabled organisational factors affecting risk maturity, decision making, risk tolerance, compliance to CCs and safety climate were considered and managed through the design and implementation processes to engage in the program.

3.3.2 MAP Program Design, Development and Tools

3.3.2.1 Defining Construction Critical Control Standards

The initial step (1) of the MAP model requires a detailed understanding of the type of major accident events (i.e., single, or multiple fatality) and the Critical Controls Standards (i.e., define this term) which prevent the unplanned release of energy with the potential to cause a fatality. The detail and specification of the Major Accident Events (MAEs) and Critical Controls form the basis for field verification (Step 4) to validate if the controls are implemented and effective. The MAP model definitions for terms used and examples are provided in Table 8.

To gain the detailed understanding, a panel of construction experts (MAE Panel) were nominated by the participating organisations to provide a mix of construction expertise (i.e., construction, commissioning managers, safety engineer, earthwork, civil, mechanical, electrical, instrument supervisors and safety advisors) each having a minimum of 15 years' experience, with the panel having an overall average of 23.2 years of experience. A total of 12 construction experts were used over a 4-month period, with every panel having as a minimum senior manager, construction manager, frontline supervision, and safety representatives together with the researcher who facilitated the workshop. Where required the MAE Panel was supplemented with specific expertise for the bow tie being analysed e.g., electrical engineer and electrical supervisor when analysing electrical risks.

The panel conducted bow-tie analysis following the methodology detailed in ICMM (2015), through a series of bow-tie risk assessment workshops averaging 4 hours duration. Development of the bow-ties comprised three sub-processes: i) defining construction MAEs, including threats and consequences, ii) identifying controls for each threat / consequence pathway and iii) determining Critical Controls.

Table 8: MAP Model Terms and Definitions

Term	Definition
Activities	Work scopes undertaken during construction projects
Consequence	Unplanned outcomes from escalation of event (post energy release) – specifically single or multiple fatality or disabling injury
Controls	Human action, system or object which prevents unplanned event or mitigates escalation of consequences
Critical Control	(as per ICMM (International Council on Mining and Metals (ICMM), 2015) definition) Is the control a human act, object, or system? and Does it directly prevent the release of hazardous energy or mitigate the consequences? or Is the control performance, specifiable, observable, measurable and auditable?
Major Accident Event (MAE)	The release of energy through an unplanned event which has the potential to result in a single or multiple fatality or disabling injury from *foreseeable events with known controls*.
Major Accident Event Hazard (Threat)	The mechanism by which the hazardous energy is released causes an MAE. (Importantly, a threat is not a failed control). e.g., Platform failure
MAE Category	Grouping of common MAE Scenarios – e.g., Working at Height

3.3.2.2 Defining MAEs and Controls

For each MAE the panel identified threats, controls, and consequences for construction fatality events with MAEs categorised in accordance with existing life-saving rules as the risk to be analysed (IOGP, 2012; Safer Together, 2016) and mechanism of fatal incidents as threats (Chi et al., 2015; Safe Work Australia, 2018e). The threats and consequences were described as the mechanism by which the ‘energy’ was released, or consequence occurred (e.g., fell through roof or person struck by falling object). A sample of five diverse construction project schedules (i.e., process plant, near shore structures, offshore oil and gas facility hook up, water treatment plant, power station, civil infrastructure) were used to identify the mechanisms of fatal events (threats). The MAE Panel analysed the project schedules and identified the standard scope of common construction activities (Appendix A) providing common definitions for use in the MAE bow-tie analysis. From the activities the panel identified potentially fatal events which were grouped into categories (Appendix B) that then formed the basis for the MAE bow-tie analysis.

For each MAE a bow-tie risk analysis was developed by the MAE Panel which included:

i. defining the construction MAE from the list shown in Appendix B.

ii. identifying controls for each threat / consequence pathway using bowtie analysis (an example shown in Appendix C); and
iii. determining Critical Controls (which were highlighted on bowties shown in Appendix C).

The MAE Scenarios were confirmed from a review of fatal incident reports as detailed in regulator databases (Safe Work Australia – fatal incident reports, NIOSH FACE database). The scenarios identified had at least one fatal incident reported in the previous ten years. A total of 10 MAE Categories, 39 MAE Scenarios (Appendix B) were developed. A bow-tie analysis was conducted on each of the 10 MAE Categories with the associated MAE Scenarios being used to help form the 'threats' on the left of the bowtie then further analysis was don't to identify controls as discussed next.

Once the bow-tie threats and consequences were identified, researcher (first author) using the industry body of knowledge of controls (Commission for Occupational Health and Safety (WA), 2004; Safe Work Australia, 2015, 2018c; Standards Australia, 2021) added the control statements to generate the bowties in the format presented in Appendix C.

The bowties with all controls were presented back to the panel of experts who individually assessed if all the MAE's had been identified, the validity of the controls that had been included and if any were missing. Each bowtie was amended based on consensus to include new controls, amended control statements or to re-assign controls to threat or consequence pathways. Then the panel of experts determined which were the critical controls.

3.3.2.3 Identifying Threat / Consequence Critical Controls

'Critical controls' were determined based on criteria adapted from Hassall et al, (2015) and ICMM (2015). Where 'critical controls' were defined within an event category (e.g., falling from a height) and the critical controls addressed more than one threat then the threats were combined. The identified MAE categories (10), fatal hazard scenarios (39) and critical control statements were used in the development of the Risk Profile tool. A total of 312 critical controls were identified across the 39 fatal hazard scenarios. An example bow tie is provided in Appendix C.

One point of contention was training as a critical control, specifically in the form of verification of competency (VOC). The ICMM guideline identifies training as an enabler of CC effectiveness but in and of itself is not a critical control (ICMM, 2015). The view was taken by the MAE Panel to incorporate VOC as a CC given the current risk maturity of the construction industry which relies heavily on VOCs to demonstrate competence to undertake high risk tasks.

The MAE Panel regularly discussed the limitations of applying 312 critical controls to a project due to i) A MAE Category (e.g., marine operations) not being associated with the work scope being undertaken on the project or ii) Specific MAE scenarios are not always present during construction activities (e.g., pressure testing). The MAE Panel proposed the design of the Project MAP Risk Profile (Section 3.2.3) as a method to address these limitations.

3.3.2.4 Design of MAP Verification Checklists

The use of safety checklists provides a systematic method for application by workers and reduces errors due to oversight (Hale & Borys, 2013; Hopkins, 2011b) or gaps in hazard recognition (Albert, et al., 2020; Bahn, 2013; Carter & Smith, 2006). Clear, concise, and relevant rules in the form of a checklist provide a structured method to test critical controls in the workplace. The acceptance and adherence to the Critical Controls practices and application of the checklists by the supervisors and workforce is determined by their safety attitude (Langford et al., 2000; Loosemore & Malouf, 2019), which is shaped by the emotional and cognitive engagement of workforce applying the safety practice (Rich et al., 2010; Wachter & Yorio, 2014).

The objective in designing the MAP Checklists was to translate the Critical Control 'rule' statements into a format that can be applied by line supervision in the field, evoke emotional engagement of the workforce, provide context of importance. A standard MAP Checklist was developed for each MAE Category for use on relevant construction activities. The MAP Checks were drafted as objective [outcome] based standards to be achieved without specifying the 'method' avoiding the pitfalls Dekker (2014) recognized which constrain cognitive solutions or innovation in response to dynamic construction environments. The MAP Checklists convert the Critical Controls identified through the MAE bow-tie risk analysis into field verification activities against specified control standards.

In discussion with the MAE Panel of experts the MAP Checklists included the 'cause and effect' pathways with preventative and mitigative controls. The MAP Checklist primary feature was the bowtie visualization which documented the threat pathways with the specified control statements easily interpreted – defining what was important. The second feature was summarizing analogue (serious injury / fatality) events providing description of previous events, causes and application of critical controls – defining 'why' critical controls are important. The third feature was guidance on 'how' supervisors could verify the critical controls were implemented and effective in the field – how to be effective when conducting the MAP Check verifications an example of a MAP Check is provided in Appendix E

The MAP checklists were implemented in the pilot project (Section 3.3) and revised based on interactive feedback with supervisors during coaching sessions or the MAP check review workshops.

3.2.3 Defining Organisational Principles for implementation of the MAP Program

A two-hour engagement workshop was held with 14 Senior Managers (CEO, Executive Management Team, and Project Manager from pilot project) to understand their perception of risk and obtain consensus on implementation principles. Questions on who owns the fatality risk; can it be delegated and how; what ALARP is (i.e., number critical control required); how frequently MAP checks should be completed; and were exceptions allowed, were discussed, and used to form the principles and used to design the implementation plan of the pilot program.

The engagement workshops resulted in the MAP Principles which would subsequently be used in the implementation of MAP in the field and incorporated into the MAP training:

- Fatality Risks and therefore MAP and CCs are owned by the CEO who remains accountable however responsibility to ensure MAP is operating is delegated to General Operating Managers and Project Managers
- MAP is an operational leader responsibility with MAP checks to be conducted by site supervision who directly control high risk work tasks.
- Stop Work is mandatory where a CC is identified as not being implemented – a CC directly prevents release of fatal energy so in the absence of the CC a fatal potentially will occur.
- Deviation from a defined CC is not acceptable without prior authorization from the General Operating Manager.
- MAP is an assurance program requiring MAP Checks to be completed for each MAE Hazard present on a project every month. (i.e., 20 MAE's identified on Risk Profile = minimum of 20 MAP Checks).

Project management and safety professionals are responsible for ensuring the quality of MAP checks is maintained.

3.2.4 *Developing the Project Risk Profile*

3.2.4.1 Defining the Project Risk Profile

Construction risks change throughout the project lifecycle as the work activities move from earthworks, through the installation of footings and foundations in preparation for steelwork and piping installation prior to fitting electrical, instrumentation and control systems of the facility. Pre-commissioning and commissioning activities further change the project risk as systems are energized whilst plant and infrastructure are still being installed (Figure 10). The workforce which undertakes these various stages of construction also change regularly as the trades and skills required transition through the project. Therefore, the workforce is in a frequent state of change, as crews mobilize and demobilize as each work scope is executed (Figure 10).

The MAP model considers how to consistently apply Critical Control verifications which were relevant to the construction activities throughout the project lifecycle.

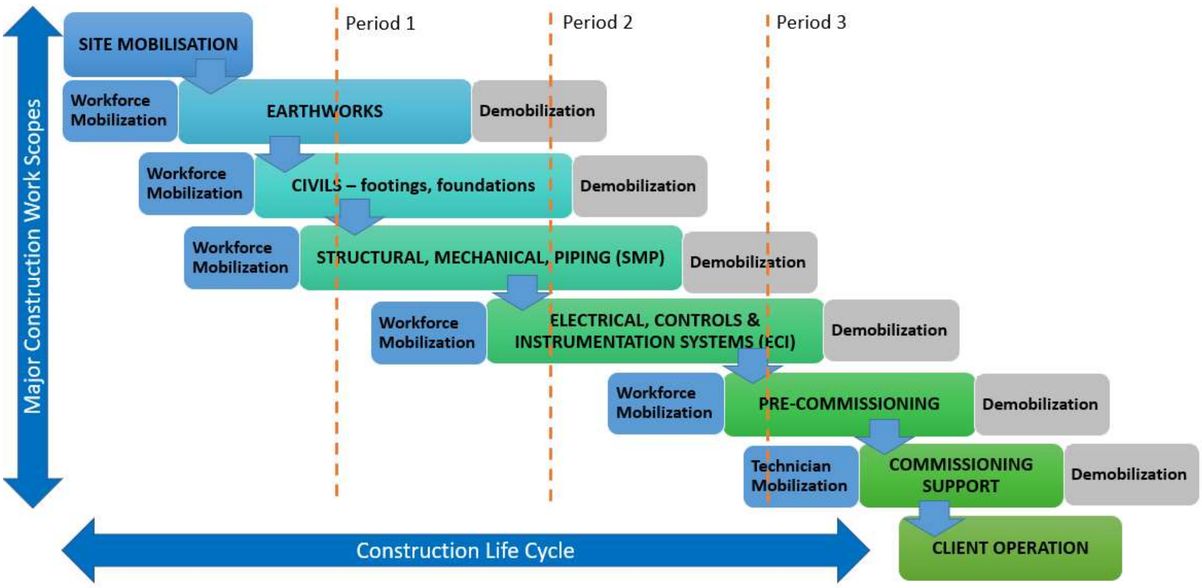

Figure 10: Construction Project Life Cycle – Post Mobilisation [5]

The MAP model applies a Project Risk Profile Matrix to define the specific MAEs and hazards which need to be addressed at a point in time during the project lifecycle in response to the dynamic construction environment.

[5] Adapted from Luo, L., He, Q., Jaselskis, E. J., & Xie, J. (2017). Construction Project Complexity: Research Trends and Implications. *Journal of Construction Engineering and Management*, *143*(7), 04017019. https://doi.org/doi:10.1061/(ASCE)CO.1943-7862.0001306

The Risk Profile has two components, MAE hazard scenarios and Activities (construction scopes of work) which are presented as a matrix and mapped based on the project contract scope of work. A sample of ten diverse construction projects (i.e., jetty, material offload facilities, offshore hookup & commissioning, infrastructure bridges / rail, power station, water processing & dam refurbishment, gas / chemical plants) from 3 companies were selected and using the third level construction schedule collated the work activities for MAE assessment. The MAE Panel of experts (construction & commissioning managers, safety engineer, earthwork, civil, mechanical, electrical, instrument supervisors and safety advisors) systematically assessed each scope of work to:

I. identify which MAE applied to the work package; and
II. consolidate third level construction work scopes into clearly defined Construction Activities (Appendix B).

The result was a consolidated matrix of ten Construction Activities mapped to 40 identified MAE hazard scenarios (Appendix D). The Risk Profile was tested across five active projects where the project manager, construction and engineering manager and safety advisor assessed the project's current work activities using the matrix to identify the MAE's applicable to existing work scopes. Feedback from the project review identified clear concise Construction Activity definitions were required to support the Risk Profile (Appendix D).

3.2.5 Design of Supervisor and Team Critical Control Verification Competence

The target audience for MAP is the line management (project and construction managers) and direct supervision (construction superintendents, supervisors / foreman) as they control the work practices. The design of the training and competency program considered project, organizational, practical, and motivational factors which reduce the effectiveness of training (Tezel et al., 2021). Supervision and workers were trained and coached to be in the application of the critical control's verifications. The training sessions were experiential using case studies in team groups and included in field MAP check verifications in facilitated coaching to improve understanding and transference of theoretical learning into practice (Demirkesen & Arditi, 2015). A series of operational tools were developed to train personnel and monitor the effectiveness of the controls:

- Training – a 2.5-hour theory session on MAP program, context for MAP (fundamental rules) and how to apply the MAP verification checks and assurance reviews.
- MAE Hazard Verification Checklists (MAP Checks) – checklists comprising i) MAE Bowtie including hazard, preventative and mitigative CC's (what it is being checked); ii) Analogous incidents – synopsis of similar historic fatality events (why is the MAE

important) and iii) verification checklist (guidance on how to conduct the CC verification).

- MAE Hazard Assurance Reviews (MAP Assurance) – process for conducting and recording the MAP assurance using completed MAP checks.

Feedback on the training program was sought through feedback forms and discussion with participants during training sessions whilst conducting the case study. The feedback was used to define the MAP Check Principles (Section 3.2.5).

3.2.6 Field Verification and MAP Check Principles

Field verification was designed to be conducted by Supervisors of work crews undertaking high risk activities. Supervisors know the work methods, understand the hazards and are in the field enabling 'immediate' action to stop work when controls are not implemented or effective.

The 'stop work' assumption is known to be impacted by organisation factors affecting supervisor decision to stop work, including lack of clarity in the control specifications (Hayes, 2012), deferring the stop work decision as it would not be supported by senior management (Hayes, 2012), normalisation of known hazards and risks (Reason, 2016). To counter these factors the following foundation principles for MAP checks were defined:

- Stop Work is mandatory, supervisors are **authorized** and **obligated** to stop work where a CC is identified as not being implemented or effective.
- MAP Checks were limited to a monthly assurance frequency – one verification of each MAE Hazard applicable to the project during the month as a minimum to ensure Critical Control standard were maintained, whilst minimizing complacency due to normalization of risk by supervisors.

Communication of the MAP Check Principles was incorporated into the MAP implementation process in the senior management alignment workshop and project specific training program.

3.2.7 Measuring MAP Performance

3.2.7.1 Monitoring –Performance Measurements

The MAP program manages fatality risk through the application of risk planning processes and the verification of identified CC's. CC performance is characterised by the reliability of the control, i.e., the degree to which the CC is implemented and effective (Hassall et al., 2015). The performance measures for MAP were selected to monitor risk planning, application of verification process and the results of the CC verifications.

A system of collecting and collating data to monitor the following performance indicators was applied:

- Risk planning: - completion of monthly MAP Risk Profile
- Participation rates:
  - Planned MAP checks versus actual conducted in the period (weekly).
  - Planned MAP assurance reviews versus actual conducted in the period (weekly).
- Risk exposure: Critical controls failure rate – number of controls failed / controls applied.

3.2.7.2 Lessons Learned

Where a CC "failed" either through not being implemented, or when implemented not effective in preventing the potentially fatal energy being released, the construction panel reviewed the relevant MAE Bow Tie and either improved the Critical Control specification or added a Critical Control if there was a gap in the threat pathways. The amended Critical Controls were then validated through field testing. This feedback continuous improvement process was termed "Lessons Learned" and it ensured the identified improvements were updated in the CC verification checklists and re-issued for use, which locked in the changes for the next time to verification was conducted.

3.3 Pilot Study

To validate the 6 step MAP program a Pilot Study was conducted to:

- Test and verify the MAP tools (MAP Risk Profile, MAP Verification Checklists) on a project across different work scopes.
- Implement MAP alignment sessions and training to refine the training requirements and material.
- Explore the contribution MAP has on the safety performance of the project and the relationship with other risk assessment practices.

The MAP program pilot implementation was conducted at an Australian construction site managed by a global construction company (Table 9). The pilot program commenced 4 weeks prior to site mobilization with the MAP risk profile workshop (Step 2), and training (Step 3) commencing 1 week after mobilization. Field verification (Step 4) commenced 4 weeks after supervisors were competent in the CC verification process.

The Pilot Study ran for eighteen months, finishing prior to the start of pre-commissioning works.

Table 9: Project Details

Project Parameters	Details
Location	Perth - Western Australia
Scope	Infrastructure: all process and ancillary buildings Process plant: wastewater treatment facility, bore field, pipelines, discharge lines
Contract Model	Design, Procure, Construct & Commission
Contract Structure	Joint Venture Principal Contractor – self perform with specialist subcontractors
Workhours	634,700 with 220 persons on site at peak
Duration	Total: 32 months. On site: 20 months

3.3.1 Measuring MAP Contribution to Safety Performance – Data Analysis

Application of the MAP program was in addition to existing risk assessment and hazard management practices.

The relationship between MAP and existing risk practices was explored to understand the potential contribution MAP had in preventing incident events (Table 10). The lead and lag variables were normalized by adapting Salas and Hallowell (2016) hours worked metric. Normalisation of data is important to manage the risk of comparing data with different units.

The data was analysed using R statistical package (R Core Team, 2020) applying exploratory analysis steps to understand the relationships and strength of relationships between variables (Hyndman & Athanasopoulos, 2018). Exploration of the data was conducted using correlations between the variables, principal component analysis (PCA) applied across the safety performance variables listed in Table 10.

The time series variables were tested for stationarity using the Kwiatkowsski, Phillips, Schmidt & Shin (KPPS) test. Non-stational data needs to be transformed prior to conducting regression analysis or modelling to avoid spurious results being generated (Hyndman & Athanasopoulos, 2018). Logarithmic and average mean differences transformation processes were applied to the data and retested for stationarity.

Table 10: Safety Performance Leading and Lagging Metrics and Variables

Proactive Metric	Code	Measurement	Variable type
Total recordable incident rate	TRIR	Multiplying the number of recordable injuries in a month by 200,000 / hours worked in the month	Response
Restricted Duties incident rate	RDIF	Multiplying the number of restricted duties injuries in a month by 200,000 / hours worked in the month	Not included
First Aid Injury rate	FAI_FR	Multiplying the number of first aid injuries in a month by 200,000 / hours worked in the month	Response
All injury incident rate	ALLINJ_FR	Multiplying the total number of injuries in a month by 200,000 / hours worked in the month	Response
No treatment injury rate	NO_TREAT_FR	Multiplying the total number of no treatment injuries in a month by 200,000 / hours worked in the month	Not included
All incident rate	ALLINC_FR	Multiplying the number of incident events in a month by 200,000 / hours worked in the month	Response
Supervisor Observation	SOI-FR	Multiplying the number of Supervisor observation & interventions by 200,000 / hours working in a month	Explanatory
Stop Work Authority	SWA_FR	Multiplying the number of Stop Work Authority events by 200,000 / hours working in a month	Explanatory
Hazard Report	HAZREP_FR	Multiplying the number of Hazard reports by 200,000 / hours working in a month	Explanatory
Personal Risk Assessment	PRA_FR	Multiplying the number of personal risk assessments by 200,000 / hours working in a month	Explanatory
MAP Check Rate	MAPCH	Multiplying the number of MAP Checks by 200,000 / hours working in a month	Explanatory
MAP Assurance Rate	MAPAs	Multiplying the number of MAP Assurance reviews by 200,000 / hours working in a month	Explanatory

3.4 Results

3.4.1 Step 1 & 2: Defining Project Critical Controls through the Risk Profile

The pilot study conducted the Risk Profile workshop to determine which MAE risks applied as a baseline to the entire project scope. During the workshop the participants identified areas where the team were not clear on the construction methodology, battery limits (boundaries) for tie-ins to existing client plant and where changes in design would impact construction sequencing. The risk profile review also enabled all participants to clarify work scope or construction and / or commissioning requirements which were not well understood.

A total of 8 construction activities were identified with a total of 24 MAE risks associated with the project baseline scope of work (Appendix D). Eleven months into the project an additional MAE risk, Confined Space – Working within a Contaminated Atmosphere, was added to the risk profile as the project started to work in sealed vessels. During the project timeline the risk profile changed with focus on specific MAE hazards and verifications per MAE hazard increasing and waning associated with the high-risk activities and overall number of active work fronts (Figure 11). For example, the increase in May 2018 in the WAH (Working at Heights) was due to the facility building roofing task, resulting in additional MAP checks.

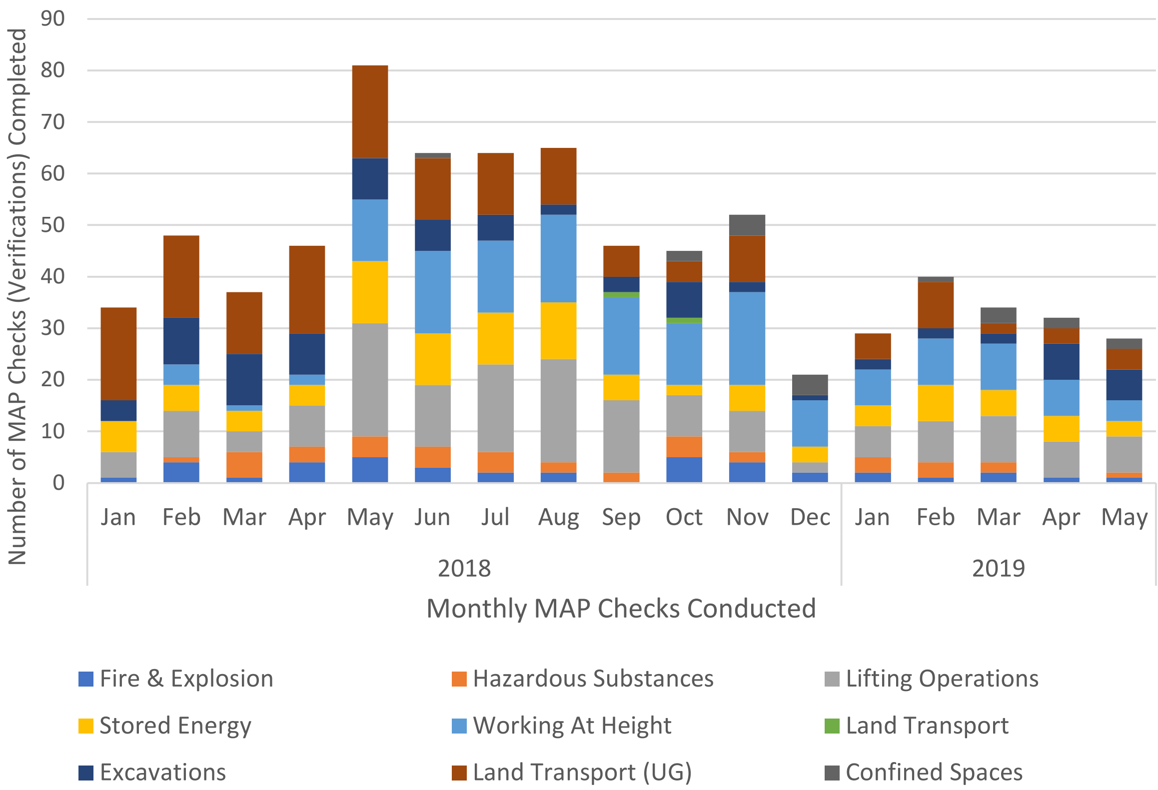

Figure 11: MAP Checks Completed by MAE Hazard Category

3.4.2 Step 3: Supervisor Competency

The project implementation was conducted across 18 months, and included 10 training sessions for supervisors, 3 senior leadership workshops, 1 with the company executives and 2 with senior project and subcontractor managers. A series of sessions (10) were held over four weeks to test, review, and clarify CC statements. A total of 58 MAP Checks were completed covering Land Transport, Excavation, Hot Works, Lifting Operations, Stored Energy and Working at Height MAE Hazard categories. The case study team after the initial 4-week training and testing period were able to apply CCs to the work site, analyse and respond to CC criteria.

3.4.3 Step 4: Field Verifications

A total of 766 MAP Checks were conducted in the 18 months of the Pilot Study with 281 MAP (37%) assurance reviews completed by the project line management. The most common MAP checks were conducted for Land Transport and Working at Height hazards, with Confined Space Entry being the more prevalent in the second half of the project after the vessels and other tanks were installed on site (Figure 12). MAP checks were completed in the month they were planned except where the high-risk activity did not occur due to a change in work scope or schedule. In four instances the monthly Risk Profile was revised during the month due to changes in work scope identified additional high-risk activities not previously planned. Changing the Risk Profile identified additional MAP Checks required to be conducted during the month to verify the additional CCs relative to the new hazards as discussed in Section 6.1.

MAP checks were conducted across 6 construction activities (work scopes) with Land Transport and Lifting Operation hazards for logistics activities (Activity 1) having the highest number of MAP checks completed followed by Structural, Mechanical & Piping (Activity 4) activities focusing on Lifting Operations and Working at Height hazards, Figure 12.

"Strike Live Services" (EXC-001) was the most common MAP check conducted and expected given the project was adjacent to an operating facility and located in an urban environment. "Fall of Ground" (EXC-004) was used in the early months of the project where deep excavations required ground support system and were fully compliant. Similarly Unsafe Atmosphere in Excavation (EXC-003) was applied during the commissioning phase of the project where gases and fumes generated from commissioning activities had the potential to accumulate in excavations

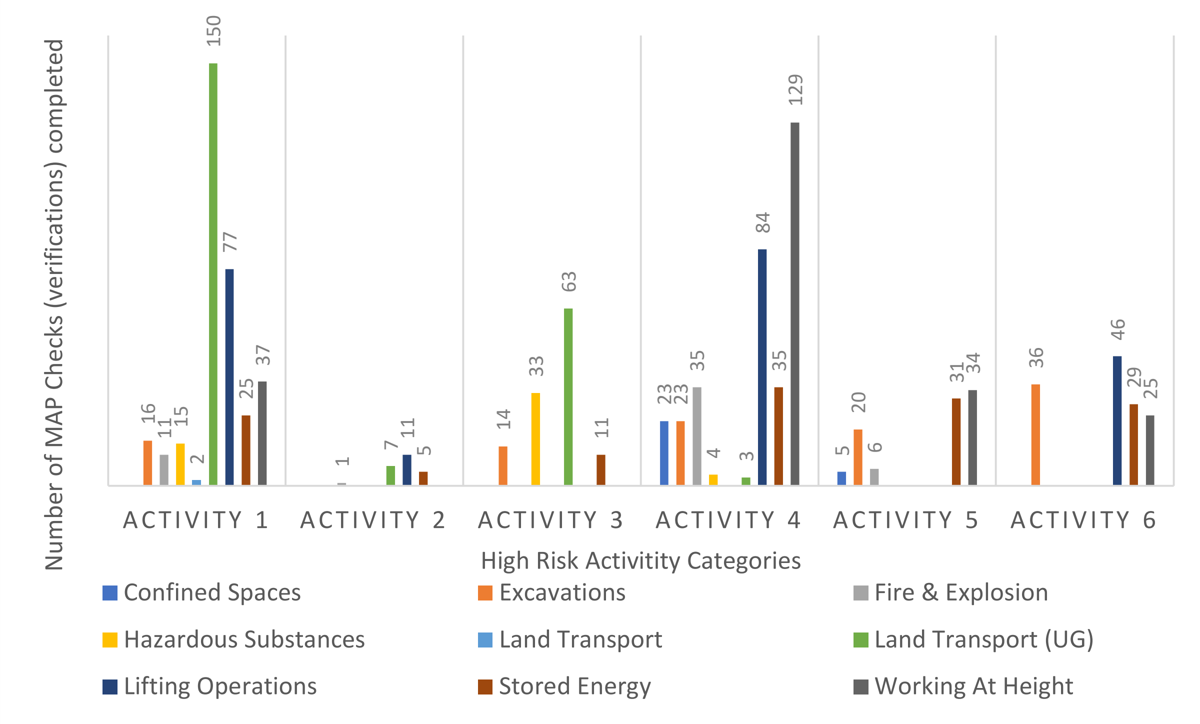

Figure 12: MAP Checks by Activity for Duration of Case Study

3.4.5 Step 5: Monitoring

An assessment of compliance rate for MAP checks critical control implementation was conducted for Excavation MAE hazards calculated as:

Equation 1

$$\text{Average compliance rate} = \frac{\text{compliant CC's documented per MAE hazard for the period} \times 100}{\text{number CC checked per MAE hazard for the period}} \quad (1)$$

A total of 84 hard copy excavation activity MAP checks were assessed to check for non-compliance of the critical control when the MAP check was conducted with an average compliance rate calculated monthly for each of the excavation related MAE hazards (Figure 13). Compliance rates measured between 80% (EXC-001) to 100% (EXC-003 & EXC-004) with an average compliance rate of 93%. Overall, for excavation related high risk activities a total of 58 (7%) non-compliant critical controls were identified through the MAP check process throughout the project. Data on Stop Work Authority (SWA) due to CC non-compliance was not captured during the study.

Further investigation is required to understand why Critical Controls were not implemented or effective when assessed in the field.

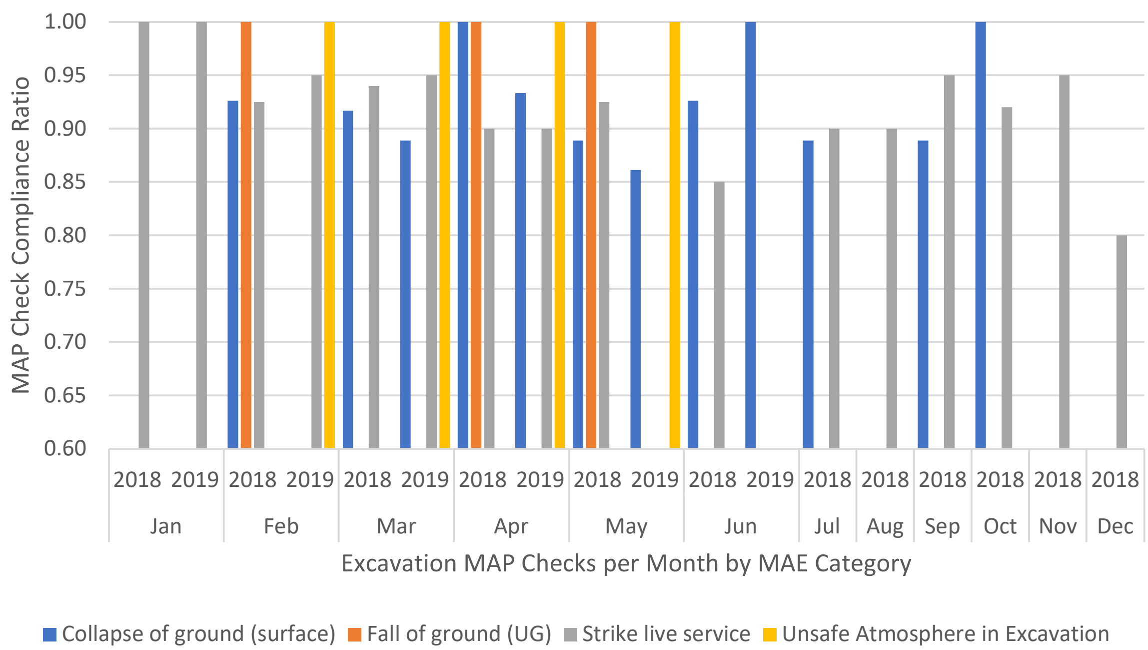

Figure 13: Excavation Activities - MAE's Critical Control Compliance Rate

3.4.6 Step 6: Lessons Learned

The project did not have any potential MAE events during the period of the trial, however incident alerts for potential and actual MAE's circulated through construction associations and regulators, were monitored by the researcher and project HSE professionals to identify is any were applicable to the project. One event, tramming a piling rig under power lines, was evaluated, and compared to Strike Live Services MAE hazard and CC's and identified a gap in the MAP model. The research SME's and project management and HSE professionals reviewed the "Strike Live Services" MAE Hazard and CC's and included power lines into the MAP check, which was particularly relevant to the project which had a HV power line running on the north side of the site.

The change in MAP check was communicated to the site supervisors and was included in the MAP checks from that point on. From identification of a potential new MAE hazard to inclusion in MAP checks occurred within seven days.

3.4.7 MAP Contribution to safety – relationship analysis

Time series plots (Figure 14, Figure 15) of each of the metrics identified increasing trends in hazard reporting rate (HAZREP_FR), and personal risk assessments (PRA_FR) over the duration of the project. The Supervisor Observation and Interventions rate (SOI_FR) and MAP check (MAPCH_FR) rate declined over the duration of the project. Injury related metrics (TRIF, RDIF, MTI_FR, HPI_FR, NO_TREAT_FR) showed intermittent events with most months having a zero value.

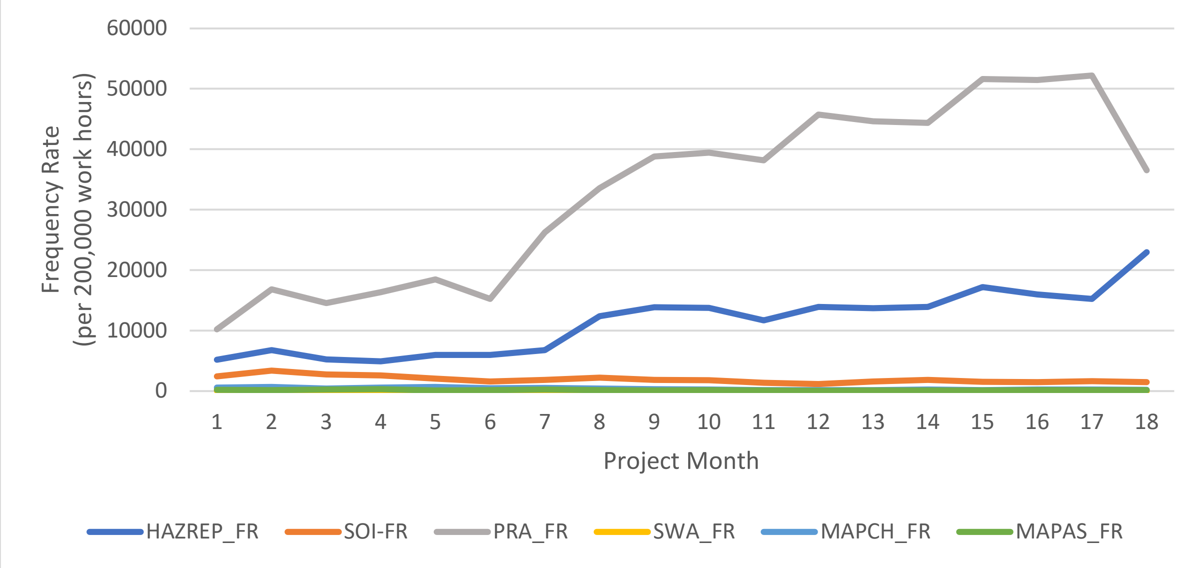

Figure 14: Performance Trends of Project Leading Indicators

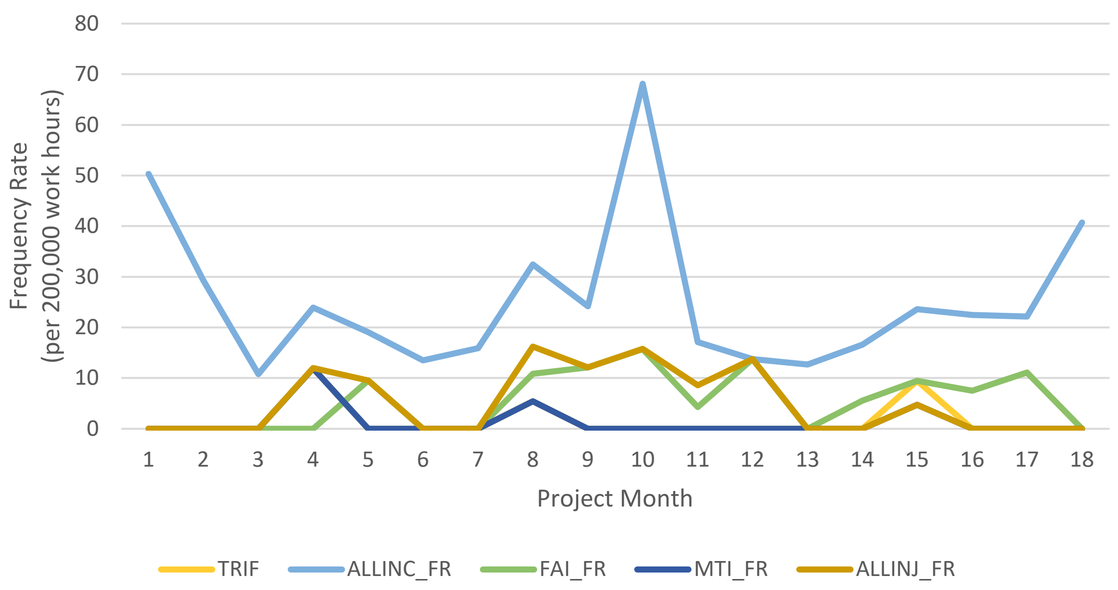

Figure 15: Performance Trends of Project Lagging Indicators

Comparison of the difference between the monthly values for each variable (Figure 16, Figure 17) indicates a decrease in mean difference between values over time for personal risk assessment rate (PRA_FR) and Stop Work Authority rate (SWA_FR). The trend for Supervisor Observation and Interventions rate (SOI_FR), MAP Check rate (MAPCH_FR), MAP Assurance review rate (MAPAS_FR) and All Incident rate show an increase in mean difference in monthly values over time.

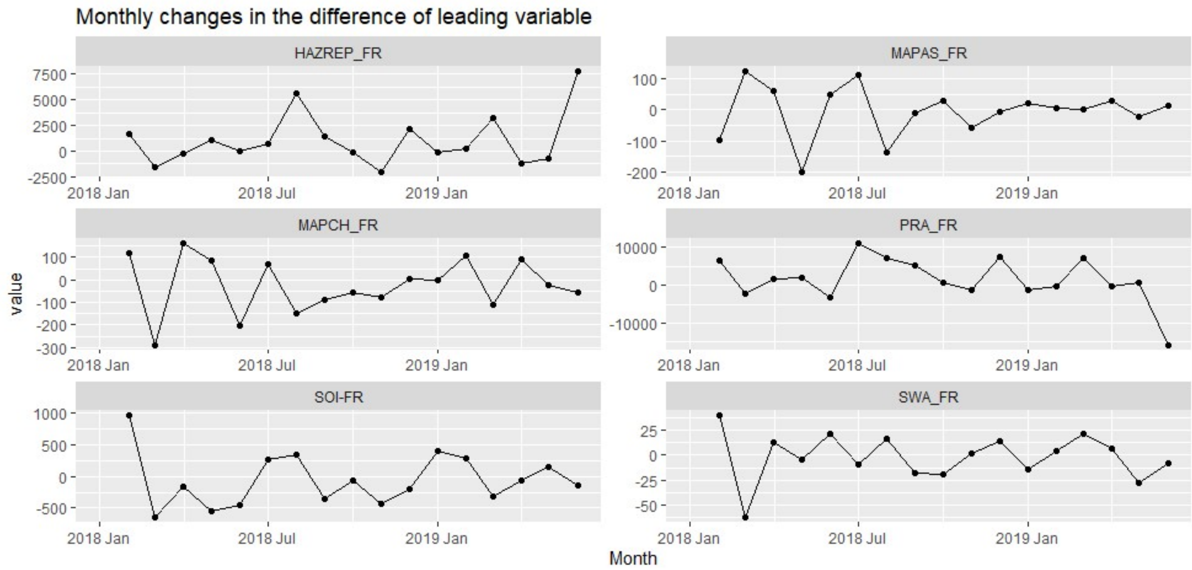

Figure 16: Monthly Changes in the Difference of Each Leading Variable

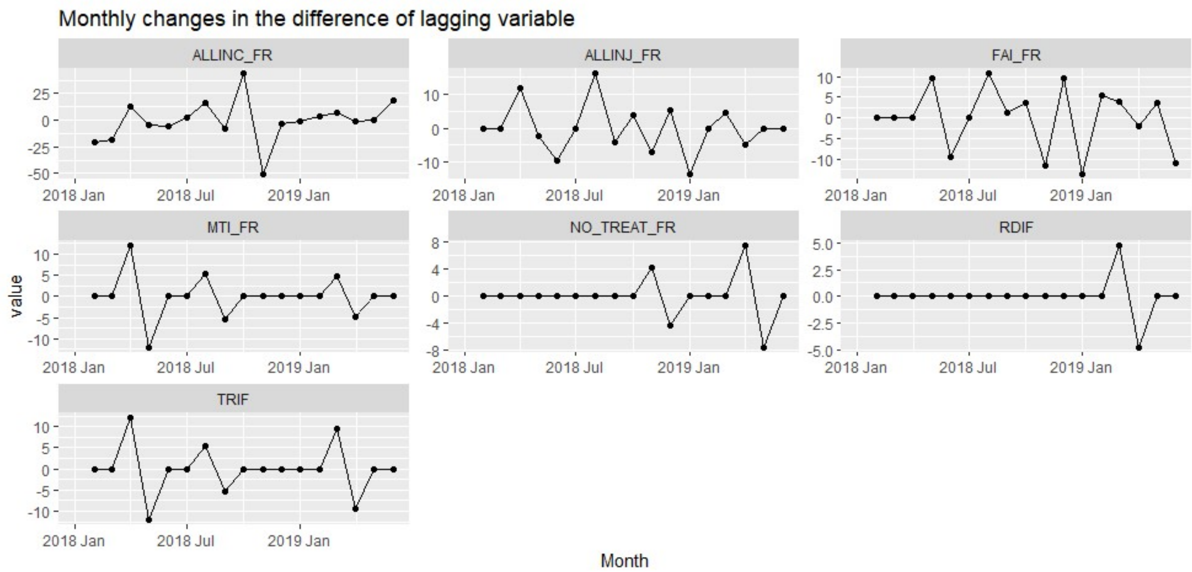

Figure 17: Monthly Changes in the Difference of Each Lagging Variable

The trends in both the time plots and monthly changes in the difference of each value indicate a limited number of variables can be used to describe the safety performance data relationships as confirmed by Principal Component Analysis (PCA). PCA identified 92.4% of the relationships were described by 7 principal components (Table 11). The statistical model was applied across all eleven variables defined in Table 5. The PCA identified the majority of the variation (92.4%) within the model can be attributed to seven variables. Determining the variables and strength of the relationships between variables was modelled through correlation analysis.

Table 11: Principal Component Analysis (PCA) of Safety Performance Series

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Standard Deviation	2.13	1.60	1.26	1.12	1/07	0.99	0.93
Proportion of variance	0.32	0.18	0.11	0.09	0.08	0.07	0.06
Cumulative Proportion	0.324	0.507	0.621	0.710	0.792	0.862	0.924

Correlation analysis (Table 12) was applied to identify variables of interest for regression modelling of two hypotheses:

i. Introduction of MAP contributes to reducing incident events
ii. Introduction of MAP contributes to frontline risk management activities

There were seven variables with statistically significant correlations: FAI_FR, HAZREP_FR, SOI_FR, PRA_FR, MAPCH_FR and MAPAS_FR. The analysis identified moderate to high correlations between time series variables:

- MAP Check rate: HAZREP_FR (-0.830), SOI_FR (0.789), PRA-FR (-0.857);
- Personal Risk Assessment rate (PRA_FR): HAZREP_FR (0.840), SOI_FR (-0.713) and MAPAS_FR (-0.613)

There were weak correlations between the time series variables:

- First Aid Injury: PRA_FR (0.585), MAPAS_FR (-0.528)

The MAP Check rate positively influences (increases) the rate of frontline risk assessment processes (HAZREP_FR, SOI_FR), however has the inverse impact on Personal Risk Assessment (PRA_FR) rate. MAP Check rate did not have a direct impact on injury rates. An increase in the MAP assurance rate (MAPAS_FR) suppressed First Aid Injury rate.

The strong correlation between MTI_FR and TRIF (0.955) was expected as medical treatments are a component of the TRIF measure. A similar relationship was noted between FAI_FR and ALLINJ_FR (0.670) as a first aid injury is a component of all jury frequency rate. Equally conducting Personal Risk Assessments results in the identification of hazards resulting in a strong positive correlation (0.840).

The strong positive relationship between MAP Check rate and SOI_FR (0.857) was expected as supervisors conduct SOIs whilst undertaking MAP Checks to reinforce the critical controls with the team involved. There is not a direct operational relationship within the project which would explain MAP Check positively improving hazard reports rate (0.857), further study is required.

Table 12 Correlation Matrix Across Performance Measures

Correlation matrix showing Pearson's r between safety performance measures											
Safety Performance Variables	**TRIF**	**ALLINC_FR**	**FAI_FR**	**MTI_FR**	**ALLINJ_FR**	**HAZREP_FR**	**SOI_FR**	**PRA_FR**	**SWA_FR**	**MAPCH_FR**	**MAPAS_FR**
TRIF											
ALLINC_FR	0.004										
FAI_FR	0.003	0.250									
MTI_FR	**0.955**	0.016	0.063								
ALLINJ_FR	0.350	0.284	**0.670**	0.408							
HAZREP_FR	0.055	0.179	0.409	0.162	0.031						
SOI_FR	0.168	0.144	0.401	0.255	0.094	**0.645**					
PRA_FR	0.023	0.064	**0.585**	0.140	0.093	**0.840**	**0.713**				
SWA_FR	0.155	0.016	0.077	0.127	0.062	0.251	0.432	0.207			
MAPCH_FR	0.080	0.034	0.410	0.185	0.093	**0.857**	**0.789**	**0.857**	0.465		
MAPAS_FR	0.345	0.066	0.528	0.451	0.143	**0.586**	0.490	**0.612**	0.024	0.530	

NOTE: **Bold text** denotes significant correlation at p=<0.05. Red text denotes negative correlations.

The FAI_FR lagging variable was selected for testing against the leading variable except SWA_FR. All time variables were assessed for stationarity, an assumption of time series regression modelling, using Kwiatkowsski, Phillips, Schmidt & Shin (KPPS) test. With kpsss_pvalues ranging from 0.0157 to 0.1 the data was non-stationary. Transformation methods were applied to the time series data (mean differences, logarithm) in attempts to achieve a stationary data set for modelling, however kpsss_pvalues still failed.

The incident or injury related (TRIR, HPI_FR, MTI_FR, RDIF, No_treat_FR) showed a high proportion of zero incidents in the months with future modelling needing to take into account zero inflation as they tend to be rare events.

Limitations of the data set, (e.g., 18 values per measure, zero inflated values) prevented further regression analysis.

3.5 Discussion

The purpose of the study was to develop a novel Major Accident Prevention program for the construction industry adapted from CCRM and applied using HRO principles to improve effectiveness of fatality risk related controls and safety performance. CCRM assumes a constant state of 'unease' consistent with HRO principles requiring CCs to be proactively verified, a concept needed in the dynamic construction environment. The development of MAP program tools considered the complexity of construction risks and hazard management amidst the dynamic changes which occur in construction projects. The MAP program and practical application of CC field verification which was tested in a pilot study.

The Pilot study increased the level of 'observation' being undertaken by supervisors and provided direct feedback to workers on the expectations of the critical control criteria. Whilst this is a desired outcome of the verification activity, Hawthorne effects due to the novelty of the critical control verification or performance feedback from supervisors may also contributed to safety performance outcomes. The duration of the study was expected to reduce the novelty factor, however further research data and analysis of factors affecting the safety outcomes is required. The duration of the pilot study tested the MAP program throughout the construction phase of the water processing facility project but finished prior to pre-commissioning which was not tested. The MAE's assessed did not cover all construction high-risk activities as construction projects occur in various environments (near shore, marine) and project scopes (e.g., power, infrastructure, mining and / or hydrocarbon processing facilities). Equally the study did not assess various cultural factors (e.g., language, religion, societal structures) and commercial and delivery strategies (e.g., self-perform, subcontractor, joint ventures) which impact construction project MAE risks.

Taking into consideration the limitations of the study several insights can be drawn from this work.

3.5.1 Can a Critical Control Management model be applied to construction?

The study demonstrated the MAP approach can be applied in practice in construction. The steps of the MAP program outlined the process for implementation and provided the system for the project leadership and line supervision to apply the tools. The MAP program was adaptable to the project lifecycle as the CC verification effort changed throughout the project as the work scope (activities) or MAE Risk profile changed.

The MAP program introduced the use of the MAE Risk Profile to identify and assess planned project activities as a monthly look ahead. The MAE Risk Profile was developed to assist in the planning for high-risk task and focus management effort on CCs. The senior project leaders through the MAE Risk Profile workshops commented on the efficiency, structure, and repeatability of the MAE Risk Profile to distil the complexity of the project MAE hazards across high-risk work scopes. The MAE Risk Profile was updated 22 times during the 18-month study taking an average of 35 minutes to complete post the initial baseline session, which was determined to be worthwhile. The outcome of the monthly MAE Risk Profile set the requirements for verification activity on the project. The MAE Risk Profile provided a structure to manage scope changes, as was evident with the inclusion of new MAE risks on four occasions. Managements' use of the MAE Risk Profile enabled the leaders to proactively respond to changes in construction work scope and MAE risks throughout the project lifecycle. The use of the MAE Risk Profile was a fundamental change in the projects risk management effort. Further research is required to determine how the MAE Risk Profile and content of the definitions of construction activities (Appendix A) and MAE risks (Appendix B) can be applied to other projects and construction activities.

Monitoring of individual CC compliance was achieved through verification process undertaken by supervision, which enabled the site teams to rectify the control prior to continuing the work. However, as a verification process and not conducted every time a high-risk task is completed the program does not comprehensively identify all CC non-compliance which may occur on the project. The compliance rate measured for Excavation activities remained variable for two of the four related MAE scenarios (EXC-001 Strike Live Services, EXC-002 Collapse of Ground) throughout the project indicating further work is required to understand other factors (e.g., transition of work to new subcontractor teams) which affect the desired performance.

The MAP implementation methodology included a series of engagement sessions involving executive and senior managers, project managers and line supervision. The executive and senior manager workshop set the MAP principles (organisational rules) for implementing the MAP program within the organisation and the study project. During the workshops, the most contentious MAP Principles was the reallocation of the "stop work" decision from project management to frontline supervisors. Project Managers who solely made the "stop work" decisions previously, argued that as they understood the work schedule, they were informed to make stop work decisions. However, executive leaders who referred to the definition of a Critical Control, deemed that the frontline supervision were authorised to stop work when CCs were not implemented, or found to be ineffective.

The organisational change which delegated the frontline supervisor's authority to stop work represented an organisational shift of power to rule-orientated leadership being exercised by frontline supervision. Hayes (2012) identified frontline supervisors with clear rules [specified controls] delineating compliance requirements are more likely to act [stop work] provided the actions are supported by managers, was evident through the MAP Check records for the duration of the study. Further work is needed to determine the degree by which the shift in stop work authority was derived from the specification of the CCs, increased monitoring of

CCs through MAP checks and supervisor engagements or as the result of the increase in oversight through the quality control MAP Reviews.

Grill and Nielsen (Grill & Nielsen, 2019) identified in the construction industry, rule orientated leadership has a positive effect on safety outcomes where the workers are involved in the decision-making process. The strong positive correlation [r= 0.789] between MAP checks and SOIs indicated supervisor engagement with work team members occurred when MAP checks were being conducted. It remains unclear if the SOIs conducted were effective in preventing incident events or raising awareness on MAE hazards across the workforce requiring further research to explore the correlation between MAE, SOI, and impact on safety performance.

3.5.2 Has MAP improved safety performance?

The Pilot Study project did not have any MAE events and no significant correlation between CC verification and MAE's events was identified.

The high correlation between MAP Check rate and frontline risk assessment processes (HAZOB, SOI) indicates MAP Checks contribute to improving the rate of frontline hazard identification and control. The confounding factor is the negative influence MAP Checks had on Personal Risk Assessment (PRA_FR). PRAs are personal task-based hazard assessment conducted by individual workers prior to commencing the task. Verification of Critical Controls managed by a personal safety CCRM program are common contributory factors in lower consequence events (Bellamy, 2015). By applying MAP Checks line supervisors also verified the common controls which prevented minor injuries and incidents.

MAP Checks are supervisor led and include interactions with their work team to conduct verifications which potentially replaces individual task risk assessments and reducing the rate of PRA's being recorded. It is unclear if the relationship between MAP_CH and PRA rates is due to changes in the criteria for completion of PRAs on the project, limitations due to the size of the data sample or another factor. Further research is required to explore the MAP, existing risk programs (PRA, HAZOB, SOI) relationship on safety performance.

The premise in developing the MAP program is through systematic identification of MAE hazards and application of CCs with specific 'control limits' will result in improved risk-based decision making within a project and reduce incidents, particularly MAEs (Grill et al., 2017). Apart from the weak correlation between first aid injuries and MAP Assurance rate [r= -0.589] it was unclear if implementation of MAP in the case study reduced the frequency of incident events.

Measuring construction safety performance given the decentralised organisation structure is complex (Woolley et al., 2020) as leading indicators are inter-related and not always directly related to lagging indicators of incident or injury performance (Lingard et al., 2017; Shohet et al., 2018). Analysis of the case study data indicated MAP verifications improve hazard identification by increasing the rate of other frontline risk assessments, however provided limited information on incident prevention. Further investigation is required to explore the relationship between MAP Checks, risk management processes and incident prevention.

3.5.3 Observations to improve MAP implementation within an organization.

The MAP program used multiple design principles to mitigate an overly complex CCM program including aggregation of MAEs with same CCs (as applied in the mining industry), evaluation of controls applying the ICMM (International Council on Mining and Metals (ICMM), 2015) control definitions, application of the monthly risk profile and verification of CCs as an 'audit' not a task-based activity.

The MAE Risk Profile process within the MAP program provided detailed identification of the MAE risk exposures when planning future works, ensuring all potential MAE exposures were identified and directly linked to the planned high-risk activities. The MAE Risk Profile focussed project management on MAE risks which prescribed the verification effort and resources required to validate CC implementation and effectiveness. The Risk Profile process minimised the 'randomness' of the CC verifications being conducted within a month and provided the organisation assurance CCs for the identified MAE hazards had been assessed. The flexibility of the Risk Profile process enabled project management to re-assess MAE risks when project scope changed and promptly commence CC verification for newly identified MAE hazards as part of the assurance program.

The effectiveness of the CCs from the sample tested identified with 7% being non-compliant indicates further understanding of factors affecting CC implementation and control standard when implemented is needed.

The organisational framework within which MAP is implemented needs to be clearly defined and agreed to by senior executives of the organization. The MAP Principles were developed by the organization involved in the case study, however, may not be applied universally across the construction industry and need to be validated and agreed prior to any implementation. Decisions on who owns the fatality risk, what is ALARP for the organization and how will MAP checks be applied and recorded will be required and then communicated by executive leaders to set up the program for success. Equally, as the risk is owned by line management the MAP program needed to be owned and implemented by line managers who were accountable for the training and application of MAP Checks and assurance activities in the field.

Major Accident Event hazards whilst defined in the MAP model need to be reviewed against an organization's operational risks which change with different scopes. Similarly, the Critical Controls defined within MAP need to be adapted to the organizational and regulatory standards and cultural differences including language.

The case study applied limited training in the MAP program, and it was identified an intensive program of in field coaching on the Critical Controls and verification requirements was needed initially and then repeated when new contractors or supervisors joined the project. Experiential, in-field training, and coaching was the most effective which is consistent with previous research (Tezel et al., 2021). Investing in the training and building of competency of the construction superintendents enabled in field coaching of supervisors whilst MAP assurance reviews were undertaken, building in efficient use of resources and improved competency across supervisors.

Every incident involving a MAE hazard is an opportunity to test if the Critical Controls have been implemented or were effective and if not understand why to improve either the application or identify if the control needs to be improved. Organizations adopting MAP would benefit from integrating CC analysis and a review of the MAE hazard bow tie as part of the incident investigation system and refinement of CC requirements from the investigations.

3.5 Conclusion

The Major Accident Prevention (MAP) program is an alternative risk based Critical Control Risk Management (CCRM) model and implementation methodology. It was shown to effectively manage construction MAE hazards through rules-based critical control management applied using high reliability organisational principles.

The MAE risk profiling process MAP adapted well to the dynamic construction environment and provided a practical platform to update MAE risks and management of Critical Control (CC) field verifications.

The MAP program provided a practical solution to manage a complex interface of high-risk tasks by limiting the number of controls and improving the specificity of control statements. The process of defining CCs for each MAE hazard reduced the overall number and complexity of controls front line leaders needed to focus their attention on.

The specificity of the CC statements aided front line leaders and supervisors to quickly assess if the CC was implemented as designed and within control tolerance limits. This resulted in the efficient assessment of CCs for high-risk tasks across multiple MAE hazards.

Supervisors were able to plan and prepare for high-risk work as part of the standard pre-work activities reinforced using the MAE verification as a communication tool during pre-task risk reviews to raise awareness of the MAE hazards and the CCs.

The MAP program resulted in a shift in decision making authority from executive to front line leaders by mandating frontline leaders were fully authorised and required to ‘stop work’ when CCs were not implemented or effective. The shift in decision making authority together with the comprehensive training in CC specifications increased the confidence of frontline leaders to manage high risk activities and act to ‘stop work’ in the absence of CCs. The organisational impact of the shift in decision making authority was not investigated in the study, with further research required to understand how MAP and CC ‘stop work’ impacts safety leadership and project safety climate within a construction organisation.

The MAP program does not operate in isolation to existing construction risk management processes, and in the absence of MAE events on the pilot project was found to enhance field risk management programs (i.e., hazard reporting, supervisor engagements) and has a relationship in reducing first aid events. The PCA and correlation analysis identified FAI-FR as the only lagging measure of safety performance which was affected by the leading risk management activities of PRAs and MAP Assurance review frequency rates. The Hazard Reporting (HAZREP) frequency rate was most sensitive of the leading measures with effects identified across SOIs, PRAs, MAP checks and MAP Assurance activities. The inter-relationship between MAP and other risk management programs used in construction organisations was both positive and perplexing as MAP contributed to higher frequency of some activities but depressed the use of personal risk assessments by work team members.

The MAP program will benefit construction organisation willing to adopt a CCRM approach to managing fatality risks. The MAE risk profiling process efficiently review high risk work and is supported by practical application through field verification of CCs. Further understanding is required on the human factors affecting CC reliability and how the MAE model will respond to changing construction methodologies? Equally getting the CC’s ‘right’ and the relationship the MAP program has on safety performance and performance of existing risk management processes needs further study.

CHAPTER 4. DETERMINING THE RELIABILITY OF CRITICAL CONTROLS IN CONSTRUCTION PROJECTS

Chapter 4 has been published as:

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4.1 Introduction

Accident prevention research has identified complex models of accident causation (Zhang et al., 2019), identifying multiple factors and numerous safety controls (Li & Guldenmund, 2018; Mohammadi et al., 2018) to prevent incidents from recurring. However, within the construction industry, serious and fatal incidents continue to result from recurring causes (Safe Work Australia, 2020). Construction industry fatalities result from high-risk work activities (e.g., operating heavy plant machinery, lifting using cranes, working at height (Betsis et al., 2019)), where the interaction between human factors and the activity gives rise to personal safety related fatalities. Equally, construction risk management strategies designed to prevent fatality events (e.g., Life Saving Rules) have relied on human action and interventions to identify hazards, assess risks, and then treat the risk by defining and applying controls in the workplace (Grattan, 2018; Kang et al., 2016).

Human actions and interventions can introduce errors through variability in hazard identification and assessment within dynamic construction environments (Carter & Smith, 2006; Perlman et al., 2014b), with workers identifying, on average, only 53% of fatal hazards in the workplace (Albertet al., 2020). In addition, human factors affect the compliance to critical controls (Petitta et al., 2017b), risk tolerance (Hopkins, 2011b) and decision making (Hayes, 2012), all of which influence the efficacy of control implementation and effectiveness. Selleck and Cattani (2019) proposed the construction industry focus on risk treatment and applying a critical control approach to prevent fatalities and to learn from similar programs being applied to process safety in the oil and gas or mining industries. Critical Controls (CCs) are specific safety barriers, which (i) directly prevent the unplanned release of energy, which cause major accident events, (ii) directly prevent the escalation of event consequences or (iii) are unique controls within an event pathway.

The concept of safety barriers as a method of preventing and mitigating unwanted events has been used extensively to identify the controls needed to address event causes and consequences (Swuste et al., 2016). The bowtie method is often used to facilitate the identification of controls for an unwanted event. The bowtie method was developed by joining fault tree and event tree (cause and consequences) surrounding an unwanted event (Nielsen et al., 1975). The bowtie method has been used extensively in the aviation, nuclear, oil and gas and chemical processing facilities to assess potential failure modes and quantify the adequacy of controls to prevent accidents through risk assessment estimation techniques (Bellamy, 2015; Dodshon & Hassall, 2017; Grattan, 2018). The process industries have an established practice of identifying barriers as independent protection layers, with a preference for hardware and technology reliability as barrier controls over human reliability. The barriers are perceived as discrete onion-like layers, formed by mechanical devices, instruments, alarms, administrative controls, and post-release mitigation measures, all acting independently (Grattan, 2018). However, an underlying factor is the influence of human action and organizational factors, which affect the reliability of the barrier (Grattan, 2018; Li et al., 2020; Størseth et al., 2014; Winge & Albrechtsen, 2018).

The reliability of control barriers is influenced by organizational psychological mechanisms, such as confirmation bias, normalization of warnings, consensus mode decision-making and group think, which occurs within work teams and across organizations (Størseth et al., 2014). Reliability of barriers is also affected by human factors (e.g., competence) and human actions in the detection of threats or changes in barrier functionality, diagnose what action is required and then act (Li et al., 2020; Nnaji & Karakhan, 2020; Winge & Albrechtsen, 2018). Construction accident causation analysis (Winge, et al., 2019) identified worker actions are heavily influenced by supervision and risk management through planning and risk control at different levels across the organization, emphasizing the need for a holistic approach to managing fatal risks and the use of barriers.

The safety barrier methodology has been applied in the mining industry through Critical Control Risk Management (CCRM). CCRM is focused on risk treatment by specifying and verifying the implementation and effectiveness of critical controls (barriers) in a model addressing organizational and inherent human factors using the principals of High-Reliability Organizations (Hassall et al., 2015; Hassall & Joy, 2016; ICMM, 2015). An adaptation of CCRM was piloted on an Australian construction project (Selleck et al., 2023a); however, further understanding of Critical Control reliability was identified.

For construction organizations to invest in the development and implementation of a safety barrier approach such as CCRM, organizational leaders who are accountable for fatality prevention will need assurance that the controls being defined will prevent fatalities (are they the ‘right’ controls?) and how will the reliability of the controls be measured? Hassall et. al. (Hassall et al., 2015), in a study on selection and optimization of risk controls, identified control performance as the product of reliability in the control to perform within the work environment and the adequacy of the control to prevent and/or mitigate unwanted events across normal and abnormal situations (Figure 18). When considered in the context of construction fatalities, regulators across multiple jurisdictions reported that between 85% and 90% of fatalities are events occurring from common high-risk activities, where controls that prevent the incident are defined within organization safety management systems, but still result in single to two-person fatalities (Health and Safety Executive (UK), 2018; Occupational Safety and Health Administration, 2016; Safe Work Australia, 2020). In summary, construction industry fatality events continue to be caused by the same high-risk activities and hazards due to failures in control reliability and less from novel or abnormal situations, where they are not defined or are inadequate in preventing the novel events.

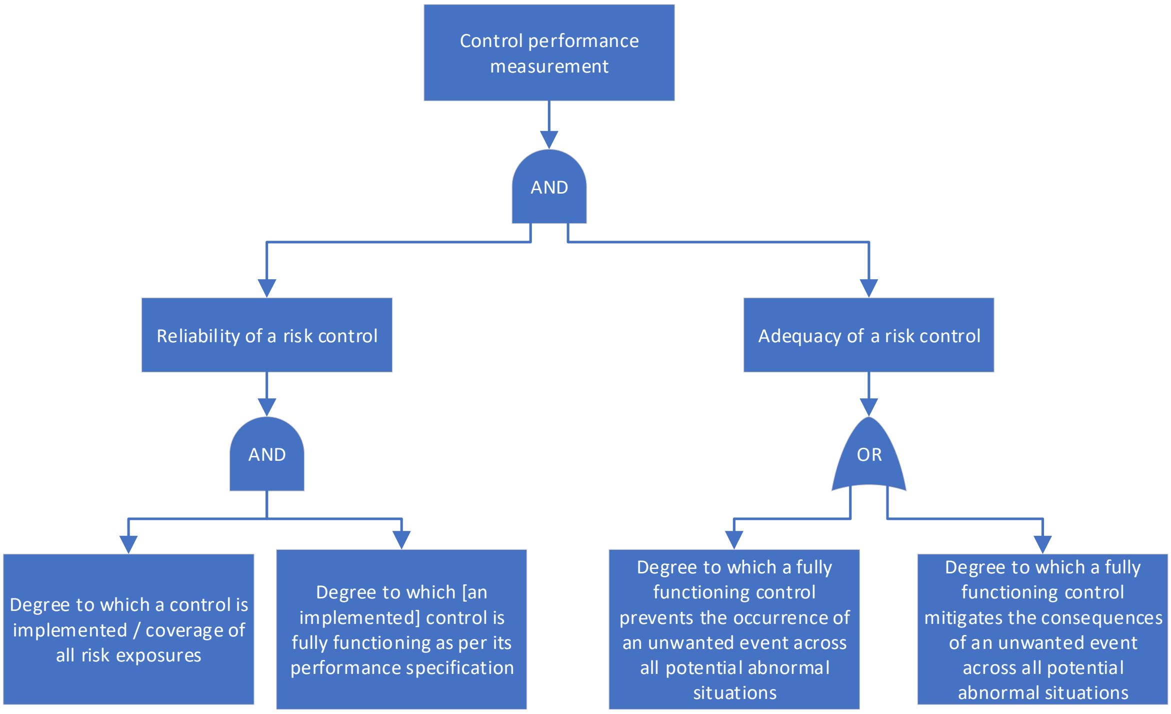


Figure 18: Measuring Control Performance

Risk control reliability is a factor of the availability and use of the control when required (i.e., control is implemented) and the effectiveness of the control to eliminate or minimize exposure to a threat or mitigate consequence severity (Hassall et al., 2015). Measuring reliability of risk controls can apply quantitative (Kang et al., 2016; Safe Work Australia, 2012), semi-quantitative (Casson Moreno et al., 2018; Grattan, 2018; Roelen et al., 2018; Winge & Albrechtsen, 2018) and qualitative processes (Hassall et al., 2015), depending upon the control to be measured, if the events where a control is challenged in the normal environment can be tracked or if the control can be tested under controlled conditions. In the simplest form, the effectiveness of a risk control is the ratio of the number of failures of the control when challenged to the number of occasions the control was challenged (Roelen et al., 2018), i.e.,

$$\text{Risk control effectiveness} = 1 - \frac{\text{Number of failures of the control when challenged}}{\text{Number of occasions the control was challenged}} \quad (1)$$

However, when being considered within a safety barrier program by a construction organization, the implementation and/or availability of the control needs to be assessed together with the adequacy of the control. Figure 15 provides a visual representation of control performance measurements, as derived from Hassall et al. (Hassall et al., 2015).

The reliability of the control (barrier) is also a factor of the type of barrier being used and the interdependency on human action and the effectiveness of the safety management system supporting the reliability of the barrier (Bellamy et al., 2010). The selection of barriers will apply the Hierarchy of Control as a means of reducing the risk of an event and improving the reliability of the barrier by selecting the most effective control type practicably available (Ajslev et al., 2022). Controls related to hardware barriers (i.e., physical and/or engineered control mechanisms or systems) only have indirect human involvement and are less likely to contribute to accidents (Winge, et al., 2019). Despite the importance of understanding control reliability, no publications could be found that analyse the reliability of the suite of controls used to manage construction related fatality risks. This study aims to begin to address this gap by first developing and testing a practical method for industry practitioners to use to determine control reliability. It also explores the use of bowtie diagrams as a means of presenting the results in a manner that helps reveal insights on risk-control vulnerabilities to decision makers. Specifically, the study explores critical control reliability through analysis of historical fatality and serious event investigations across four construction organizations to understand the historical performance of critical controls. The study aims to:

1. Evaluate if known critical controls, as documented within existing high-risk activity performance standards and organizational specifications, address known construction safety risks.
2. Identify performance factors that affect the reliability of critical controls to assist in the implementation of safety barrier programs within construction organizations.

4.2 Methods

The research involved sourcing incident investigations for potential accidents, coding the investigation reports and analysis of CC reliability as outlined in Figure 19.

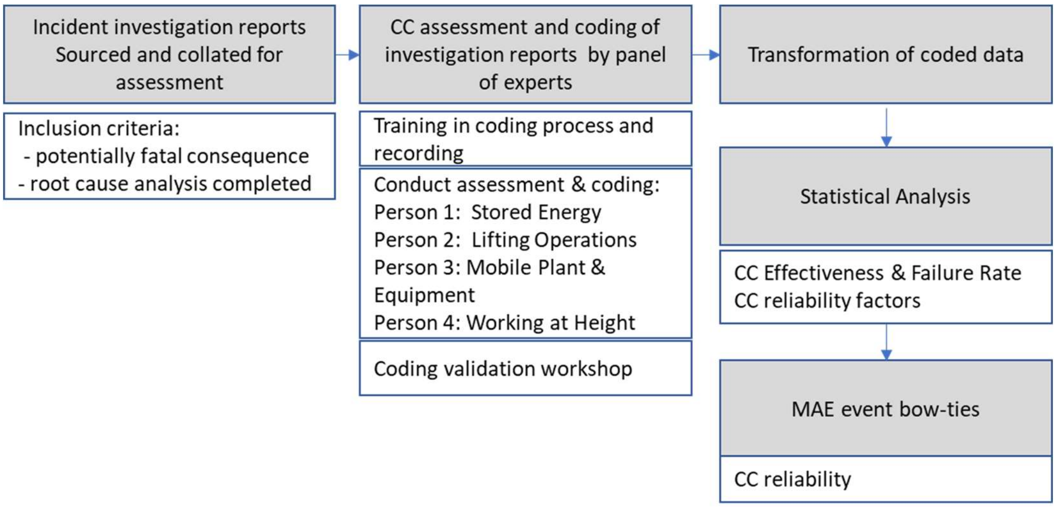


Figure 19: CC Measurement - Research workflow

Incident investigation reports for serious and fatal incidents which occurred over a 10 year period (2010 to 2020) was sourced from four construction companies based in Australia, South Africa, Canada, and the USA. To be included in the study the incidents had potentially fatal consequences and a root cause analysis investigation had been completed. Sourcing of actual, potentially fatal consequence investigation reports from construction companies is problematic as the reports are highly confidential and often subject to legal privilege. The value of the research to the participating organizations and grouping of data across multiple companies made the research possible given the sensitivity of the events and causal factors. Alternative open source data sources were explored (e.g., FACE database (NIOSH), 2020)); however, details on root causes were not able to be mapped to CCs and information was unclear on CC reliability factors.

The incident investigation reports were collated by the researcher for analysis by a focus group panel of four HSE professionals. The incident investigation reports were grouped into 11 event categories (e.g., Working at Height) and assessed to determine if the quality of the report was sufficiently detailed to identify Major Accident Event ('MAE') hazards, applicable controls, and causal factors. If the investigation report details were insufficient, the report was excluded from the study.

The four HSE professionals (i.e., 1 representative from each company) each had more than 15 years' construction experience (ranging from 15 to 25 years of experience) including competence in incident investigation, which enabled the analysis of the incident investigation reports. The HSE professionals were assigned an MAE category and assessed all incident events from all four companies applicable to the category. The were assessed against the MAP CC specifications for the category and MAE relying on the information on root causes and controls provided in the investigation reports. The focus group members were trained in the assessment methodology using worked examples with a follow-up session once five incident event assessments had been completed by each member to ensure alignment and consistency of assessment and coding of the events. A workshop was conducted following the completion of all analysis, where the outcomes were reviewed from each event and focus group members challenged the assessment rating until consensus was reached.

4.2.1 Critical Control Categorization and Assessment

Each investigation report was assessed to determine the mechanism (s) of failure to match the event to the MAE hazard (threat), then compare controls detailed in the investigation to known Critical Controls (CC) defined in the Major Accident Prevention (MAP) model (Figure 20, event classification method).

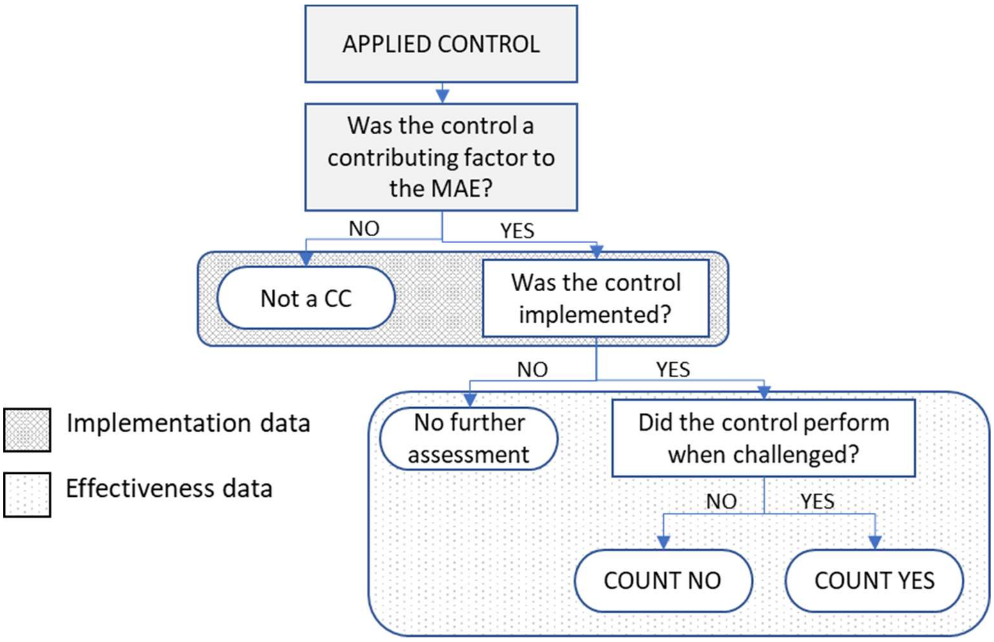


Figure 20: Process for assessing control effectiveness

Each applicable CC was assessed to:

1. Determine if the CC was a contributing factor in the event (yes/no).
2. Determine if CC had been implemented (yes/no).
3. Had the CC performed as required, i.e., was it adequate to prevent events using a rating of good, needs improvement or inadequate?
4. What was the mechanism of the injury? (List)
5. Were improvements in the of CCs required? (Yes/no, free text)
6. Were any improvements in CC specification or additional CCs required? (Free text)

The mechanism of injury list used in the assessment process was in accordance with AS1885.1-1990 (Standards Australia, 1990). The assessment also identified improvements in the application of CCs and gaps in the MAP model of CCs. The free-text comments were reviewed by the panel and collated into common themes. The assessment details were recorded in an online Microsoft Form® database stored on a secure site.

4.2.2 Transformation of CC-Coded Data

Each MAE category data group was exported into MS Excel for transformation and consolidation by CCs. Scoring of the data was applied by converting the three CC assessment ratings into numerical values as per Table 13 to produce the variables used for calculating control reliability.

Table 13: CC data transformation

Event Assessment Criteria	Code Response	Output Variable	Calculated Output
CC Contributing factor	Yes	Number of times CC Challenged	$\sum_n$(CC = "yes")
	No	-	-
CC Implemented	Yes	Number of times CC implemented	$\sum_n$(CC = "yes")
	No	Number of times CC **not** implemented	$\sum_n$(CC = "no")
CC Adequacy rating	Inadequate Poor Good	Adequacy score	$\sum_n$(CC = "adequate")

NOTE: n = number of times CC was assessed.

$$\text{Implementation ratio (\%)} = \frac{\text{number of times the CC was implemented} \times 100}{\text{number of occasions the control was challenged}} \quad (1)$$

$$\text{CC effectiveness (\%)} = \frac{\text{number of times the CC was rated adequate (i.e., good)} \times 100}{\text{number of occasions the control was challenged}} \tag{2}$$

$$\text{CC Reliability (\%)} = \text{Implementation ratio} \times \text{CC effectiveness ratio} \tag{3}$$

Critical control reliability percentages were mapped against the MAE hazard Bowtie. The mapping of the result from applying real data calculations for individual CC reliability to the bowtie is a novel extension of bowtie analysis that visually highlighted control gaps and provided feedback on the performance of control pathways and improvements required in the verification processes.

4.2.3 Failure Rate by CC Hierarchy of Control Type

CC reliability ratings were compared by hierarchy of control type of CC for each MAE category to review the reliability of CC type. Observations on critical control gaps and improvements were collated and provided to the participating organizations.

4.2.4 CC Comparative Performance by Implementation and Effectiveness Ratios

The data were analysed using R statistical package (R Core Team, 2020) applying exploratory analysis steps to understand the relationships and strength of relationships between variables. Oneway ANOVA was applied to the implementation and effectiveness ratio (%) variables to understand the importance of the measures in assisting construction projects to improve CC management.

4.2.5 Human Ethics Statement

The research was conducted in accordance with Edith Cowan University Human Research Ethics Committee (HREC) approval for Project number 20293 Selleck granted on 12 June 2018 (valid from 12 June 2018 to 31 March 2022) which meets the requirements of the National Statement on Ethical Conduct in Human Research.

No harm has resulted from the focus group process or the analysis of the reports.

4.3 Results

Sourcing of actual potentially fatal consequence investigation reports from construction companies is problematic, as the reports are highly confidential and often subject to legal privilege. The value of the research to the participating organizations and grouping of data across multiple companies made the research possible given the sensitivity of the event and causal factors. This resulted in 186 serious and fatal event investigation reports collated, covering a period from July 2011 to December 2019. Five investigations were rejected due to insufficient detail on contributing causes. The events were sorted by MAE category (Table 14), with all events assessed; however, statistical analysis was limited to MAE categories where there were greater than 30 event reports, which included: Lifting Operations; Mobile Equipment/Light Vehicles; Stored Energy and Working at Height.

Table 14: Number of L4/5 event reports by category

Fatal Risk (MAEs)	Number of Events	Fatal Risk (MAEs)	Number of Events
Excavations	3	Marine Operations	2
Fall of Ground	12	Mobile Equipment	30
Fire & Explosion	4	Falling & Rolling Objects	1
Lifting Operations	49	Stored Energy	33
Light Vehicle	10	Working at Height	36
Machinery & Equipment Safeguarding	0		

Lifting Operation comprised the strongest frequency rate (27%) of all events and mobile equipment, stored energy and working at height represented, collectively, 87% of all events analysed. Where the event report did not provide sufficient information to assess the event or the event related to another failure mode, these were rejected (Table 15).

Table 15: Data analysed by MAE category

High Risk Activity	Number of Event Report	% Events	Number Rejected
Operating Mobile Plant and Equipment	40	22%	4
Lifting Operations	49	27%	0
Stored Energy	33	18%	7
Working at Height	36	20%	5

The most frequent MAE hazards included ‘driving interactions and operator error’, ‘lifting operations—dropped load’, ‘uncontrolled electrical energy release’ and ‘falls due to access/egress from plant or unstable ground’ (Figure 21).

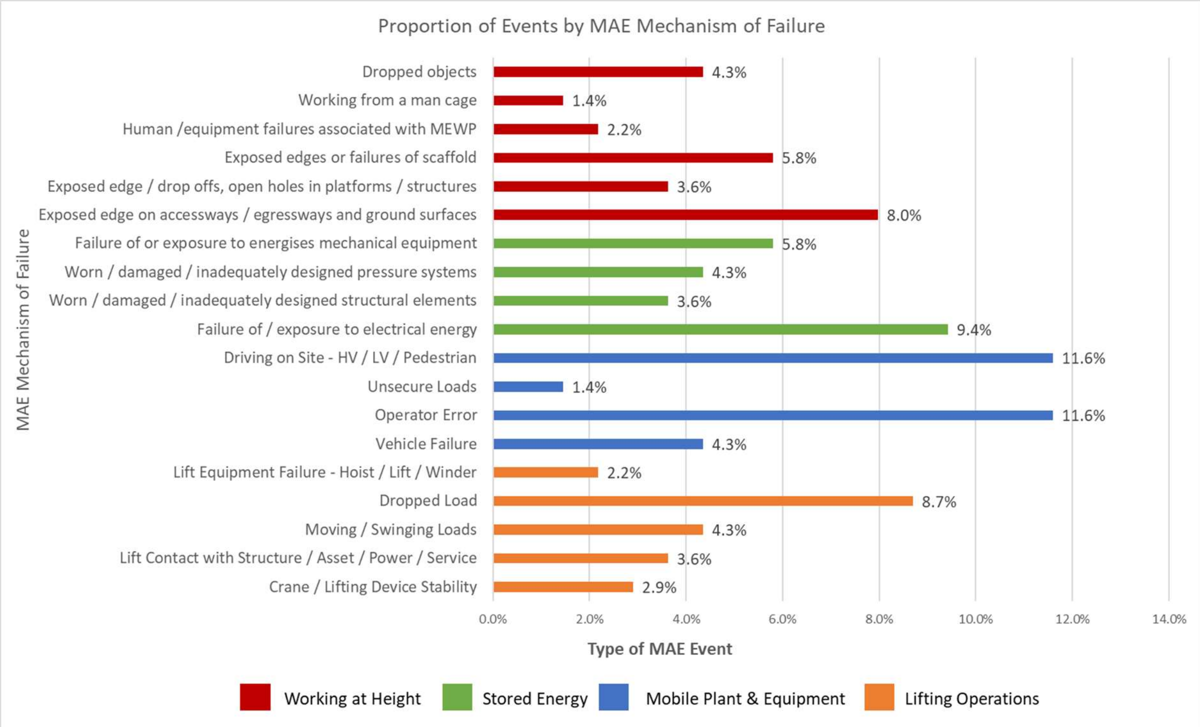


Figure 21: Proportion of events by MAE hazard

4.3.1 Critical Control Performance Measures

Implementation of CCs across all MAE categories were analysed at an average 57%, with a standard deviation of +/− 35.5%, indicating considerable variation in the implementation of CCs. Effectiveness of the CCs when implemented averaged 41.2%, with a standard deviation of +/− 38.6%. (Figure 22). The performance of CCs had limited reliability (23%), with a high rate of variability (+/− 37%) in preventing or mitigating MAE threats or consequences.

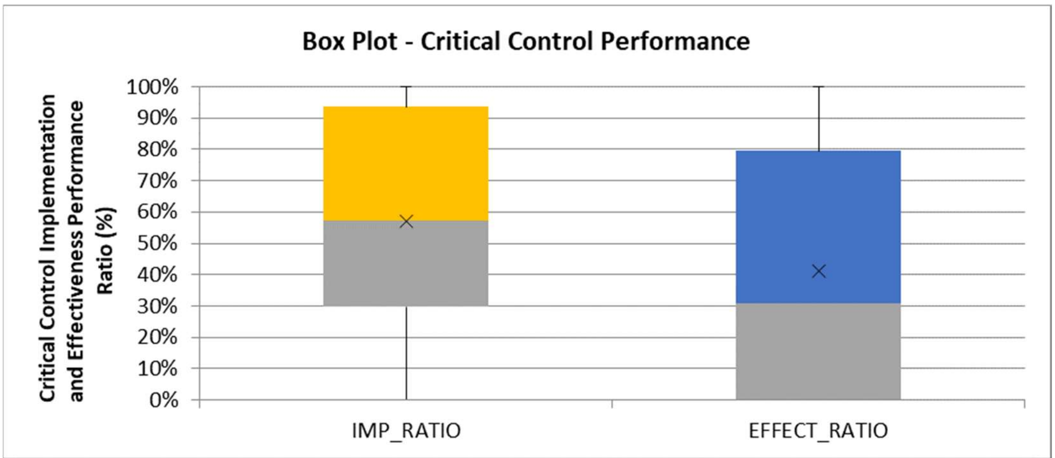


Figure 22: Statistical comparison of control performance measures

Comparison of CC performance measures (implementation, effectiveness) by MAE category (Figure 23) identified Mobile Equipment (77%) and Lifting Operations (77.2%) as having the strongest CC implementation rate, with Stored Energy (24.5%) having, overall, the weakest CC implementation rate. The CC effectiveness rate was, on average, 30% lower than the CC implementation across the MAE categories, except for Stored Energy.

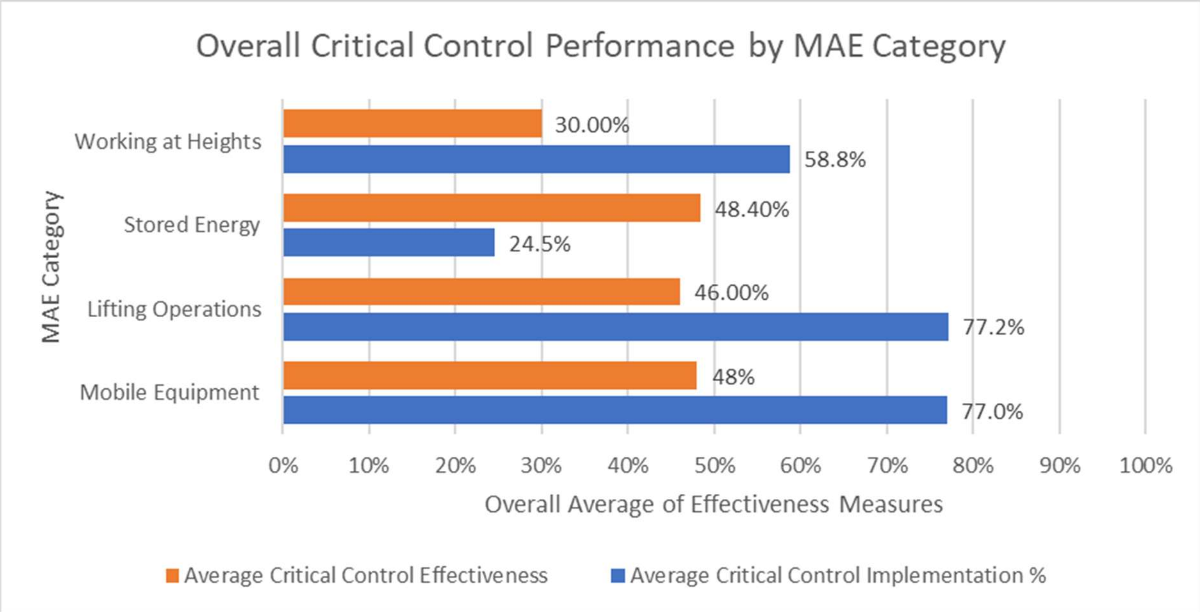


Figure 23: Overall Critical Control performance by MAE category

Comparison of CCs by the hierarchy of control types was conducted using the control types defined in the CC data set used for comparative analysis (Selleck, 2022a). In this model, the higher levels of the hierarchy of controls 'elimination' and 'substitution' are not applied, as the focus is on action and verification in the field. The 'administrative' controls are broken down by the action taken, e.g., 'inspection', 'monitoring', 'procedural' and 'competency'. The comparison identified Engineering controls as having the strongest rate of implementation (73.3%), with the other control types ranging between 46.7% and 53.6%. Engineering and administrative procedural CCs had similar effectiveness ratings at 47.0% and 45.5%, with the rest performing between 34.5% and 35.9% (Figures 24 a- d)

Engineering controls are closely monitored by field construction managers and project engineers as part of monitoring the integrity of the facility being constructed, with the extra focus reflected in the higher implementation rate and, to a lesser extent, the adequacy of the engineering controls compared to the other control types.

Comparing hierarchy of CC types across the MAE categories, the Stored Energy CCs have a consistently lower rate of implementation yet deliver a higher rate of effectiveness (Figure 24c).

The best performing control type was procedural CCs when conducting Lifting Operations, with a high rate of implementation (69.3%) and being effective 79.1% of the time (Figure 24a). The weakest performance was monitoring controls in the Stored Energy MAE category, with no monitoring type of controls across the category having been implemented (e.g., verify monitoring of pressurized systems to be within design and test limits).

Implementation of administrative type controls (e.g., competency) in the Mobile Plant and Equipment was 97.0% (Figure 24b) and Lifting Operations (Figure 24a) was analysed at 82.2%, demonstrating a high rate of implementation compliance. The effectiveness of the CCs for the same control type once implemented was weak, with Lifting Operations competency controls only being effective 28.3% of the time when implemented and Mobile Plant and Equipment only 62.5% of the time.

In total, 119 CCs were assessed across the four MAE categories, and all were found to be a primary causal factor in a minimum of one MAE incident when the CC was not implemented or effective. This was a fundamental assessment of whether controls being evaluated were Critical Controls. It was observed that CCs could also be contributory factors in MAE incidents.

4.3.2 Lifting Operations

Lifting Operations MAE hazards had the strongest level of implementation for CCs, with 15 of the 32 CCs having a greater than 80% implementation rate, with an overall average of 77.2% (Figure 23).

Activities involving the stability of the crane or lifting device had the lowest rate of CC implementation, 48.8% of CCs. Lift plans, risk assessment, inspection of ground conditions, stability devices and exclusion zones had low implementation ratings. The CCs applicable to the design of hoists, lifts and winders used in construction to move people and materials had a low implementation rate at 44.4%. Two CCs involved in managing moving and swinging loads specifically, line of fire risk assessments and assessing environmental conditions had low implementation rates at 57.1% and 50%, respectively. Work pressure was identified as a contributory cause in lifting events due to limited windows in the day’s schedule being available to complete lifts.

The effectiveness of lifting operation CCs has an overall average of 46%, with five CCs being 100% effective and six CCs being 0% effective (Figure 25). The stability of crane or lifting devices has the least level of prevention control, with six of the seven CCs having weak effectiveness ratings, with an average of 11.5%.

All Lifting Operation MAE hazards compromised CC prevention pathways with two or more CC effectiveness measures being compromised by having a 50% or lower failure rate when the control is implemented (Figure 25).

4.3.3 Mobile Plant and Equipment

Mobile Plant and Equipment MAE hazards had, overall, a high level of implementation of CCs, with 11 of the 22 CCs having a greater than 80% implementation rate, with an overall average of 77% (Figure 26), marginally behind Lifting Operations (Figure 22).

CCs that managed Operator Error Hazards had a strong implementation average at 85%, with the two lower implementation rates (67%) associated with operating within vehicle specifications and driving off road with rollover protection. The weakest level of CC implementation (47%) was heavy vehicles or plant operators not responding to alarms. The CC implementation and effectiveness ratings for the Unsecured Loads MAE hazard are indicative only as the CCs were only challenged twice by the assessment of incident events.

The effectiveness of mobile plant and equipment CCs has an overall average of 48%, with two CCs associated with emergency response drills being 100% effective and two CCs (excluding the Unsecured Loads MAE hazards noted above) being 0% effective. One of the two completely not effective was heavy vehicles or plant operators not responding to alarms (Figure 26).

The vehicle failure MAE hazard has the strongest level of prevention control, with all CCs in the prevention pathway having CC effectiveness ratings above 62%, with an average of 74.9%. The least effective prevention pathway is associated with driving on site, where the effectiveness ratings of five from seven are weak (<50%) and range between 0 and 33.3% (Figure 26). Three of the four Mobile Plant and Equipment MAE hazards have compromised CC prevention pathways, with two or more CC effectiveness measures being compromised by having a 50% or lower failure rate when the control is implemented.

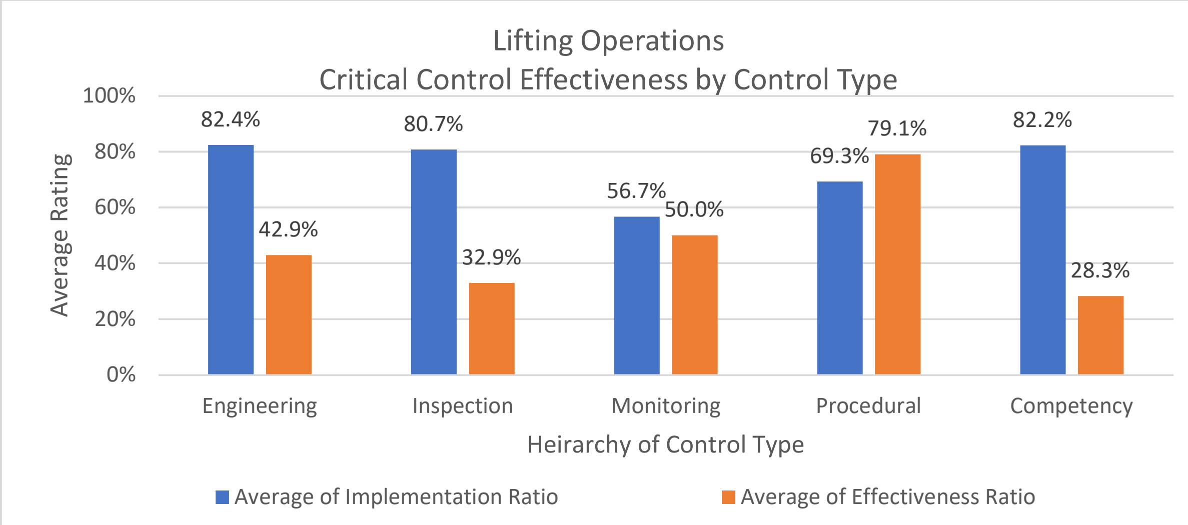


*Figure 24 (**a**)*

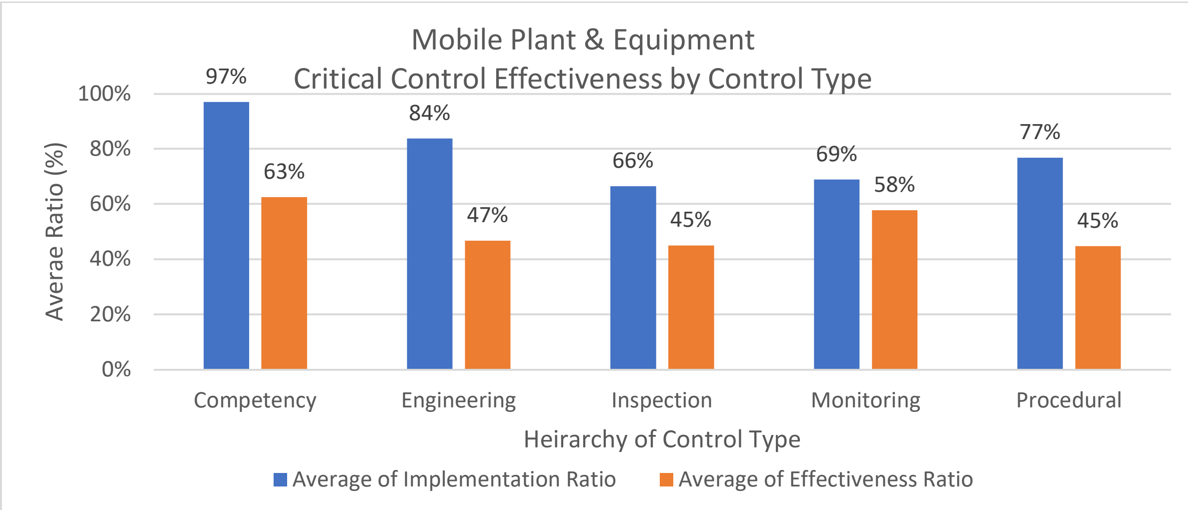


*Figure 24 (**b**)*

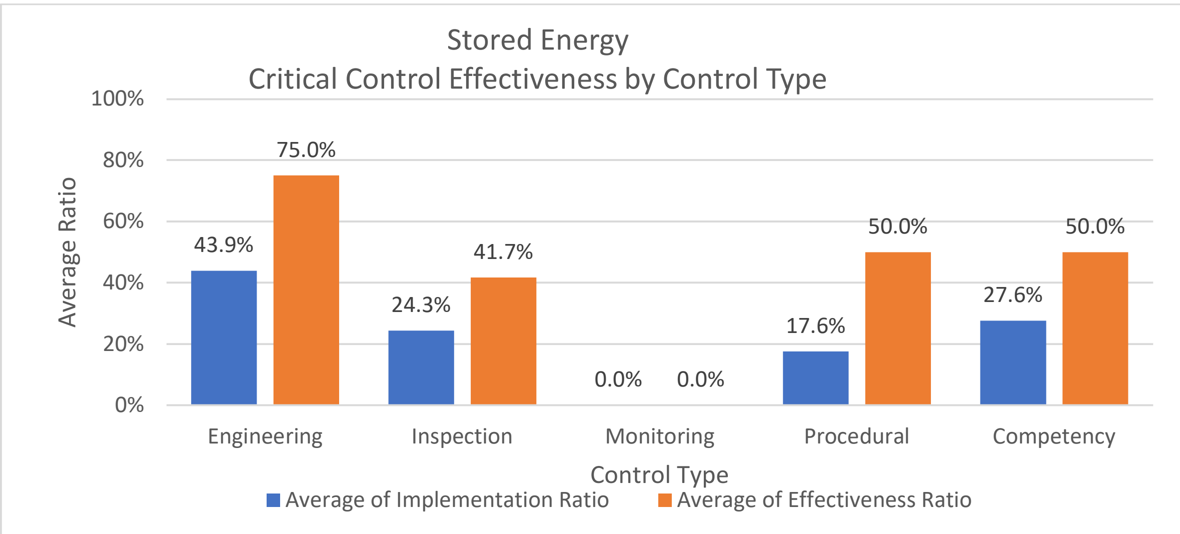


*Figure 24 (**c**)*

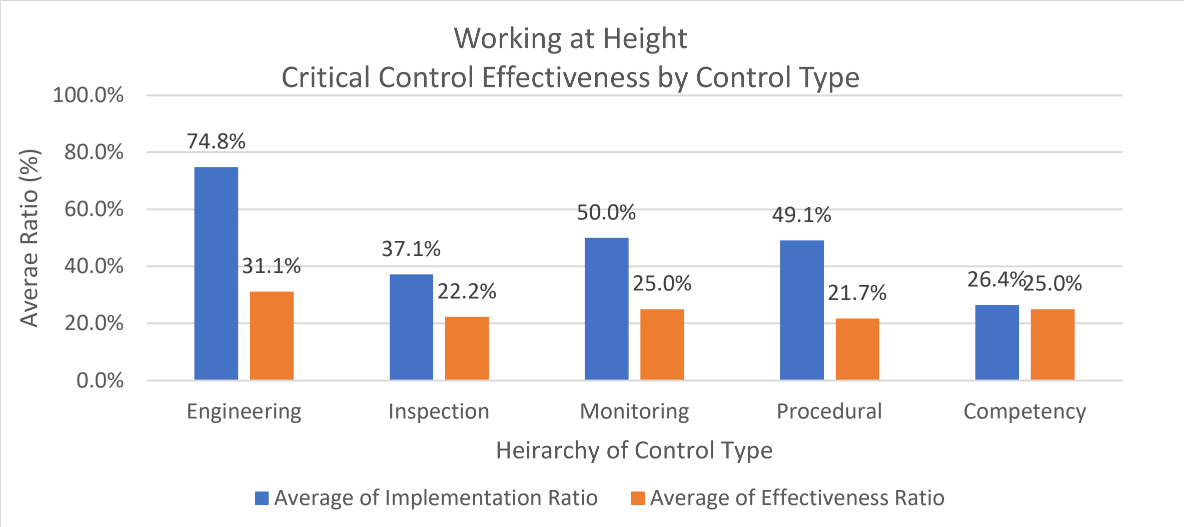


*Figure 24 (**d**)*

Figure 24: Critical Control performance by hierarchy of control (a) Lifting Operations; (b) Mobile Plant and Equipment; (c) Stored Energy; (d) Working at Height

4.3.4 Stored Energy

In total, 36 major accident events were analysed that were associated with stored energy. Uncontrolled Electrical Energy Release was the most common MAE event by which personnel were harmed, with inadequate isolation methods and application of exclusion zones around live systems. Contributing to the failure of isolation methods was due to perceived schedule pressure, either from the issuing of permits without full validation ("we needed to get the permit issued as work had already been held up") or isolation placed on the wrong system ("crew were waiting to start").

An average 4.4% of events analysed identified the critical controls as not implemented as the primary failure. Failure to apply isolations and/or exclusion zones was identified as a common failure across all Stored Energy MAEs (Figure 27).

4.3.5 Working at Height

In total, 36 working at height major accident events were analysed. Falling Down: access and egress and working on unstable ground, together with Dropped Objects were the most common MAE events by which personnel were harmed due to inadequate design of access/egress, inspections and maintaining exclusion zones and inadequate risk and simultaneous operation assessments.

An average 10.5% of events analysed identified the critical controls were not implemented as the primary failure. Failure to undertake inspections of work environment, pre-start/pre-use inspections and fall protection and inadequate job planning were identified as a common failure across all Working at Height MAEs (Figure 28).

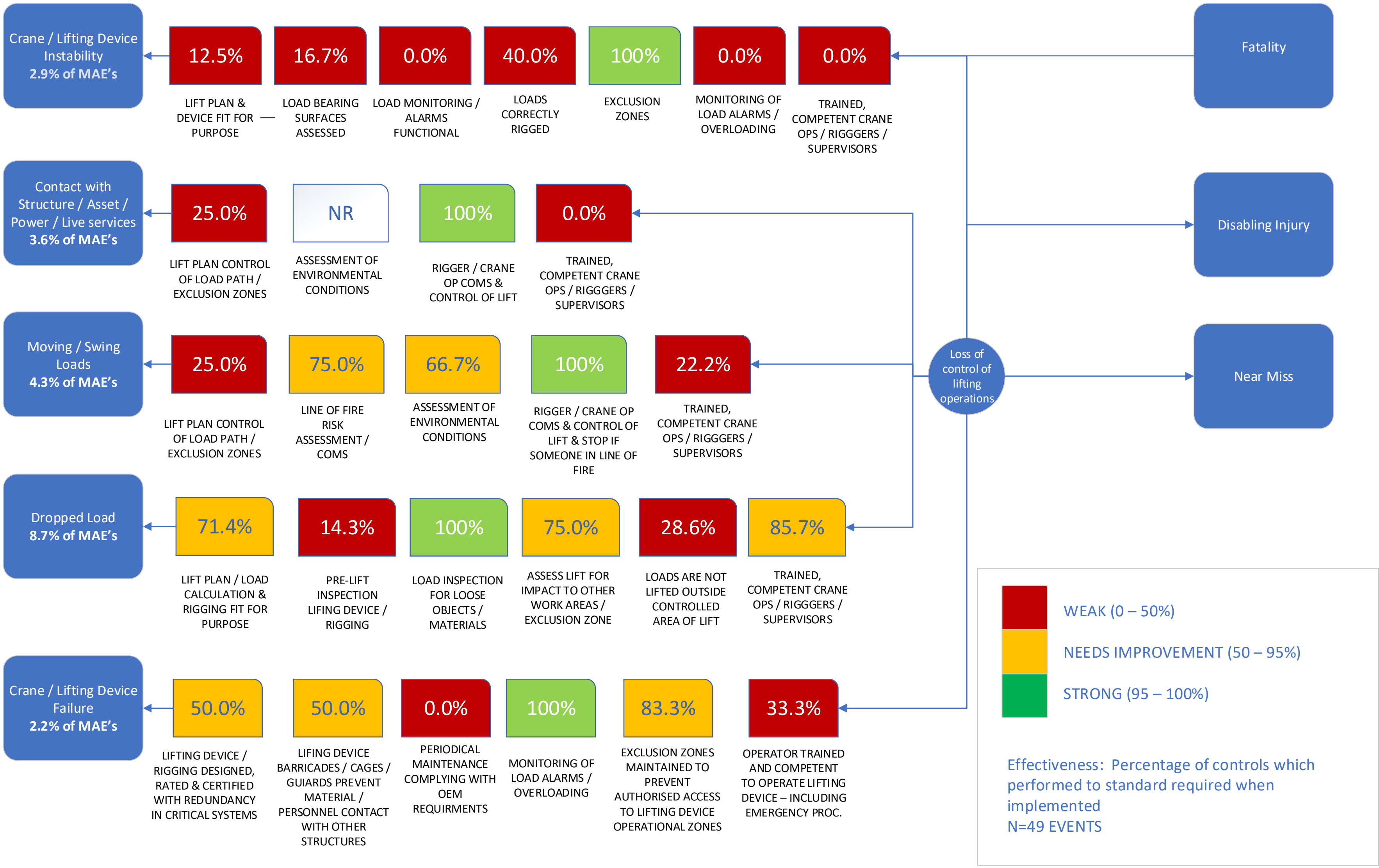


Figure 25: Lifting Operations - Critical Control Reliability

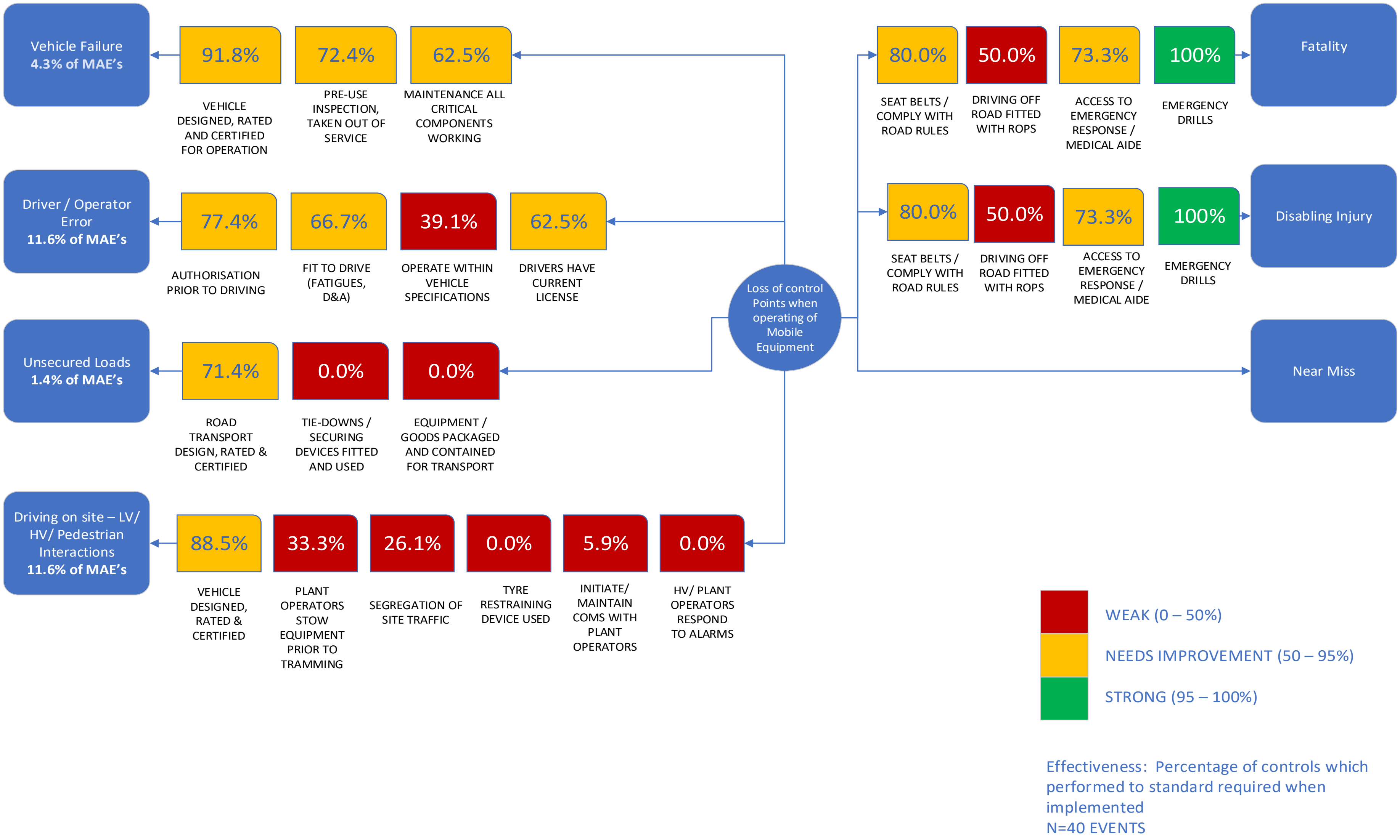


Figure 26: Mobile Plant and Equipment - Critical Control Reliability

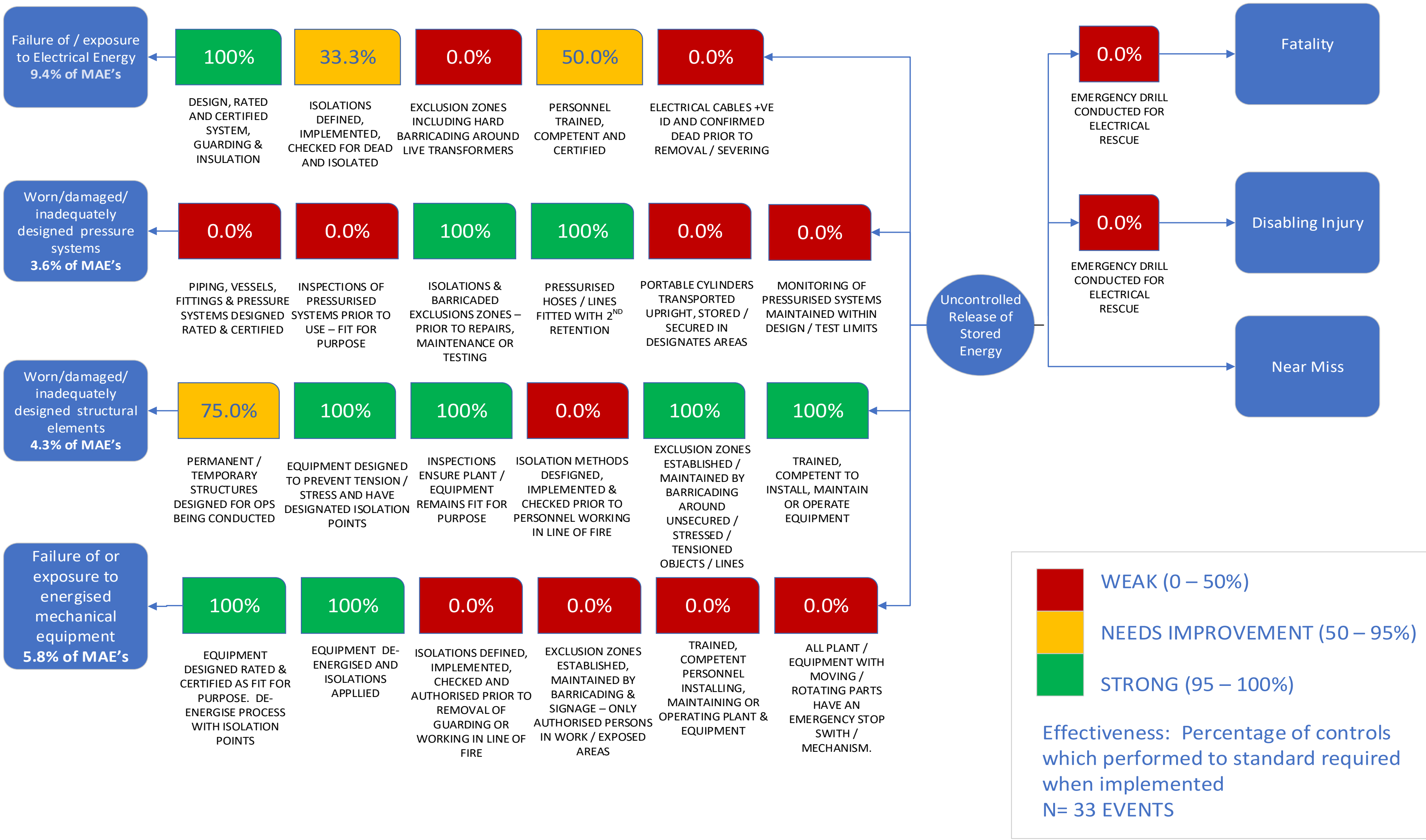


Figure 27: Stored Energy - Critical Control Reliability

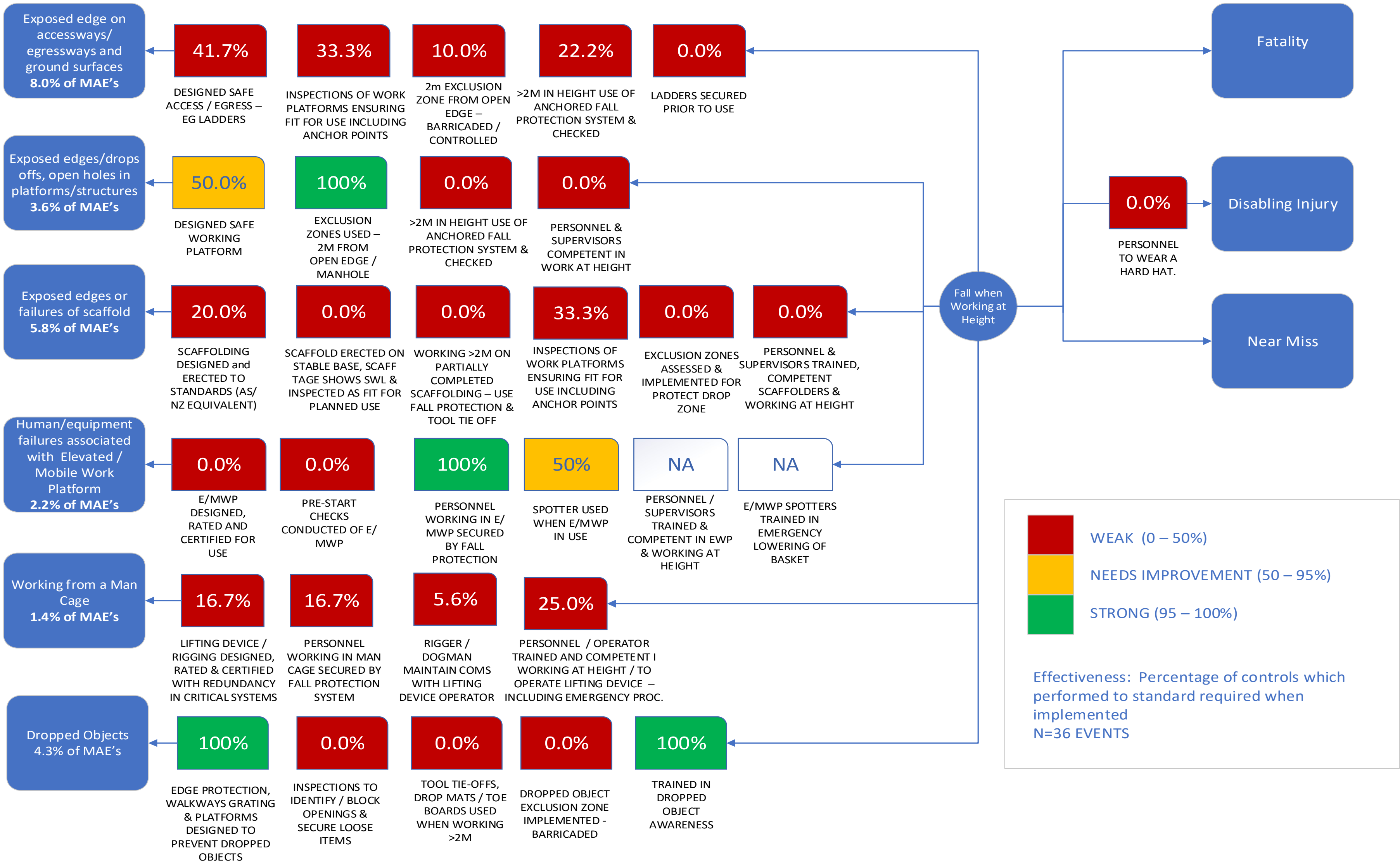


Figure 28: Working at Height - Critical Control Reliability.

4.3.6 CC Improvements and Gap Analysis

In total, eighteen (18) CC performance improvements and nine (9) gaps in CC specifications were identified during the event analysis (Table 16). The recommendations provide insight into the type of errors that contributed to the incident events, including design failures, system errors and human factors. The CC performance improvements and gaps were not able to be validated beyond the statements provided within the historical investigation reports. The recommendations provide insight into the type of CC performance errors occurring historically and areas for management focus in current projects.

4.4 Discussion

The research evaluated historical incident investigation reports of significant construction incidents for four international construction companies across a ten-year period. The study evaluated known CCs, as documented in existing high-risk activity performance standards, to identify performance factors that affect the reliability of CCs. The relative control reliability level for each of the CCs was calculated to provide a baseline measure for future assessment of construction critical controls. The analysis does provide insights into the applicability of CCs for the construction industry and factors affecting CC reliability across the different hazard categories.

4.4.1 Validity of Construction CCs

One of the key questions asked by the construction companies participating in the study and one of the aims of the study was to determine whether the CCs being applied in their organizations are the ‘right’ CCs to prevent major accident events. The CC verification process requires management investment in resources to undertake the verification tasks, monitor performance, report on the risks and is expected to demonstrate management duty of care in respect to MAE risks. The CCs applied in the companies were reviewed by internal construction and safety professionals. However, no definitive review against major incident events was conducted and the organizations continued to experience significant incidents post the implementation of the CC verification process. The study confirmed all 119 CCs being applied by the organizations were valid, with a further 7 CCs being recommended. The additional seven CCs were recommended for MAE hazards where the threat was not identified (e.g., loading/unloading from haulage vehicles) or there were gaps in the control specification.

Table 16: Identified improvements and gaps in Critical Controls by MAE category.

	Identified CC Performance Improvement	Identified Gaps in CC Specifications
Lifting Operations	The quality, definition and details provided in lift plans Identifying, delineating and communication of line of fire exclusion zones Control of exclusion zones (requirement for trained and competent spotters) Communication between crane operators and riggers Competency of crane operators/riggers used for the task being performed	Mechanical locking system mandated for storage of crane booms during transit Overhaul and/or major maintenance service of lifting devices to apply NDT to all critical welds and joints and ensure lubrication/inspection of critical components. Safety critical materials (e.g., rigging components) required for lifting operations are identified, sourced, and applied as designed.
Mobile Plant and Equipment	Load factors for trucks and mobile equipment not defined or applied in work activities Malfunction of automated processes, vehicle proximity alerts/alarms—inadequate inspection, maintenance, and testing. Deliberately disabled. Operator fitness for work—fatigue, under the influence of drugs/alcohol, mental distraction, and physical conditions. Personnel operating within blind spots, line of fire and inadequate use of the spotters for tramming, reversing, and loading/unloading operations Inadequate traffic/pedestrian segregation	Development of loading/unloading critical controls—positions/lifting/offloading with heavy equipment
Stored Energy	Personal discipline to use isolations and lock out system. Identification, installation, and monitoring of exclusion zones Permit to work application—wrong systems identified, systems not de-energized and inadequate lock out/tag out.	Risk assessments extend beyond project perimeter to include tramming route of mobile equipment (e.g., overhead power lines) Line of fire risk assessments to include securing systems (e.g., chains, clamps)
Working at Height	Line of fire assessment Engineering and design reviews of new scaffolding/barrier systems Competency of personnel installation/using scaffolding (e.g., overloading) and managing materials, tools and equipment when working at height Integrity of work surfaces—multiple trips/slips on work platforms Design of working at height systems, anchor points and hookup by work team members	Design, inspection and loading specifications of temporary works including loading platforms

The type of CC gaps occurred across a range of control types, including engineering, inspection and procedural, which focus on the higher end of hierarchy of controls. By contrast, observations on factors affecting implementation of the CCs identified gaps in lower level hierarchy controls.

The gaps included procedural, administrative and training associated with human performance factors, resulting in CCs not being implemented.

All four major-accident event categories were found to have a high proportion of weakly or not implemented Critical Controls and, therefore, were not effective in preventing the release of hazardous energies. The CCs rated 'weak' (<50% reliability) were considered unreliable as they failed more times than the CC was effective. The ratings (weak, needs improvement, strong) highlight where construction organizations need to prioritize action to improve implementation and the quality of the CC being considered. The ratings also inform where CC verification programs need to prioritize organizational effort to validate CC reliability. In the case of Working at Height events (Figure 28), three of the control pathways (i.e., falling down, working from scaffolding, working from man cage) identified each Critical Control as being weakly implemented or not effective. For example, Falling from Scaffold identified three CCs as being implemented: design of the scaffold, inspections on standard of scaffold being built and scaffold foundation inspections; however, only the design CC was assessed as being only 20% effective. Similarly, when assessed in the overall context of the study, the CCs that had a high reliance on human performance (e.g., operating plant and vehicles, inspections, maintaining exclusion zones) had a higher rate of failure (Figure 22), which aligns to hierarchy of control principles (Winge, Albrechtsen, & Mostue, 2019). Human performance factors that affect either the implementation or quality of the Critical Control, including decisions to intervene when a CC is not performing as specified, need further consideration.

The Stored Energy hazard category provides a case in point, with Stored Energy events having the least proportion (18%) of incident events in the study. Arguably, Stored Energy should have the best CC performance. Comparing hierarchy of CC type across the MAE categories, the Stored Energy CCs have a consistently lower rate of implementation yet deliver a higher rate of effectiveness (Figure 23). All four Stored Energy MAE hazards had a minimum of two CCs assessed as having a 100% reliability rating (Figure 23). These CCs were engineering and inspection type controls and, whilst overall more effective in the absence of other CCs (i.e., those relying on human performance), the incident events still occurred.

4.4.2 Human Performance Factors

The analysis of the incident investigation reports identified a range of organizational, supervisory, and human performance factors contributing to poor implementation of CCs. Eighteen (18) recommendations on improving implementation of CCs (Table 16) provide insight into the type of human performance factors affecting CC implementation and effectiveness. These are observations made by the experienced panel members to assist construction organizations intending to implement CCRM or improve management focus on the verification of CCs.

The failure to recognize hazards was identified across multiple incidents, particularly when working in and around mobile plants, where personnel were working in blind spots (reversing plant), in the line of fire (swinging loads), during loading/unloading of equipment and working above others. Failure to recognize hazards adversely impacts the effectiveness and reliability of critical controls, as human actions are not applied either to implement the Critical Control or act when the Critical Control deviates from the required specified standard (Nnaji & Karakhan, 2020). The analysis identified multiple MAE incidents where an erosion in control integrity or changes in barrier functionality (e.g., exclusion barriers, maintenance of scaffold in use, proximity alarms) were tolerated by the work team and supervision. Where the risks become normalized through repetition or familiarity (e.g., continuously working around mobile plant, working on scaffolding), workers are desensitized to the risk exposure and become ‘complacent’ (Størseth et al., 2014). Under these circumstances, workers are less likely to respond to changing conditions, resulting in the type of ‘line of fire’ incidents observed in the study. This has implications in the design, implementation, and operational integrity of a CCRM program where the reliability of the CC can be eroded.

Failures were identified in the competency of crane operators and riggers, application of work permits to isolate stored energy, spotters failing to maintain exclusions zones around plant and equipment or ineffective communication with mobile plant operators (Table 16).

The incident investigations readily identified competency, (i.e., inexperienced, or untrained workers) as a factor when CCs were not implemented. Competency, as a factor in CCs that were not applied to the standard required, is more complex. Worker competency is linked to their ability to either adapt the standards to the work or decide to stop work and seek clarification from supervision and management (Chan et al., 2018; Hale & Borys, 2013). In both options, the CC system must provide direction on how to manage deviations (Hale & Borys, 2013), as major incident investigation studies identified deviations from controls (rules/barriers) that are inevitable in high-risk industries, including construction (Chan et al., 2018; Chiang et al., 2018; Hopkins, 2011b; Suraji et al., 2001). One option to improve competency and consistent application of controls (rules) was to improve the specificity of the control and detail the control tolerance limits (Hayes, 2012).

CC reliability was attributed to an individual’s decision making, which resulted in aberration from accepted safety standards (e.g., not fit for work, not applying danger lock and tag), substandard actions (e.g., inadequate inspections) or errors and lapses (e.g., wrong system isolated), (Table

16). Individual risk-based decision making in the application of CCs (rules and/or barriers) is influenced by a complex interface of personal, work team, organizational and psychological factors (Hale & Borys, 2013; Hayes, 2012; Størseth et al., 2014). Rules are perceived as 'guidance', with workers applying adaptive thinking to achieve work tasks and goals (Boskeljon-Horst et al., 2022). Further investigation into individual's decision making and the impact on CC implementation and effectiveness would benefit construction organizations looking to improve CC reliability.

Maintaining risk awareness is an inherent duty of supervisors through job planning and risk reviews, which focus on the hazards inherent in the tasks being undertaken and how hazards will be controlled (NSW Government, 2011; Occupational Safety and Health Administration, 1970; Work Safe WA, 2020). Both factors were identified as being inadequate and contributed to the events analysed. Winge, (2019) identified immediate supervision as strongly connected to worker actions, with the effectiveness of supervision a direct factor of job planning and risk management. In the absence of effective supervision, workers are less likely to act to implement or maintain CCs.

A major impact on job planning is the reactive nature of construction due to delays in the provision of materials, plant, equipment, or labour, which causes compression of the schedule (Mitropoulos & Memarian, 2012). The delays result in perceived production pressure to 'get the job done', meaning work teams and supervisors become focused on task completion and fail to recognize changes in the work environment or hazards (Carter & Smith, 2006; Rafindadi et al., 2022) or continue to work in the absence of effective safety supervision (Winge, et al., 2019). Where production pressure adversely affects safety performance through compression of work schedules (Mitropoulos & Memarian, 2012; Woolley et al., 2020) or rework from poor quality of execution (Love et al., 2018), this also impacts performance of control barriers that rely on human action (Grattan, 2018).

By focusing on CCs, construction organizations become more resilient as risk assessment, integrated into all systems; the verification process identifies and eliminates problems before they occur (Woolley et al., 2020). The study used historical incident data where the risk maturity of the participant organizations was reactive or, at best, risk compliant (Goncalves et al., 2018; Woolley et al., 2020). As organizations further develop and improve CCRM, the verification audits provide additional data to model safety performance. This shifts management focus from incidents (lagging measure) to proactive risk management and provides opportunities for predicting risks.

4.4.3 Limitations

The calculated control reliability level is biased and over represents the failure rate, as the assessment was conducted on incident events with known control failures and does not represent every time a Critical Control was challenged when executing work. The Critical Controls assessed did not cover all construction high-risk activities and were limited to four hazard categories. Equally, the study did not assess various cultural factors (e.g., language, religion, societal structures) and commercial and delivery strategies (e.g., self-perform, subcontractor, joint ventures), which potentially impact control of construction project fatal hazards.

4.5 Conclusions

The study confirmed that the controls identified for the four MAE hazard categories (Lifting Operations, Mobile Plant and Equipment, Stored Energy, Working at Heights) were valid as CCs through the control of energies associated with high-risk construction activities. Implementing and maintaining a CCRM is a significant investment in time, resources, and cost, all of which are significantly constrained in the construction environment (Woolley, et al., 2019). Senior managers want assurance that the investment in CCRM delivers safety improvements, which, in the absence of incidents, is difficult to quantify. Construction organizations participating in the research questioned the validity of CCRM to prevent potentially fatal accidents, specifically how does the organization know effort is invested in the ‘right’ CCs? The study was able to validate CCs for the four MAE hazards tested and identified gaps in CC standards within the safety management system (s), which the organizations were able to act upon. The methodology of CCRM incident analysis provides a basis to improve incident investigation root cause analysis by comparing incident root causes to CCs generating focused improvement actions. The study highlighted a need for further research how to measure the impact CCRM has in preventing serious incidents within a construction project.

The study provided insight into the individual and organizational factors, which potentially impact the reliability of CCs. Human performance factors, including hazard identification, personal decision making and competency, were common findings in the investigation reports analysed. Worker competency was attributed to inexperience or lack of training or the lack of competency to assess, adapt and apply CCs to the work activity being conducted.

In complex construction environments, individuals need to be adaptive in the application of the CC to the situation, not just follow a black and white ‘rule’. It is the competency to apply CCs to the work environment that individuals need to develop, which informs their decision to stop work when the ‘rule’ is found not to apply to the situation. In the absence of an organization providing clear direction regarding CC deviations, failures will occur as workers influenced by their own risk perceptions will decide on how and whether to apply the CC and to what standard. The human performance factors can be addressed by the organization improving worker competency to assess and apply CCs across all high-risk tasks and, critically, the actions and/or behavior of competent supervisors to verify CC implementation and effectiveness for the given task being undertaken.

Organizational factors also contributed to the reliability of CCs. Supervisors having reacted to changes in construction schedule, materials and labour resourcing failed to undertake the CC activities, including job planning, risk assessments or communicating the risks and CCs to the work team.

The study benefits construction organizations applying CCs as a risk management tool as the results confirm the applicability of CCs for the MAE hazards analyzed and highlight the factors that need to be considered when implementing a CC program. Organizational processes need to ensure supervision and workers are trained and competent in the application of CCs, direction is provided to manage deviations and management oversight to ensure implementation and quality is maintained. The method presented and the use of the bowties to illustrate the results represents a novel contribution to the literature on controlling fatal risks on construction sites. Future work to continue the contribution to research is planned to extend the analysis to additional risks and additional construction projects.

CHAPTER 5. HOW DID COVID-19 PANDEMIC IMPACT SAFETY ON A CONSTRUCTION PROJECT? A CASE STUDY COMPARING PRE AND POST COVID-19 INFLUENCE ON SAFETY AT AN AUSTRALIAN CONSTRUCTION SITE.

Chapter 5 has been published as:

Selleck R. J., Hassall M., Cattani M. (2022) How did COVID-19 pandemic impact safety performance on a Construction Project? A case study comparing pre and post COVID-19 Influence on Safety at an Australian Construction Site. *Safety* 2022, *8(4).*

5.1 Introduction

In early 2020 the COVID-19 pandemic caused major disruption to the global and Australian construction industry. Prior to the COVID-19 pandemic, global employment within the construction industry was 7.7% and projected to contribute up to 13.4% of the GDP (International Labor Organization (ILO), 2021). High COVID-19 case numbers resulted in government orders restricting movement to reduce spread of the disease and to slow transmission (Australian Health Protection Principal Committee (AHPPC), 2020a, 2020b; WA Government, 2020). In Australia, the result was a 13.9 billion AUD annual contraction in construction work and the loss of an estimated 76,500 jobs with further reductions of 7.3% predicted in 2020/2021 (Bleby, 2020; Deloitte, 2020; Department of Infrastructure Transport Regional Development Communications and the Arts, 2020; European International Contractors, 2020). The restrictions together with construction workers contracting COVID-19 also impacted labour supply for construction projects with an average 35–40% of a projects workforce either ill or not working whilst completing isolation requirements. The industry has also experienced supply chain disruptions, increases in the cost and shortage of building materials as COVID-19 caused factory closures and port to port shipment delays (Deloitte, 2020; European International Contractors, 2020). The European International Contractors (European International Contractors, 2020) predicted economic setbacks across the industry including “insolvency of stakeholders along entire supply chains”. However, the Australian Federal and State governments recognized continued investment in construction and mining sectors would buffer the Australian economy and provided stimulus to keep people working. The Federal government invested in a $1.5 billion infrastructure COVID-19 stimulus package on road and rail projects across all states (Department of Infrastructure Transport Regional Development Communications and the Arts, 2020). Subsequently the construction, mining and resources sectors were classified as ‘essential’ industries allowing the work to continue provided mandatory COVID-19 controls were implemented.

In response, organisational COVID-19 management plans were developed to formalize compliance with Governmental mandates and internal approaches to manage the health risk to construction workers. COVID-19 management plans were developed to minimize the risk of introducing COVID-19 into the work environment and minimize spreading of the disease in the workplace. The COVID-19 management plans comprised COVID-19 policy, risk management, health factors (COVID-19 symptom monitoring, hygiene, mental wellbeing) with a heavy reliance on communication. The constant evolution of COVID-19 and the change in management response required by organization meant effective communication was critical to effective COVID-19 risk management. The workforce relied on organizations to interpret and make sense of the COVID-19 restrictions and protection measures being mandated by government agencies which kept the workforce informed throughout the evolution of the pandemic (Alsharef et al., 2021).

Organization COVID-19 impacts have resulted in changes to daily work routines, work methods, logistics, material supplies and resource constraints at all levels of the organization (Pamidimukkala & Kermanshachi, 2021). The effect of these changes has increased levels of worker anxiety and stress (Stiles et al., 2021) with the associated risk to the health and safety of the workforce by the extended periods of COVID-19 conditions and distractions. To reduce worker stress and anxiety the construction organizations need to provide a safe working environment preventing the spread of COVID-19 across construction sites through health and hygiene controls, reduction in community contacts and keeping the site teams informed on the status of changes in COVID-19 controls and conditions (Del Rio-Chanona et al., 2020). Organizations had to develop strategies to manage the constantly changing conditions, the effects of delays in supply chains and labour shortages with project leaders under increased pressure to deliver project work schedules with reduced manning, extended hours of work and uncertainty of future COVID-19 conditions.

To meet the COVID-19 risk management objectives fly in/fly out (FIFO) workers were required to work extended rosters, adhere to minimal contact measures in the workplace and in accommodation camps. To minimize close contact work teams began working in ‘bubbles’ with enhancement of personal hygiene measures and separate meal arrangements with workers usually eating alone in their rooms at camp. For those workers who travelled internationally or interstate as travel restrictions were imposed, they had to make the decision to either stay work or return home resulting in workers being away from their family and support networks for extended durations (6 to 9 months). Changes in work schedules in response to COVID-19 including extended shifts and rosters, uncertainty of FIFO logistical arrangements, introduction of COVID-19 testing affected workers' job satisfaction, attitude and wellbeing as workers attempt to cope with factors outside of their control (Parker & Fruhen, 2018). The measures implemented to reduce potential spread and contain COVID-19 infections in the workplace and FIFO accommodation also increased social isolation for workers, a psychological risk (Almohassen et al., 2022) for workers already removed from their normal social networks and support arrangements. Therefore, the construction industry has mitigated the social isolation through the inclusion of mental health measures in COVID-19 management plans (Alsharef et al., 2021).

This paper presents the impact of COVID-19 on a construction project safety performance using actual project safety data and the moderating effect of site leadership measured through safety climate perceptions.

5.2 Literature Review

5.2.1 Impact of COVID-19 on Safety Performance

Research on the effect that COVID-19 had on the health and safety performance within the construction industry has been predominantly post the advent of COVID-19 and based on interview and/or survey techniques or a review of policies and control practices (Almohassen et al., 2022; Del Rio-Chanona et al., 2020; Jones et al., 2022; Nnaji et al., 2022; Pamidimukkala & Kermanshachi, 2021). The early COVID-19 pandemic research (Almohassen et al., 2022; Choudhari, 2020; Fargnoli & Lombardi, 2021; Onubi et al., 2021; Stiles et al., 2021) provided a better understanding of the perceptions of people working within the industry and enabled construction organizations to adapt risk management programs to prevent and/or mitigate COVID-19 effects on worker health and wellbeing. However, minimal research has measured the direct impact of COVID-19 on construction worker safety performance using actual project safety performance leading and lagging indicators.

Construction workplace safety performance measurement currently uses a variety of indicators which measure event frequency (injury and/or incident) which are considered 'lagging indicators. Leading indicators in the form of actions taken to mitigate safety hazards (safety observations, hazard reports) and communication activities (pre-start briefing, toolbox meeting) and viewed as antecedents of events (Hinze et al., 2013; Shea et al., 2016). Incident and injury frequency rates are indirect safety performance measures as they measure the 'absence of safety' (Dekker & Pitzer, 2016). The risk of relying on incident and injury frequency rates is they fail to detect escalating risks that deteriorate safety performance until after the events have occurred (Hopkins, 2011a; Lofquist, 2010). Due to the limitations of using event rates to measure safety alternative leading indicators using measures of safety related activity have been identified and modelled to predict safety events in a workplace (Hallowell et al., 2013; Hinze et al., 2013; Salas & Hallowell, 2016). Lingard (2017) identified the relationship between leading indicators and event frequency is variable and depending on the timing of the measure may have a circular relationship. An event (injury) may cause an increase in safety activity (e.g., toolbox meeting), so the event predicts an increase in a leading indicator, equally the leading indicator (low frequency of the activity) may predict the event.

Measuring construction safety performance, given the decentralized organization structure (Lingard et al., 2017), is complex as leading indicators are interrelated and not always directly related to the lagging indicators of incident or injury performance (Saunders et al., 2017). To measure the impact of COVID-19 on safety performance consideration needs to be given to lagging measures (incident and/or injury rates), leading indicators which measure field level risk activity (e.g., hazard reporting, critical control verifications) and the leadership behaviours which support the creation of positive safety climate (e.g., supervisor observations).

5.2.2 Interrelationship between Safety Performance and Safety Climate

Workplaces with more positive safety climate have a better safety performance as workers hazard recognition and safety risk perception increase (Pandit et al., 2019), improve safety compliance as a function of supervisor safety leadership (Kapp, 2012; Petitta et al., 2017) and participation in safety practices (Zhang et al., 2020). Safety climate models differentiate two dimensions of safety performance; safety participation and safety compliance through determinants of performance (e.g., personal risk tolerance), performance antecedents (e.g., knowledge, skills) and measuring behaviours specifically involved in work tasks (Al-Bayati, 2021; Griffin & Neal, 2000; Pandit et al., 2019). Safety compliance is the adherence to rules and procedures whereas safety participation is the engagement in safety activities to improve safety outcomes (Zohar, 2008; Griffin & Neal, 2000). Significantly safety compliance is adhered to as it serves as it is cost effective and immediately available choice strategy and readily adaptable to the situation compared with more engineered solutions (Reason, 2016). Whereas safety participation can be viewed as a form of safety citizenship relating to discretionary actions which contribute to organization safety outcomes (Newton & LePine, 2018). Both dimensions, safety participation and safety compliance, are required in a safety management program. Compliance and discipline provide routine and reliability whilst initiative and participation improve the capacity for safe decisions and behaviours in less predictable situations (Zohar, 2008).

5.2.3 Leadership Aspects Impacting Workers during COVID-19

Leaders create safety climate at the organizational and supervisory levels (Zohar, 2008; Griffin & Neal, 2000; Kapp, 2012), and frontline supervisors influence the safety behaviours of their workers (Barling et al., 2002; Zohar, 2002). However, the organizational safety climate will modify the effects of supervisory safety climate (Griffin & Neal, 2000; Kapp, 2012; Neal et al., 2000). COVID-19 was a major disruption to the relationships between project management, supervisors, and the workers. By studying pre and post COVID-19 safety climate, the factors affecting the relationships between stakeholders became more evident. Establishing these factors enabled management to improve support to frontline leaders to positively influence workers compliance and participation in safety processes, and the project safety performance.

Safety climate arises from individual's experiences and perceptions being shared socially in the workplace. These shared perceptions arise from two antecedents being, symbolic social interactions and supervisory leadership (Schneider et al., 2017; Zohar & Tenne-Gazit, 2008). When faced with complex and potentially ambiguous work situations individuals will attempt to make sense of the situations through social interactions with others, to gain an understanding of how to interpret and respond to the situations (Weick et al., 2005). Through the repeated social exchanges, particularly supervisors, the leader creates the safety climate as they make sense of organisational requirements and the observed supervisor actions and practices (Dragoni, 2005).

Effective leaders establish meaningful high quality relationships with their workers and care for their wellbeing particularly in high-risk situations found on construction projects. The observed practices and social exchanges between supervisor and worker, or between workers, affect the work group safety climate perceptions and perceived priorities within the work unit, e.g., prioritizing safety over production demands (Zohar & Tenne-Gazit, 2008). Measuring safety climate builds an understanding of the social mechanisms impacting either the social interactions which build common and aligned safety attitudes within a project, or factors affecting frontline leaders at the point in time.

An early study indicated COVID-19 acted as a distraction reducing workers and line supervision capacity to focus on the day-to-day safety risks (Del Rio-Chanona et al., 2020). Almohassen et al., (2022) identified whilst there was a general heightened awareness of core safety elements during the pandemic the importance rating of the elements was not different after COVID-19. Three exceptions were identified, 'participation in safety programs', 'report safety and health concerns', and 'identification of hazards associated with emergency and non-routine situations'.

All relate to the heightened awareness of COVID-19 and the health controls imposed on construction sites to prevent spread of the disease.

The COVID-19 pandemic progressed it was a major disruption event on projects with increased pressure on site leaders to implement the COVID-19 management plan. Leaders were expected to communicate COVID-19 changes to the workforce, maintain morale, ensure hygiene measures and social distancing were applied whilst maintaining production schedules. Amidst the juggling of COVID-19 measures site leaders were responsible to maintain a positive safety climate as the project safety risks had not diminished with high-risk activities continuing to be conducted. In the absence of a positive safety climate (Guo et al., 2016; Onubi et al., 2021) workers' perception of COVID-19 risks, and the systems, practices, and behaviours of leaders to manage COVID-19 risks, had the potential to increase workers anxiety or become a distraction from the high-risk work being conducted (Jones et al., 2022; Nnaji & Karakhan, 2020; Onubi et al., 2021). The site leaders (project manager, construction manager, supervisors) set the safety climate on the project site which directly affects the attitude and behaviours of the workers (Onubi et al., 2021). Site leaders who can establish a positive safety climate will generate higher levels of safety participation across the workforce and reduce "at risk' behaviours of the workers (Al-Bayati, 2021; Clark, 2006; Kapp, 2012). To achieve a reduction in risk during COVID-19 leaders needed to have the skill, knowledge, and capability to communicate changes to keep workers informed whilst balancing project schedule, materials, equipment (Stiles et al., 2018). Site leaders also need to moderate perceived increased work pressures as sites continue to meet construction schedules impacted by labour and material shortages (Choudhari, 2020). Almohassen et al. (Almohassen et al., 2022) identified the changes in safety practices which occurred during the pandemic, however a greater understanding of leadership factors and safety climate which support safe outcomes would benefit site leaders managing major project disruptions like the COVID-19 pandemic.

5.2.4 Measuring Construction Safety Climate

Building on Mohamed's (Mohamed, 2002) safety climate measurement model designed for the construction industry Saunders (Saunders et al., 2017) further developed the instrument to extend to other stakeholders (e.g., owners, engineers, subcontractors). The safety cultures which shape construction project safety 'decision making' in Australian construction projects is complex (Mohamed, 2002) so it is important to discern differences between safety climate perceptions between organizations. The outputs of safety climate surveys provide project management an insight into organization, team and individual safety perceptions and factors influencing either the social interaction or effective supervisor modelling of positive safety.

5.3 Study Objectives

Insights gained from comparison of safety performance and safety climate measures pre and post COVID-19 disruptions will benefit organizations and project leaders to focus on practices and behaviours which support effective risk management throughout the disruption event.

The study aims to:

i. Evaluate COVID-19 influence on the safety climate and safety performance of a construction project.

ii. Evaluate the influence of leadership on a construction project safety performance under the impact of COVID-19.

This paper is novel in that it provides insights from a construction project which experienced pre and post COVID-19 conditions and provides direct measurement of safety performance throughout the pandemic phenomenon. The data and safety perceptions of the workers reflect the journey the construction project went through learning to manage COVID-19 on site, the direct impacts on labour and material shortages, isolation of the workers and the challenges facing the site leaders. The study also provides commentary of the additional complexity facing construction project throughout COVID-19 and the decisions taken by organizations to maintain ‘safe work environments’ on remote sites.

5.4 Methods

5.4.1 Project Selection

An Australian construction project (Table 17) was opportunistically selected for the study as the project had mobilized to the field prior to the COVID-19 pandemic (August 2019–6 months prior to first wave) and continued for a further eighteen months through the COVID-19 pandemic for a total of 72 weeks. Two safety climate surveys were conducted one in January 2020 (pre-COVID), and one in October 2020 (post COVID). The participating organization changed out the Project Manager (Lead A) to (Lead B) at the end of week 43 which provided a comparison of the safety impact between two different leaders on the same project.

Table 17: Case study - project details

Project Parameters	Details
Location	Pilbara Western Australia
Scope	Infrastructure–earthworks, rail formation, tunnel, and bridges
Contract Model	Procure, Construct
Contract Structure	Joint Venture–self perform with specialist subcontractors
Workhours	1,120,000 with 270 persons on site at peak
Duration	Total: 23 months. On site: 16 months
Value	>$500 k AUD

5.4.2 Safety Climate Survey

The Saunders et al., (Pandit et al., 2019) safety climate survey was selected as it had been developed for construction organizations and measured individual, team, supervisor, and management factors. The safety climate survey provided a point in time benchmarking tool measuring eleven (11) attributes of worker safety climate perceptions (Table 18) comprising 35 questions. The safety climate survey was structured to measure organization, team, and individual safety perceptions across eleven Likert like units of questions (Table 18) with two questions of free text on safety risks and safety improvements identified by participants. The question responses were formatted into a Likert-5 level response format and uploaded to the Microsoft Forms® survey tool for digital data capture and produced in hard copy for field based personnel.

Table 18: Structure of safety climate survey

Organizational Elements	Likert Scale Units–Group of Questions
Company (ORG Avg)	Management Commitment (MC Avg) Communication (COM Avg) Rules and Procedures (RUL Avg) Overall Safety Climate
Team (TEAM Avg)	Supportive Environment (SUP Avg) Supervisory Environment (VIS Avg) Workers Involvement (WI Avg)
Individual (IND Avg)	Personal Appreciation of Risk Work Hazard Identification (HAZ Avg) Work Pressure (WKP Avg) Competence (CMP Avg)
Context Questions	Safety Risks Safety Improvements

Participants in the survey were recruited in two ways, attendance at a site safety meeting and through an email distribution list provided by the organization. Site based surveys were facilitated by the organization, where the researcher (Selleck) attended the project work site, attended the weekly safety toolbox meeting with the workers, provided an overview of the survey aims, ethics being applied and handed out hard copy survey forms. Workers were provided time to complete the survey which were deposited by the participants anonymously in a box provided. The collection box remained available until the shift. The process was repeated for the cross shift a week later.

Personnel with access to computers were emailed the Microsoft Forms® survey link to complete the survey within the two weeks, with a reminder on day 7 and day 13. Participation in the survey was voluntary and anonymous with basic demographical information and response to questions collated into the MS Form® database for analysis. All participants were asked to provide consent on the survey forms consistent with the ethics requirements for the research and where consent was not provided to use the data, the information was excluded from the analysis. Incomplete hard copy forms were excluded from the survey results and not uploaded into Microsoft Forms® data set.

The safety climate survey was deployed twice during the study, one month after the mobilization of the project into the field prior to COVID-19 pandemic being present in the region (end of January 2020) under Leader A and repeated post COVID-19 impact on the project in October 2020 under Leader B. The survey in both instances was conducted across two weeks to capture all three crews on the project with time provided for the site team to complete during the weekly safety meeting.

The Microsoft Forms® survey analytics was used for comparative analysis and to provide a report of the response summary to the participating company.

Each participant's Likert Scale scores were averaged using following formulas to transform data so comparative statistical analysis could be conducted on responses from the two sets of surveys.

$$\text{Average Likert Scale Score } (x) = \text{sum } (Qi \text{ score} + Qii \text{ score} + \ldots Qn \text{ score})/n \text{ scores} \quad (4)$$

where: Qi = participant score for (i) Likert scale question, n = number of Likert questions with Likert Scale (Minimum value = 0, Maximum value = 5).

Statistical analysis was conducted to highlight the significance of the relationship between variables including organisational elements and safety climate factors.

5.4.3 Safety Performance

The participating organization provided two safety performance data sets; incident events and counts of risk management activities (Table 19).

Table 19: Summary of project safety performance data / risk management activities

Measure	Unit
Personal Risk Assessments	% completed [a]
Hazard Reports	% completed
Supervisor Observations and Interventions	% completed
Major Accident Prevention (MAP) Critical Control Checks	% completed
Major Accident Prevention (MAP) Audits	% completed
Exposure hours	Count
Total number of incidents	Count
Total incident frequency rates	Frequency rate [b]

[a] % completed = (number of activities completed/planned number of activities) * 100. [b] Frequency rate = No of injuries in period * 1,000,000/exposure hours in period.

5.4.4 Statistical Analysis Method

The data was analysed using R statistical package applying exploratory analysis steps to understand the relationships and strength of relationships between the data set factors and the independent variables (R Core Team, 2020).

5.4.4.1 Safety Climate Survey Model

The Safety Climate Survey statistical model tests each of the Likert Scale like parameter to identify if there is a significant difference in the means due to the factors (COVID, Organization, Gender, Age). The model analysed for differences in means between pre/post COVID surveys, participant Organizations (Client, Principal Contractor, Subcontractor), gender (male, female, non-disclosed) and age groups (<18, 18–29, 30–39, 40–49, 50–59, 60–69, >69). Each of the factors may contribute to differences in safety climate measures between the two survey events and is represented by Equation (2):

Lm(var x ~ COVID + ORGANIZATION + GENDER + AGE, data = data set)

(5)

e.g., Lm(COM_Avg ~ COVID + ORGANIZATION + GENDER + AGE, data = sc_survey_data)

where linear regression of the mean scores (Lm) is applied to ‘var x’ which represents the climate measure (Likert scale unit or Organization Element) being analysed. The linear regression model includes all four factors (COVID, Organization, Gender, Age) to determine significance (p = <0.05).

The results return regression analysis of the mean scores (F) and determines significance (Pr > F) at 0.05% significance level. Variables identified as potentially different from the exploratory analysis were fitted to linear regression model with significance calculated using multi-regression analysis (ANOVA) and checked for assumptions of normality and homoskedasticity. The effect size was for significant variables (p = 0.05) was calculated using the estimated marginal means of the variable within the statistical model (Equation (3)).

Emmeans (var x, pairwise ~ FACTOR)

(6)

e.g., emmeans(COM_avg, pairwise ~ AGE)

The significance between groups was confirmed through post hoc Tukey honest significant difference (Equation (4)) which compares other means of every factor to the means of every other factor and identifies any difference between two means that is greater than the standard error.

$$Qs = (Y_A – Y_B)/SE \quad (7)$$

where Y_A is the larger of the two means being compared, Y_B is the smaller of the two means being compared, and SE is the standard error of the sum of the means.

4.4.2. Safety Performance Model

The Safety Performance model tests the factors (COVID, LEAD) which may contribute to differences in safety measures between the two survey events and is represented by Equation (5).

Lm(var x ~ COVID + LEAD < data = data set)

(8)

e.g., Lm(INCIDENT Rate ~ COVID + LEAD, data = P1_safety_stats)

where linear regression is applied to ‘var x’ which represents the perception measure (Likert scale unit) being analysed.

Variables identified as potentially different from the exploratory analysis were fitted to linear regression model with significance calculated using multi-regression analysis (ANOVA) and checked for assumptions of normality and homoskedasticity. The effect size was for significant variables (p = 0.05) was calculated using the estimated marginal means of the variable within the statistical model (Equation (6)).

$$\text{Emmeans (var x, pairwise} \sim \text{FACTOR)} \tag{9}$$

5.5 Results

5.5.1 Safety Climate Survey

The COVID-19 surveys were undertaken by a total of 194 participants across the two survey events. Sixty eight (68) participants completed surveys in the pre-COVID survey and 126 in the post-COVID survey representing 79% and 91%, respectively of the onsite workforce, an overall response rate of 85%. Fourteen (14) surveys were incomplete, and 14 participants elected to not participate in the research leaving 166 surveys included in the study. The response rate compares favourably for similar research-based safety climate surveys including construction industry surveys (Barbaranelli et al., 2015; Cheung & Zhang, 2020; Hyndman & Athanasopoulos, 2018; Kasim et al., 2019; Saunders et al., 2017). Participation rate in the initial baseline safety climate survey was impacted by the rostering of workers and limited involvement by white collar workers. The post-COVID-19 survey had an increase in participation rate, however access to participants across the three different rosters was limited due to COVID-19 restrictions.

5.5.1.1 Demographics

A shift in the age distribution for the project's working population was observed between the two surveys. The second survey had a 11.1% reduction in the 18 to 29 age group an increase of 9.5% and 4.9% in the 40 to 49 and 50 to 59 age groups, respectively. (Figure 29).

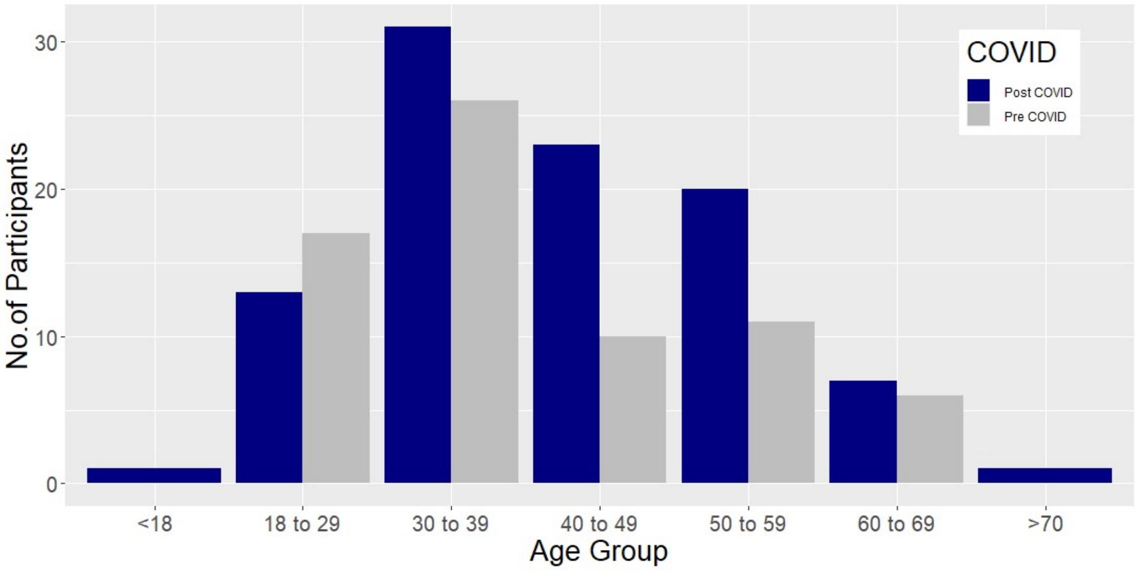


Figure 29: Comparative age demographic

There was a change in participation with subcontractors representing 81.2% of the October 2020 survey participants compared to 56.5% in January 2020. (Figure 30). There was limited participation in either survey by Owner organization representatives (2 participants).

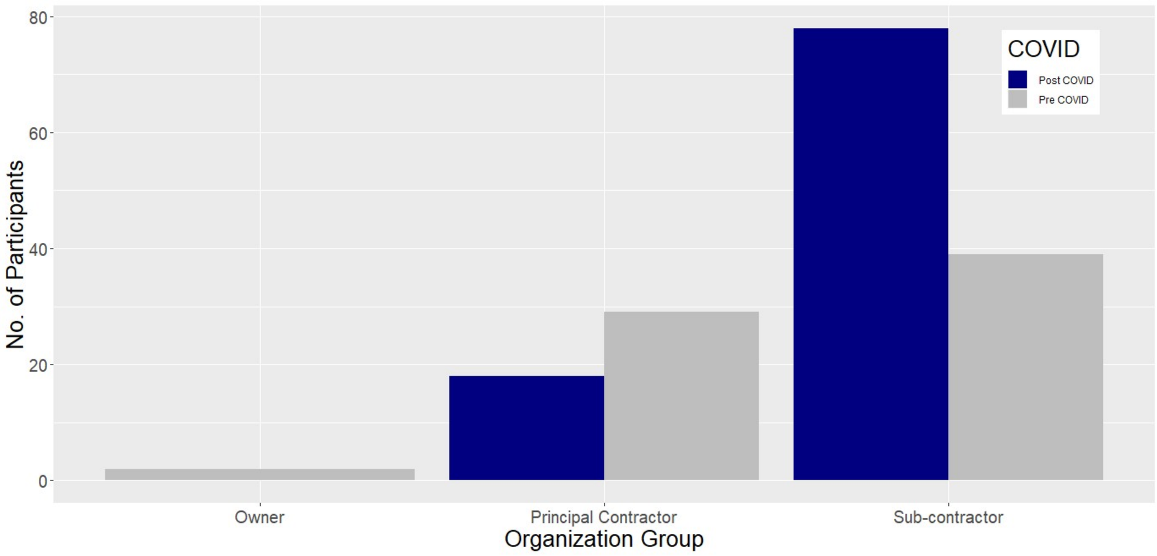


Figure 30: Participating organizations

The participants surveyed were predominantly from the equipment operator and trades occupations with limited input from superintendent/construction management, engineering, catering, and administration occupations. There was a significant increase in the Equipment Operator roles between the January and October surveys. (Figure 31).

The site based field occupations conduct high risk activities which means understanding their safety perceptions provides an opportunity for project leaders to effectively manage potential safety risks.

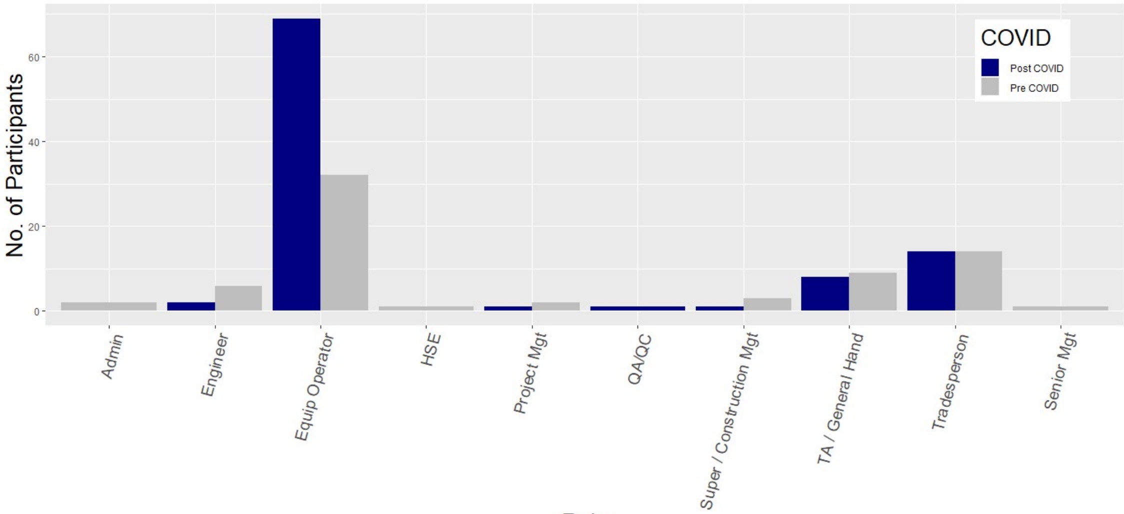


Figure 31: Comparative participation by roles

5.5.1.2 Measures of Difference between Safety Climate Surveys–Pre/Post COVID-19

Plotting of participant scores by Likert scales identified a similar profile and spread of scores between the two surveys except for Safety Communication (COM_Avg). The average safety climate communication scores have improved between the two surveys with more participants ranking the communication higher on the Likert scale (0–5) with 0 low score and 5 high score of safety rated perceptions (Figure 32).

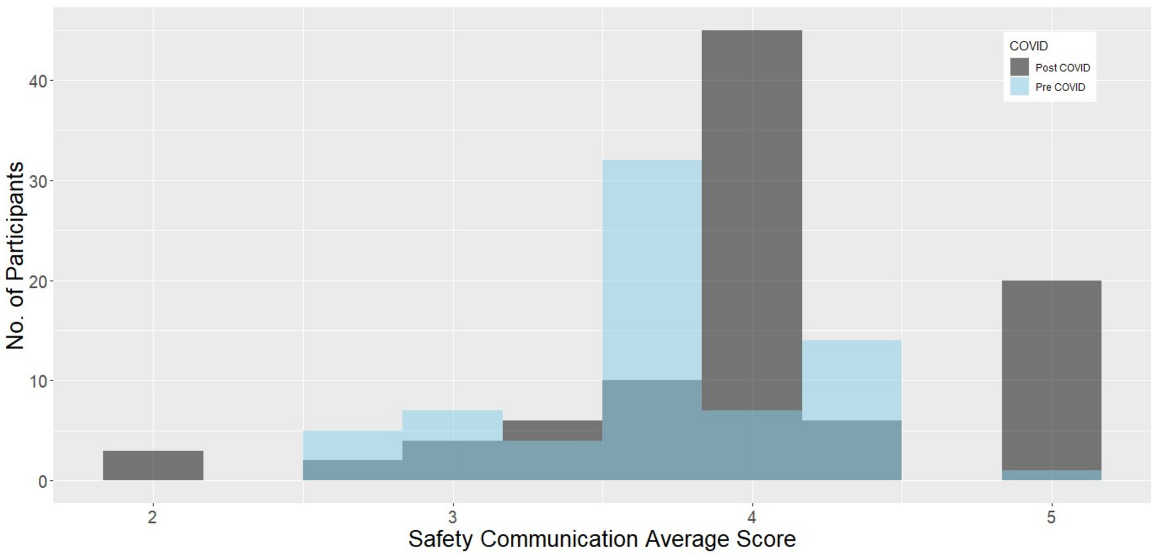


Figure 32: Safety communication average scores by participants (n=166)

Linear regression models were fitted to all variables (Likert scale units) and the different organization elements (organization, team or individual) with ANOVA of the fitted means used to identify significance between the Likert scale units. The analysis identified significant difference between the survey results for Likert Scale measures of Communication, Supportive Environment, Work Hazard Identification, Worker Involvement and organization elements of Team and Individual safety perceptions (Table 20).

Table 20: Safety climate survey Likert scale & organization elements ANOVA results

Factor: COVID-19 (df 1:154)					
Likert Scale	Sum Squares	Mean Square	*F* Values	Pr (>F)	Significant
Communication	4.455	4.455	12.063	<0.001	Yes
Supporting Environment	0.000	0.00003	0.0001	0.994	-
Work Hazard Identification	0.058	0.058	0.107	0.744	-
Workers Involvement	0.500	0.5003	1.087	0.299	-
Individual Element	0.032	0.032	0.122	0.727	-
Team Element	0.003	0.003	0.008	0.929	-
Factor: ORGANIZATION (df 2:154)					
Likert Scale	Sum Squares	Mean Square	*F* values	Pr (>F)	Significant
Communication	0.028	0.028	0.772	0.782	-
Supporting Environment	2.274	1.137	2.168	0.118	-
Work Hazard Identification	4.623	4.623	8.515	0.004	Yes
Workers Involvement	2.782	2.781	6.042	0.015	Yes
Individual Element	1.018	1.018	3.916	0.049	Yes
Team Element	2.195	2.194	6.966	0.009	Yes
Factor: GENDER (df 2:154)					
Likert Scale	Sum Squares	Mean Square	*F* values	Pr (>F)	Significant
Communication	0.384	0.192	0.595	0.594	-
Supporting Environment	0.287	0.143	0.272	0.761	-
Work Hazard Identification	0.062	0.031	0.057	0.944	-
Workers Involvement	0.234	0.117	0.254	0.776	-
Individual Element	0.008	0.004	0.015	0.985	-
Team Element	0.326	0.163	0.517	0.597	-
Factor: AGE (df 6:154)					
Likert Scale	Sum Squares	Mean Square	*F* values	Pr (>F)	Significant
Communication	3.915	0.652	1.767	0.109 *	Outliers skew
Supporting Environment	11.039	1.839	3.508	0.003	Yes
Work Hazard Identification	1.996	0.333	0.613	0.719	-
Workers Involvement	3.370	0.561	1.219	0.299	-
Individual Element	1.000	0.167	0.641	0.697	-
Team Element	3.752	0.635	1.984	0.071 *	Outliers skew

* Further model analysis required given data distribution across the groups with potential outliers skewing results.

5.5.1.3 Safety Climate Communication –COVID and Age Factor Analysis

Initial data exploration identified potential data 'outliers' in the Organization (Owners–Figure 33) and Age (<18 and >70–Figure 34) factor groups where participants of the age group were only in one of the surveys. Further analysis of the data excluded 'Owners' and the two outlier age groups.

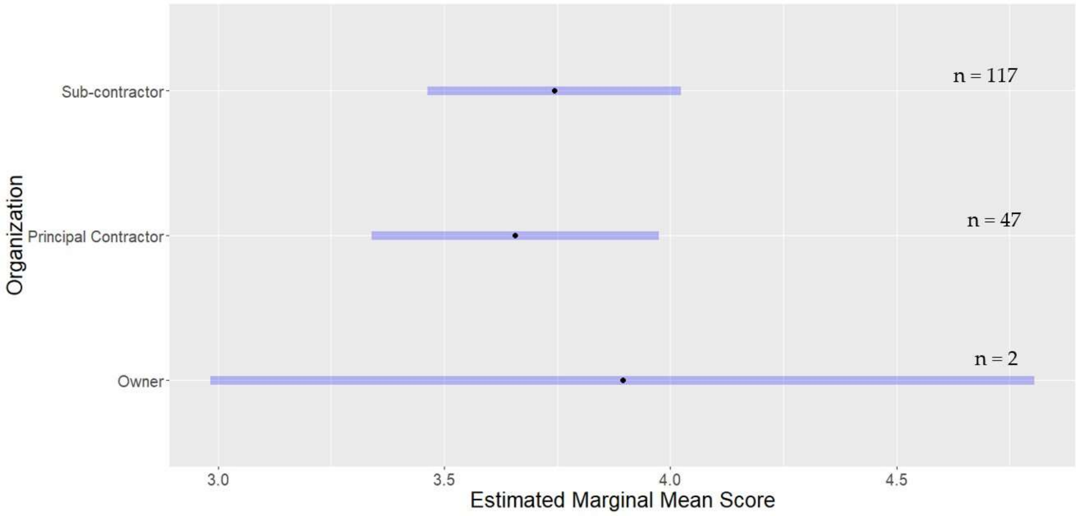


Figure 33: Estimated Marginal Means distribution by organization safety communication.

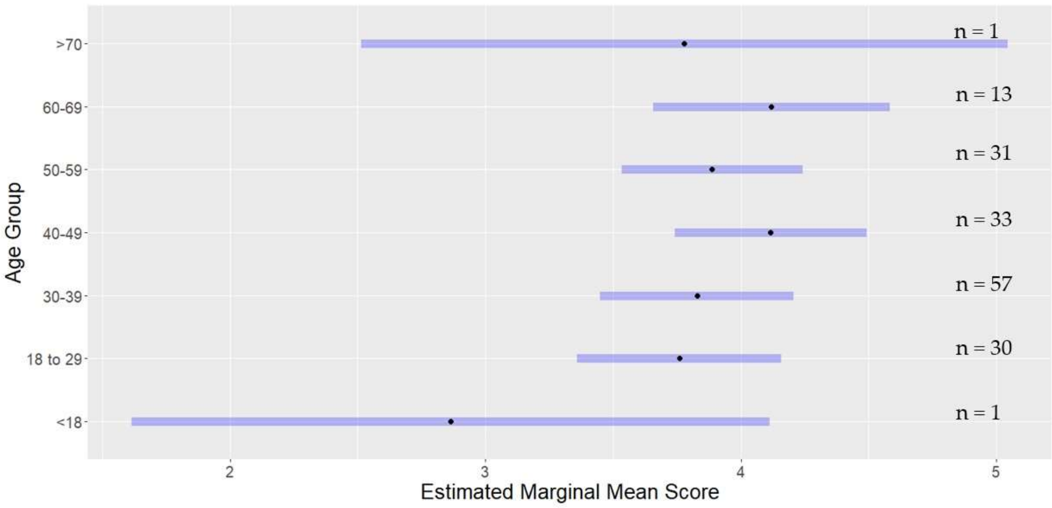


Figure 34: Estimated Marginal Means distribution by age group for safety communication.

The average safety climate communication scores were affected by two factors, COVID-19 (p = <0.001) and age (p = 0.1) with the distribution of the data by age (Figure 35). The size of the effect was tested by Estimated Marginal Means with results for COVID and AGE factors shown in Table 21. ANOVA assumptions of normality and homoskedasticity were confirmed through visual inspection of residuals plots.

At the 5% confidence level there is sufficient evidence (F(1, 154) = 12.38, p = 0.0006) to claim the mean Communication Average score between COVID groups are different. Post COVID scores are on average 0.289 units higher.

Statistical evaluation of AGE factor identified a weak correlation with Communication Average scores (F(4154) = 1.99, p = 0.098). The 40–49 age group (group a) were significantly different (t = 2.246, p = 0.026) and confirmed through post hoc Tukey analysis (Figure 35. The 18–29 age group was not significant at the 5% confidence level, however, was identified as a separate group (group b) in post hoc Tukey analysis (Figure 35). The other age groups (group ab) were not differentiated from each other, however, was identified through post hoc Tukey analysis as being different from both the 18–29 age group and 40–49 age group (Figure 35).

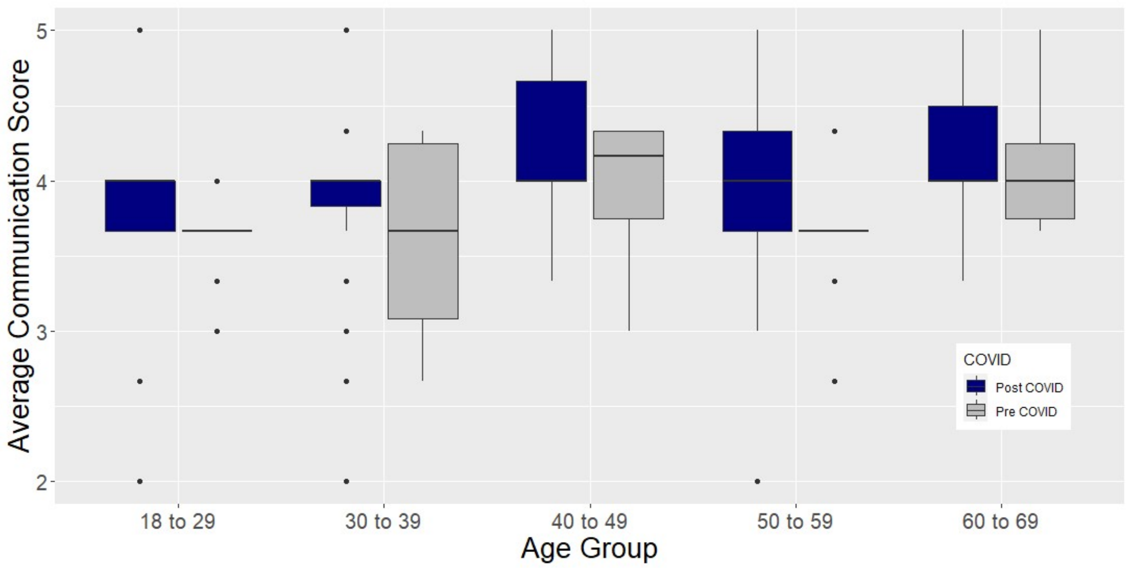


Figure 35: Communication safety climate by COVID and AGE factors (n=166)

Table 21: Safety communication by age group Estimated Marginal Means across COVID phase.

Age Group	Estimate Marginal Mean	Standard Error	*T* Value	Pr (>[t])
30–39	0.069	0.140	0.495	0.621
40–49	0359	0.160	2.246	0.026
50–59	0.129	0.165	0.781	0.436
60–69	0.362	0.204	1.772	0.078 [1]

[1] significant at 10% confidence level when further tested ad hoc by Tukey (HSD).

5.5.1.4 Supportive Environment Safety Perceptions–Age Factor Analysis

Data analysis without the outlier age groups (<18 and >70) identified a significant difference in the average safety perceptions around Supportive Environment between age groups (F(4154) = 4.53, p = 0.0017) at the 5% confidence level. Post hoc analysis (Tukey HSD mean = 3.85) identified three different sub age groups. The 40–49 and 60–69 formed group a with average supportive environment score > 4. The 30–39 and 50–59 age groups (group b) had the lowest average scores with the 30–39 age group having the widest variance in mean scores. The 18–29 age group (group ab) was differentiated from the other ages with a median average score and moderate variation in mean scores.

5.5.1.5 Organization Factor Analysis–Work Hazard Identification and Workers Involvement

The exclusion of outliers (Owner, age groups) was applied to the linear regression model for both Work Hazard Identification and Workers Involvement sets of Likert Scale data with size effects measured by Estimated Marginal Means.

Safety perceptions for Work Hazard Identification and Workers Involvement were significantly different between Principal Contractor and Subcontractor organizations at the 5% confidence level confirmed through post hoc Tukey analysis. Principal Contractor average scores are lower than Subcontractor average scores (Table 22).

Table 22: Safety communication by Age group Estimated Marginal Means across COVID phase

Likert Scale	*F* Value	Pr > (F)	Emmeans (Principal Contractor/Subcontractor)
Work Hazard Identification	8.515	0.004	−0.428
Workers Involvement	6.042	0.016	−0.298

5.5.1.6 Organization Factor Analysis–Team and Individual Safety Perception Elements

The exclusion of outliers (Owner, age groups) was applied to the linear regression model for both Team and Individual elements data for ANOVA analysis with size effects measured by Estimated Marginal Means (Table 23).

Safety climate scores for Team was significantly different between Principal Contractor and Subcontractor at the 5% confidence level and confirmed by post hoc Tukey analysis. Individual average safety climate scores were not different when measured by post hoc Tukey analysis.

Table 23: Organizational factors for Team and individual elements of safety climate scores.

Likert Scale	*F* Value	Pr > (F)	Emmeans (Principal Contractor/Subcontractor)
Team	6.984	0.009	−0.304
Individual	3.916	0.049 *	−0.214

* Confirmed not to be different when measured by post hoc Tukey analysis.

5.5.1.7 Safety Climate Survey Summary

The safety climate scores were significantly influenced by COVID, Organization and Age factors. COVID influenced Communication safety perceptions which varied by age group as did Supportive Environment. Differences in safety climate between Principal Contractor and Subcontractors was identified for Work Hazard Identification, Worker Involvement and Team attributes. Results identified COVID-19 adversely impacted management safety communication which as Table 21 shows also influences organizations and different age groups safety perceptions.

5.5.2 Safety Performance Results

The leading and lagging safety performance measure trends over time were graphed for the COVID and LEAD factors for exploratory analysis. Visual trends were observed for hazard observation (Figure 36 a, b) incident rate (Figure 37a, b), Supervisor Observation & Interventions (Figure 38 a, b) and MAP checks (Figure 39 a, b) and were selected for statistical analysis.

Each selected safety performance parameter was fitted to linear regression model for ANOVA to test significance by COVID and Leader factors with Estimated Marginal Means used to assess the scale of the difference. ANOVA assumptions of normality and homoskedasticity were confirmed through visual inspection of residuals plots.

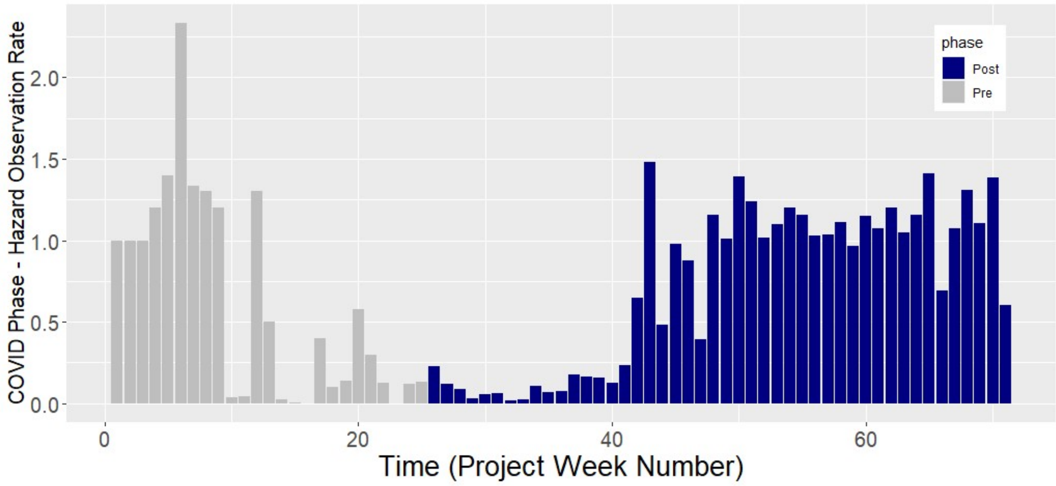


*Figure 36(**a**)*

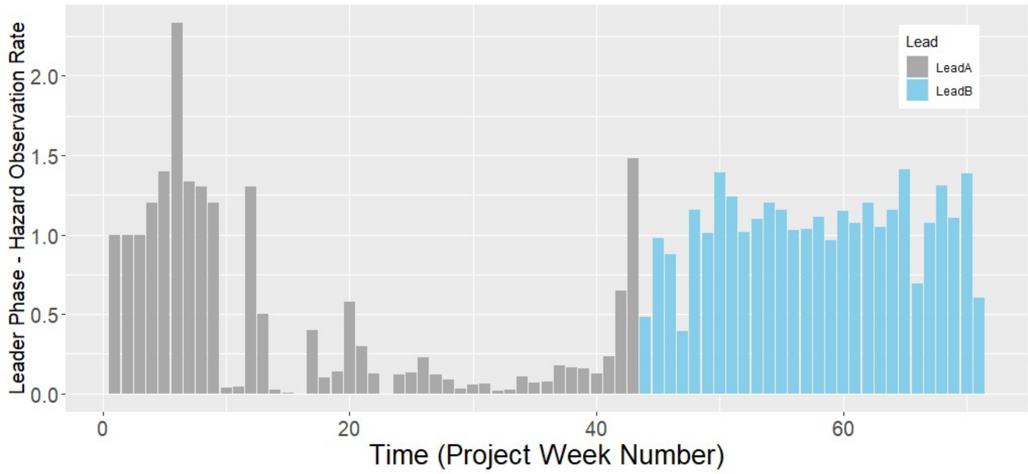
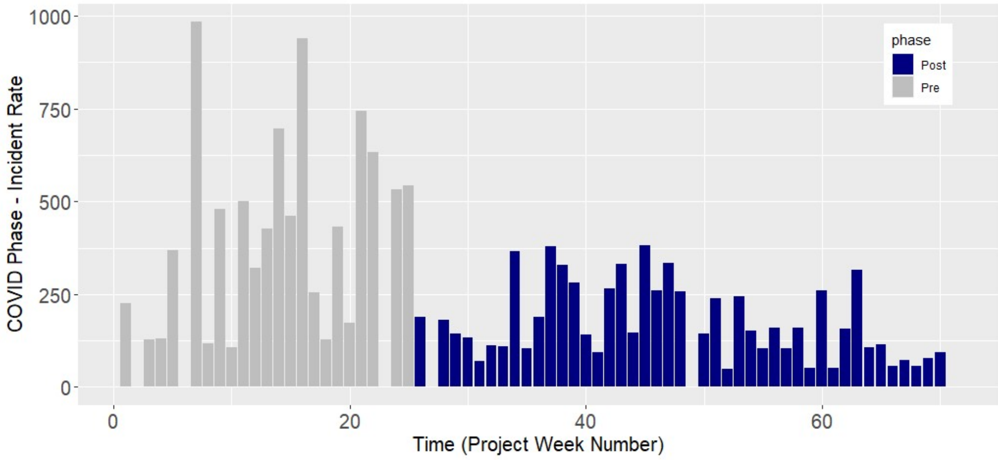


*Figure 36(**b**)*

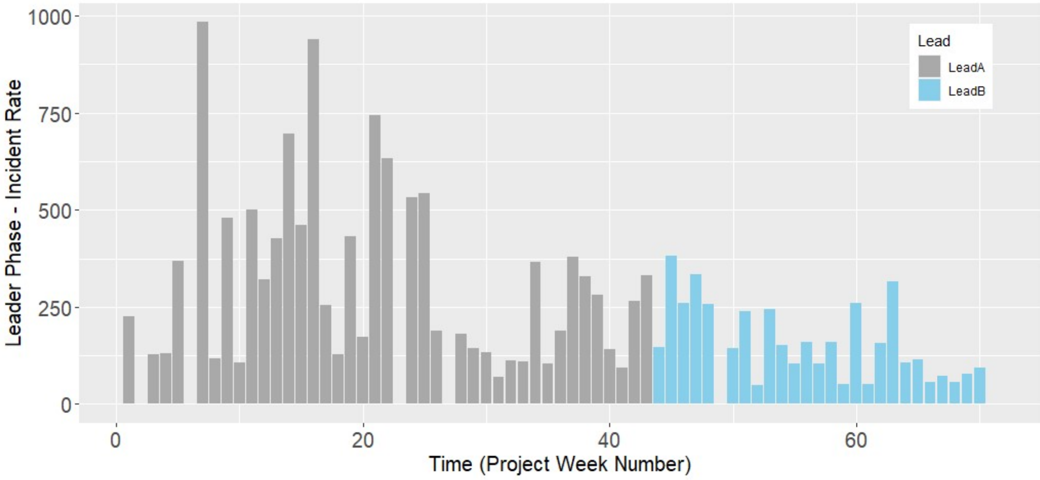
*Figure 36: Hazard observation rate by **(a)** COVID Phase; **(b)** Different Project Leaders*

5.5.2.1 COVID-19 Effect

The project safety performance as measured by Total Incident rate improved significantly in the eight weeks post COVID-19 affecting site operations (Figure 37a & b). The incident rate deteriorated again and plateaued but did not return to the original levels and was on average significantly lower post COVID-19. The mean incident rate between Pre and Post COVID was different ($F(1,68) = 19.9$, $p = 3.1e{-}05$) where the post COVID incident frequency rate is on average 183 units lower.



(**a**)



*(**b**)*

Figure 37: Total incident rate by (a) COVID Phase; (b) Different project leaders

The Supervisor Observation (SO&I) rate was significantly different between Pre and Post COVID (F(1,18)=8.2, p=0.0056) with the Post COVID rate being on average 0.23 units higher than Pre-COVID rate (Figure 38 a & b).

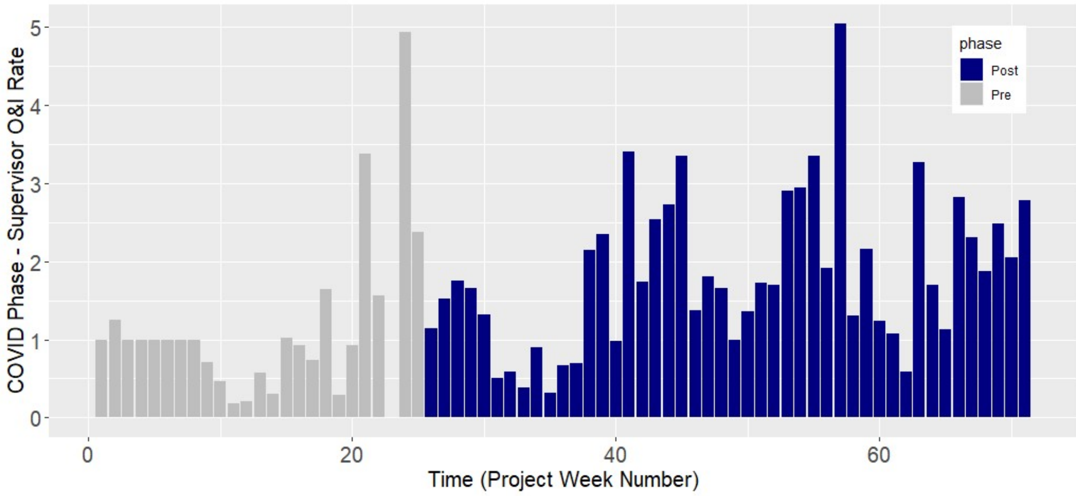


Figure 37(a)

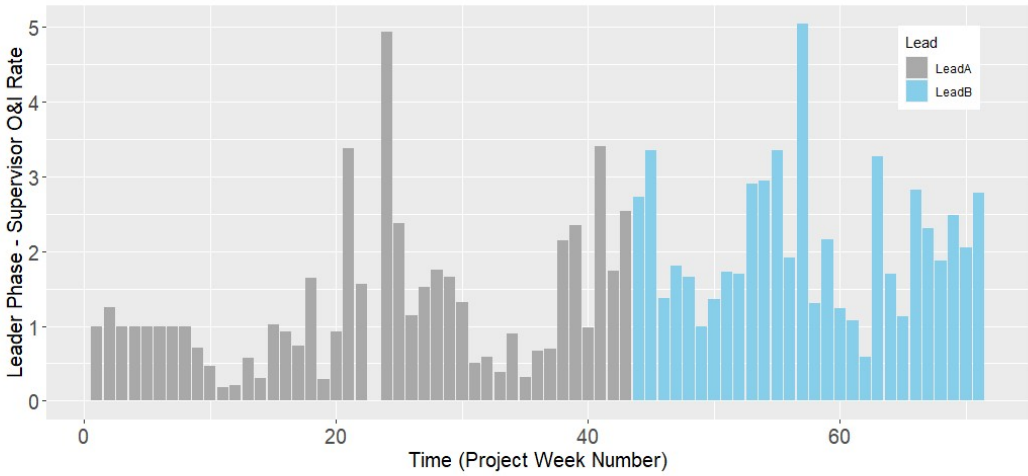


*Figure 37(**b**)*

Figure 38: Supervisor observation and intervention rate by (a) COVID Phase; (b) Different project leaders

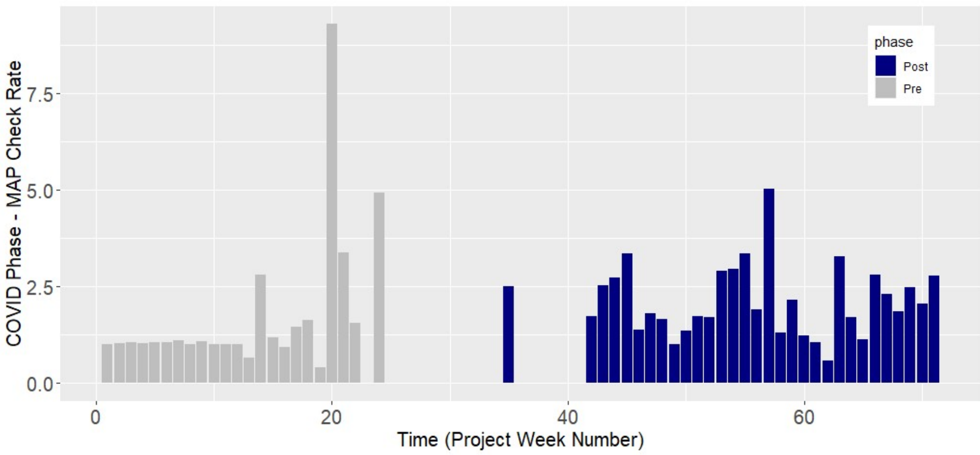


*Figure 39(**a**)*

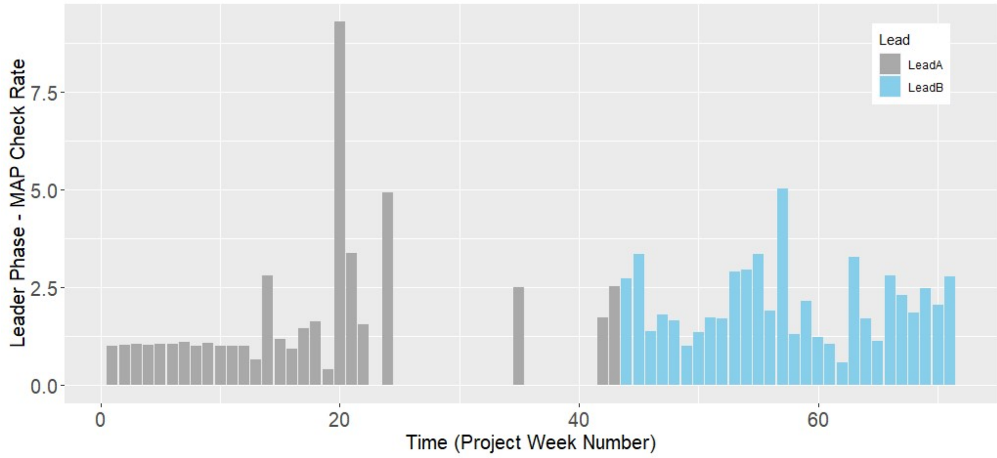


*Figure 39(**b**)*

Figure 39: MAP check rate by (a) COVID Phase; (b) Different project leaders

5.5.2.2 Leader Effect

Leaders influenced frontline risk management practices of Hazard Observations (HAZOB), Supervisor Observations (SO&Is) and Critical Control verification (MAP Check) rates. On average Leader B improved the rate of all frontline risk management practices, HAZOBs by 0.83 units (F(1,68) = 38.7, p = 3.5e−08), SOIs by 0.76 units (F(1,68) = 6.7, p = 0.11) and Critical Control verification rate by 1.75 units (F(1,68) = 18.36, p = 5.905e−05).

The times series graphs (Figure 37 a, b; Figure 38 a, b; Figure 39 a, b) for each of the risk management practices show a similar trend with risk management practices slowing down or ceasing in the case of MAP Checks with the onset of COVID-19 impacts (week 25) and not increasing again until under the influence of Leader B.

In summary the project had a significant improvement in incident rate and SOIs post COVID. Leader B improved the rate of leading indicators including Hazard Observations, Supervisor Observations & Interventions and MAP Checks (Table 24).

Table 24: Safety performance for COVID and LEADER factors - ANOVA Results

Factor: COVID-19 (df 1:68)					
Performance Indicator	Sum Squares	Mean Square	*F* Values	Pr (>F)	Significant
Hazard Observations	0.164	0.164	0.819	0.369	-
Supervisor Observations	7.769	7.769	8.192	0.0056	Yes
Critical Control Verifications	0.543	0.543	0.295	0.589	-

Factor: COVID-19 (df 1:68)					
Performance Indicator	Sum Squares	Mean Square	*F* Values	Pr (>F)	Significant
Total Incident Rate	703,387	703,387	19.937	3.096e−05	Yes
Factor: ORGANIZATION (df 2:154)					
Performance Indicator	Sum Squares	Mean Square	*F* values	Pr (>F)	Significant
Hazard Observations	7.624	7.624	38.687	3.49e−08	Yes
Supervisor Observations	6.401	6.401	6.749	0.011	Yes
Critical Control Verifications	33.737	33.737	18.356	5.905e−05	Yes
Total Incident Rate	19,059	19,059	0.540	0.469	-

5.6 Discussion

The research evaluated the effect of COVID-19 on a construction project by comparing pre and post COVID-19 safety performance and the influence of leaders on the worker safety perceptions. The project was operational prior to COVID-19 and had completed a baseline safety climate survey to compare post COVID-19 results. The results are unique as the data shows the project throughout the COVID-19 transition period and operating under the new COVID-19 conditions and provides direct comparative data pre and post COVID-19.

COVID-19 as a factor was identified in total incident rate and supervisor observations and worker safety climate ratings around safety conversations. Leaders influenced the frontline risk management activities of hazard observations, supervisor observations and critical control verifications (MAP Checks). Project leadership was not static during the study as the Project Manager (primary leader) was changed by the organization in response to deteriorating safety performance and broader management of COVID-19 effects on the project. The statistical modelling did factor in the change to ensure the effects of COVID-19 were not over estimated due to the change in leaders. The analysis does provide insights into the safety climate dynamics operating within a construction site when external stress events are introduced.

The overall reduction in incident rate following the impact of COVID-19 is consistent with other studies where COVID-19 heightened the risk awareness of workers (Almohassen et al., 2022; Alsharef et al., 2021; Pamidimukkala & Kermanshachi, 2021; Stiles et al., 2021). The decentralization of construction organizations (Lingard et al., 2017) with management control at site directed through the Project Manager and supervisors has meant front line leaders have a direct influence of on safety performance (Glendon & Litherland, 2001). The supervisor role is pivotal on a construction project as it directly influences work group safety attitudes and risk-taking behaviour (Onubi et al., 2021) resulting in a reduction in injuries (Saunders et al., 2017). Alruqi & Hallowell, (2019) supported this view when comparing safety climate to safety performance within the construction industry whereby supervisor behaviour is important in improving safety climate and reducing injuries.

5.6.1 Influence of Leadership through COVID-19 and Perceptions of Safety Climate

Studies have also reported the heightened level of risk awareness by workers due to COVID-19 has also applied to other safety management practices (Zohar, 2008; Pamidimukkala & Kermanshachi, 2021). The results from this study differ from previous findings as the frontline risk management practices do not increase worker risk management practice in response to COVID-19 but decrease under Leader A. However, the trend does reinforce the relationship between supervisors and the safety climate set on the project. Supervisors responded to COVID-19 by increasing the SOIs with the workers including associated safety orientated communication. The engagement by supervisors was recognized by the workers in the safety climate surveys where workers identified there was an increase in ‘safety communication’ post COVID-19 than pre-COVID-19.

The increased worker engagement through SOI’s by supervisors in the post COVID-19 period and prior to the commencement by Leader B did not result in an increase in other risk management activity by the workers as measured by hazard observations (HAZOBs). The increase on average of worker hazard observations (HAZOBs) and reinstatement of supervisors completing Critical Control (MAP Check) verifications was associated with the influence of Leader B. The safety climate at the site is set by the Project Manager (Leader A/Leader B) who can influence positively by providing support for supervisors and their work teams or negatively with a focus on production and ongoing perceived production pressure by supervisors and the workers (Onubi et al., 2021).

Project supervisors and workers will perceive to be under greater production pressure due to delays caused by material and labour shortage, disrupted rosters and imposed COVID-19 control activities (Stiles et al., 2021). In the absence of proactive and positive safety leadership under COVID-19, the project safety climate will deteriorate and a reduction in worker safety motivation, participation in safety programs and safety compliance will occur (Onubi et al., 2021; Saunders et al., 2017). The decline in worker hazard observations (HAZOBs) and Critical Control verifications post COVID-19 under Leader A supports Guo’s (Guo et al., 2016) safety climate prediction.

Post COVID-19 when the project was under stress due to the health, logistics and supply issues the safety climate improved. Initially under Leader A as the continuous changes, due to COVID-19 increasing rate of spread, were communicated, and then improved even further under Leader

B. In the post COVID-19 period the change in safety communication positively influenced the safety climate and safety participation as the frequency of risk management activities (HAZOBs, MAP Checks) increased, a finding consistent with previous research (Guo et al., 2016; Kapp, 2012; Saunders et al., 2017). Leader B in the post COVID-19 period set up the communications and actions required to reinstate supervisor interactions improving the 'social support' for the workers and establish a positive 'supporting environment'. COVID-19 factors including increased work pressure arising from shortage of labour and restricted logistics arrangements initially caused a deterioration in worker safety participation and safety compliance. Under Leader B's guidance the work pressure improved, workers became more involved and hazard identification improved. By increasing the rate of supervisor observations (SOIs) and Critical Control (MAP Check) verifications, Leader B reinstated the social interactions and supervisory leadership both antecedents of a shared safety climate (Schneider et al., 2017; Zohar & Tenne-Gazit, 2008). COVID-19 was a major disruption on the project which caused a drop in frontline risk activities after the initial three week period. However, Leader B demonstrated generating a positive safety climate through communication and committed risk management actions offset the impact of the COVID-19 disruption and improved safety performance. A similar conclusion was reached in an oil and gas COVID-19 study recommending 'companies should maintain a positive health and safety culture to improve workplace safety even during the pandemic' (Alruqi & Hallowell, 2019).

5.6.2 Influence of Age on Safety Perceptions

Safety communications across the project were influenced by age group of the workers with younger personnel (18–29 year old group) with lower scores on the effectiveness of safety communication and the supporting environment than other age groups. Younger worker safety is influenced by organisational relationships, mental stress, and job security (Guzman et al., 2022) all of which were subject to changes and the associated pressure due to the COVID-19 impact on the project. The 'supporting environment' provides the organisational structure and support to safely undertake work under instruction from the supervisor and guidance of the work team. Across this age group rating of the 'supporting environment' was on average > 1.05 units lower than all other age groups surveyed and reflects the dependency younger construction workers have on stable organisational support.

Older construction workers, (in these instance > 30 years old) safety views are dominated by factors of workload and job satisfaction (Guzman et al., 2022; Siu et al., 2003; Stoilkovska et al., 2015). Two age groups (40–49 and 60–69 years old) rated safety communication on average at a higher level than the other age groups. One theory is these groups represent supervisory or management roles and have a more positive perspective as they are directly engaged in the safety communication processes on projects. This was unable to be validated due to limitations of the data set.

5.6.3 Influence of Organization on Safety Perceptions

Organisational factors, specifically differences between principal contractor and subcontractor safety ratings were identified for Work Hazard Identification, Worker Involvement and Team factors with subcontractors on average having a higher safety score. Subcontractors are used on construction projects to undertake specific scopes of work relevant to the specific skill sets of the contracting company and usually operate independently of other subcontractors with oversight provided by principal contractor representatives. In working within self-contained teams, the subcontractor leaders have more direct contact with their workers. The higher level of safety rating by subcontractors reflects this organisational structure with subcontractor leaders directly influence frontline risk management activities, engaging with the workers and engendering a team environment.

The differences Identified in safety ratings between principal contractor and subcontractors reflects the complex social ecosystem which exists within a construction project. Principal contractor representatives in Australian construction industry were found to be more focused on getting the job done given the range and scope of the project than consulting or communicating with subcontractor personnel to resolve schedule clashes or other issues or ensuring safe work practices (Wadick, 2010). The safety attitudes and behaviours are shaped by professional; organization and industry cultures which influence the operations at site, and it is common for misalignment between organizations, even to the point there is no shared view of safe practices (Wadick, 2010).

Leadership attributes were potentially more pronounced due to COVID-19 given the pressures on resources, time and schedule COVID-19 introduced which resulted in a change of Project Manager during the study. The change in leaders however also provided an opportunity to model the effect of different leaders under COVID-19 conditions.

Two disruption events occurred during the study, COVID-19 and change in project leaders, resulting in transition periods as the project personnel learned how to ‘normalize’ the effect of the change in day-to-day work. The data indicates during the transition periods (3 to 4 weeks) the change had an exaggerated short term effect on the performance measure (e.g., MAP checks, incident rate) which was not quantified. Further analysis is required to explore the impact of “transitions” on safety performance.

COVID-19 presented a major disruption event to the study project with increased level of stress within the organizations involved through impacts to workers, labour shortage, supply chain and increased schedule pressure. Organizations have become entrenched in ‘administering’ safety with a focus on producing ‘pieces of paper’ and by default the pieces of paper have become more important than the activities which produce them (Lingard & Oswald, 2020). The comparative difference between the project leaders in the study emphasized the importance frontline leaders have in delivering safety outcomes primarily through worker engagement and effective communication on safety priorities. Organizations looking to manage through disruption events, and, by extension, catastrophic incidents would benefit from ‘checking in’ with workers and how to improve worker engagement to ensure the wellbeing and safety of workers.

5.7 Limitations

There are a few limitations of the study which need to be acknowledged. First the study was limited to one construction project operating under fly in: fly out manning in remote Western Australia with personnel experiencing long periods of isolation physically away from immediate personal support networks. Managed under joint venture management structures with stringent client COVID-19 imperatives which constantly changed, a level of misalignment occurred between organizations not usually present within a construction project. While the study confirmed the importance of site leaders in setting the safety climate identified in previous research (Kapp, 2012; Zohar & Tenne-Gazit, 2008) further longitudinal research is needed to validate the inter-relationships identified. Second, under the unique circumstances the aspects directly related to participation rates (high rates) and misaligned safety perceptions between organizations, these should not be extrapolated as typical construction project work arrangements. Further research to across multiple projects is needed to test the results from this study. Third, the safety climate survey used was modelled and validated through research (Saunders et al., 2017) to test inter-organization and supervisor level safety climate factors, while the safety climate measures were sensitive enough to detect differences in real test situations further validation across multiple case study sites is needed. Finally, COVID-19 was a significant disruptive event and while being a focus of the study also introduced a potential bias in perceptions relevant to management commitment as organization management were not able to have a present on the work site.

5.8 Conclusions

Safety performance as measured by incident rate improved under the effect of COVID-19 which is consistent with the inherent increase in safety awareness due to COVID-19 reported in previous studies (Alsharef et al., 2021; Pamidimukkala & Kermanshachi, 2021). The increased safety and wellbeing awareness due to COVID-19 did not result in an increased level of engagement in front line risk management activities. The frontline risk management activities reduced over time under the influence of COVID-19 and did not improve until a change of Project Manager occurred. The study identified the effect of leadership and power of setting a positive safety climate to increase worker motivation, participation in risk management processes and compliance to safety requirements.

The safety climate on a project is perceived differently by different organizations working with the site environment or by different age groups. The dynamics with the construction site organizations collectively shape the safety climate on site with the subcontractors having a more direct relationship with their worker generating a more positive safety climate than the principal contractor. Younger members of a construction workforce rate the safety climate more negatively than older workforce members.

The study benefits construction frontline leaders managing disruption events, either externally imposed (e.g., COVID-19) or internally (e.g., organization changes), the positive impact of worker engagement and consistent safety communication has on safety climate and safety performance. Through positive engagement frontline leaders enable workers to build resilience and maintain a focus on risk management practices.

CHAPTER 6. CRITICAL CONTROL RISK MANAGEMENT (CCRM) – DOES IT IMPACT CONSTRUCTION SAFETY PERFORMANCE?

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6.1 Introduction

The construction project site is complex through the multitude of participating organisations, work scopes, contractual arrangements, disconnects between levels of management and different perspectives on how to construct safely (Erdogan et al., 2017; Winge,et al., 2019; Woolley et al., 2020). Throughout a construction project lifecycle responsibilities and duty for safety transfers between the different stakeholders (owner, engineer, principal contractor, subcontractor, workers) and adds to the complexity (Smallwood & Emuze, 2016; Wu et al., 2015; Zhang et al., 2018) in managing construction safety risks and preventing fatality events. Comprehensive construction safety management requires the application of safety standards, programs, the evaluation of safety performance, reporting across multiple stakeholders, incident investigation and emergency management (Hinze et al., 2013; Winge et al., 2019; Yu et al., 2014). Additionally, construction schedule pressures, design quality, cost, geological conditions, weather events and disruption events (e.g., COVID-19) impact safety performance (Almohassen et al., 2022; Choe et al., 2020; Han et al., 2014; Hinze, 1997).

Against this background of complexity construction work involves daily management of high-risk work with simultaneous potentially fatal risks including working at height, lifting operations, heavy vehicle movements and other stored energies. Fatalities on construction sites continue to occur with annual regulator statistics ranking the construction industry third behind the agricultural and transport sectors (Safe Work Australia, 2020). Construction fatalities are usually single person accidents where the risks are foreseeable and the controls to prevent the release of fatal injuries are known. The complex construction environment with daily shifting priorities, work assignments and distractions affect the workers focus on the hazards surrounding the task, including potentially fatal risks resulting between 15% to 45% of hazards not identified or managed (Albert et al., 2017; Albert et al., 2020; Carter & Smith, 2006; Perlman et al., 2014a).

A previous study proposed Critical Control Risk Management (CCRM) as a risk strategy was explored to reduce recurring fatal events. The Major Accident Prevention (MAP) program was developed and validated on a single construction project over a twelve month period (Selleck et al., 2023a). This study presents a longitudinal investigation into the affect CCRM (MAP program) has on construction safety performance, safety attitudes of frontline management and workers and cultural differences between countries.

6.2 Literature Review

6.2.1 Critical Control Risk Management

In recognition of the hazard identification and control management gap construction organisations have applied a 'rules based' approach (e.g., golden rules, lifesaving rules) to distil the complexity of the controls into rules, which aim to prevent worker exposure to fatal risks (Fulton Hogan, 2023; IOGP, 2013b; Safer Together, 2016). However, these relatively simple rule statements are limited as they cannot include the range of fatal risks construction workers are exposed to or provide detail on the performance standards to be applied.

Effective decision making in high-risk environments to apply effective controls is predicated on clear performance standards (Hopkins, 2011b; Selleck et al., 2022a) and the engagement of supervisors in supporting workers to apply effective controls (Grill et al., 2017; Hayes, 2012). Critical Control Risk Management (CCRM) offers an alternative strategy to manage construction fatal risks with the benefit of providing clear, concise Critical Control (CC) standards which minimises personal risk perception bias when supervision or workers are deciding if the work is 'safe' to continue.

CCRM emerged from mining industry research and has a parallel to the oil and gas industry or major hazard facility safety cases managing 'process safety' (ICMM, 2015; Lord Cullen, 1990). CCRM shifts management focus from risk assessment to risk treatment through the identification and definition of CCs that address major unwanted events, threats, and consequences. Organisational resilience to ensure CCs are systematically implemented and effective is developed by applying High Reliability Organisation (HRO) monitoring and verification processes.

In the construction industry fatal events are typically personal safety events resulting from high-risk work activities being conducted by workers in a dynamic and changing work environment. The controls to manage the potentially fatal energies are known and documented in safety standards and codes of practice (Safe Work Australia, 2011, 2018c), however fatalities continue to occur from these fatal energies (Safe Work Australia, 2020). In Selleck et al (2022b) the reliability of these controls identified two primary reasons for failure, the control was not implemented, or it was not implemented to the standard required. The HRO element of CCRM address these types of issues by ensuring that a process of monitoring and verifying CC implementation is undertaken (ICMM, 2015). In addition, CCRM requirement to clearly specify CC performance standards enables supervisors conducting CC checks at work fronts to clearly identify aberrations and stop at risk practices until the CC returns to within specification.

Initial research in the application of CCRM on construction projects developed the Major Accident Prevention (MAP) program which adapted CCRM to the dynamic and complex construction environment (Selleck et al., 2023a). The field trial of MAP indicated the application of CCRM had potentially contributed to improving existing risk management processes and the occurrence of first aid injuries, however the outcomes were inconclusive due to the limitations of the field trial.

6.2.2 Fatal Hazard Identification and CCRM

Others have identified that workers are unlikely to identify hazards in a dynamic construction environment and will put themselves or others at risk (Albert et al., 2017; Neitzel et al., 2013; Perlman et al., 2014b). Workers on construction sites have varying abilities to identify hazards, and overall hazard identification is poor with between 34% and 57% of hazards not being recognized (Albert et al., 2014; Bahn, 2013; Carter & Smith, 2006). However, hazard identification does improve where the hazard is likely to impose a higher level of safety risk (Albert et al., 2020). Workers' familiarity with common fatal hazards (falls, caught in / between, struck by and electrocution) increases hazard recognition (Albert et al., 2020) and provides an opportunity to act to implement CCs. However, where the workers are not as familiar with potentially fatal hazards (e.g., exposure to chemicals, gases) the hazard identification is low (Albert et al., 2020) and different cognitive responses occur (Liao et al., 2021) further limiting worker awareness and response. A primary objective of CCRM is to improve fatal risk awareness to facilitate effective CC management. In the construction industry CCRM effectiveness is managed by construction teams and frontline supervision.

6.2.3 CCRM and the Changing Role of the Construction Supervisor

Supervisor interventions (e.g., safety observations) provide recognition and feedback during daily exchanges and are perceived to be the best indication of safety priorities by workers, particularly when decisions are made due to competing operational demands like safety, cost, or schedule (Zohar & Luria, 2003). Alignment of frontline supervision to organizational safety expectations and programs is key for the successful implementation of CCRM (Luria et al., 2008).

Equally the visibility of supervisors actively implementing risk management practices and intervening when unsafe practices or acts are observed has a direct effect on worker adoption of the same practices and the safety perceptions held by the workforce, (Luria et al., 2008; Petitta et al., 2017). In the construction industry where, fatal risks are a fact of daily work supervisors are a primary resource to visibly enact CCRM safety process setting the standard for the workers. Daily supervisor interactions reinforce the CC standards and improve worker critical risk knowledge and awareness.

Marin and Roelofs (2017) identified supervisor better fulfill their role as safety leaders when they have knowledge, skills, and confidence to make changes in response hazards in the workplace. For a CCRM to be effective, supervisors will require new skills and knowledge and the authority to stop work when the integrity of CCs is substandard to be effective CCRM leaders. Production pressure, perceived or real, can result in a degradation of safety which has an impact on both accident rates and safety management in construction projects (Hinze, 1997; Mitropoulos & Memarian, 2012; Mohammadi et al., 2018). The investment in CCRM training and competency will provide supervisors the skills and knowledge to implement CCRM in the field. CCRM in part resolves the variability in risk perception of individuals by defining the CC operational parameters enabling frontline supervisors to identify when CCs are deviating from the standard and act. The specification of CCs creates ‘rules’ governing the safe parameter of the CC and alleviates an individual’s risk perception bias (Hopkins, 2011b). However, the organisational management commitment (Mohammadfam et al., 2016) and safety culture (Kasim et al., 2019) will determine the level of decision making frontline supervisors will be granted to stop work due to gaps CCs integrity when there are competing production demands.

Under existing construction risk management processes, when a significant production delay is likely to occur the decision to stop work for a safety risk is deferred to senior construction or project management. A premise of CCRM program like MAP, when a CC gap is identified the supervisor identifying the gap takes immediate action to stop work or rectify the CC and informs senior management of the actions. The shift in decision making authority creates organisational tension and will challenge the organisational management commitment to effective CCRM when schedule, cost or other production delays occur.

6.2.4 Measuring CCRM Impact on Safety

Construction projects with the decentralised organization structure (Woolley et al., 2020) means measuring safety performance is complex as lagging indicators are not always directly inter-related to leading indicators or performance metrics (Saunders et al., 2017). To measure CCRM impact on safety performance a combination of lagging measures (incident and / or injury rates), leading indicators which measure participation in field level risk activity (hazard reporting, CC verifications) and leadership behaviour which support a positive safety climate (supervisor observations) need to be considered.

The objective of CCRM programs like MAP is to prevent major accidents (fatality events) through effective and reliable CCs. Fatality events are infrequent and are not a statistically valid measure so alternative antecedent events (high potential and/or near miss incidents) and risk activities (hazard reports, personal risk assessments) provide indicative measure of CCRM influence on safety performance (Hallowell et al., 2013; Hinze, 1997).

CCRM relies on fatal hazards being identified, recognition of the personal safety risk (Pandit et al., 2019) and high level of safety compliance as a function of safety leadership (Kapp, 2012; Pettita et al., 2017) to implement and enforce the integrity of CCs, all attributes of workplaces with a positive safety climate. Two safety performance dimensions are differentiated in safety climate models: safety participation and safety compliance. Safety climate dimensions are measured through determinants of performance (personal risk tolerance), performance antecedents (knowledge, skills) and behaviours specifically involved in work tasks (Griffin & Neal, 2000; Pandit et al., 2019).

Safety participation is the engagement in safety activities to improve safety outcomes and can be perceived as 'safety citizenship' where the discretionary actions of an individual contribute to organization safety outcomes (Newton & LePine, 2018). Safety compliance is the adherence to rules and procedures as choice strategy, as it is cost effective (conserves energy), immediately available readily adaptable to the situation compared with more engineered solutions (Reason, 2016). Both safety climate dimensions are required in a CCRM program. Safety participation improves the capacity for safe decisions in less predictable situations and safety compliance provides discipline, routine and reliability in the risk management practices (Zohar, 2008).

6.2.5 Influence of cultural differences between countries on CCRM

Construction organizations are influenced by the safety standards imposed by the governing safety bodies which varies between developing and developed nations (Raheem & Hinze, 2014). In developing nations where governing safety authority is often weak or non-existent, safety standards are not adhered to, or injuries are often not reported (Abbas et al., 2018; Awwad et al., 2016). The effect of CCRM within the various organizations is expected to be influenced by the safety maturity of the organization and the background cultural differences of the country in which the CCRM is being implemented.

6.2.6 Summary of Research into CCRM in Construction

Studies on the construction industry have been conducted across different CCRM attributes but have not been brought together to provide a cohesive perspective on the value CCRM may bring to prevent fatalities within the industry. The research has explored fatal hazard recognition (Albertet al., 2020; Bellamy, 2015), predictive incident causation models (Allexander et al., 2017; Arboleda & Abraham, 2004; Choe & Leite, 2020; Shao et al., 2018), resilience in safety systems (Azeez & Gambatese, 2018; Bellamy et al., 2018; Chen et al., 2017), safety risk perception (Abbas et al., 2018; Chaswa et al., 2020; Chen et al., 2018; Gao et al., 2017) together with safety culture and / or safety climate at the individual and organisation level (Al-Bayati, 2021; Alruqi et al., 2018; Chen et al., 2017; Grill et al., 2017; Guo et al., 2016; Lingard et al., 2019; Wu et al., 2016). In the absence of a holistic fatality prevention program like CCRM the construction industry has continued to rely on rule based systems (e.g., lifesaving rules) to manage fatal risks as hazard identification remains unreliable (Albert et al., 2020). The application of 'lifesaving rules' has been inconsistent across the industry as the programs are reliant on human and organisational factors which are inherently flawed. Selleck et al (2022b) highlighted inadequate implementation of CCs, an aspect of human error, was a significant factor in the reliability of 'rules' (CCs). When deciding to implement the safety rules individuals are influenced by their perception of safety risk which varies depending on their familiarity with the risk (Perlman et al., 2014b), social factors operating within a construction project (Andersen & Grytnes, 2021; Lingard et al., 2012; Pandit et al., 2019) and risk tolerance of the organisation (Pandit et al., 2019). An alternative approach has been to develop predictive fatal incident causation models associated with construction high-risk activities. The models identified precedent organisational and safety systems elements (Awolusi et al., 2022; Choe & Leite, 2020) which reflect administrative processes and organisational system controls (Allexander et al., 2017) but have not focussed on risk treatment or specifically identification of CCs. Studies have also identified human factors associated with fatal hazard identification and risk perception contribute to human error and breakdown in the resilience of safety systems, including organisation and individual safety decision making (Azeez & Gambatese, 2018; Bellamy et al., 2018; Chen et al., 2017). Socio-economic factors in the complex construction environment also erode the resilience of rule based practices (Lingard & Oswald, 2020) due to the absence of reliable verification programs (Hassall, 2017) and the inherent contracting pressures (Albert et al., 2020; Lingard & Oswald, 2020; Woolley et al., 2020). This paper addresses the research gaps by considering the effect of CCRM in preventing fatal and serious incidents when CCRM is applied holistically and implemented on construction projects (Selleck et al., 2023a) and the factors which affect safety performance.

6.3 Study Objectives

The objective of this research was to conduct a comprehensive study that provides construction managers and safety professionals with detailed insights into the influence CCRM has on safety performance and project safety climate.

Specifically, this study aims to:

1. Evaluate the effect CCRM has on leading and lagging safety performance measures.
2. Determine the relationship CCRM has on existing frontline risk management processes on construction projects.
3. Evaluate if CCRM is affected by cultural differences when implement on construction projects in different countries.
4. Study cross section of parameters (company, organizations, country, project, safety indicators and safety perception factors) to see if they reveal insights into the organisation and human factors influencing risk management practices including CCRM activities.

The study is novel in the use of safety leading and lagging indicators together with safety climate factor analysis to assess the influence CCRM has on existing safety risk management performance. The extent of the study which was conducted across a cross section of international projects over a five year timeframe, provided a unique opportunity to critically assess multiple risk management factors within the context of organisation safety culture and projects safety climate.

6.4 Methodology

A summary of the research workflow provides an overview of how data was resourced from participating companies, reviewed, coded, and analysed for both safety performance and safety climate perceptions (Figure 40).

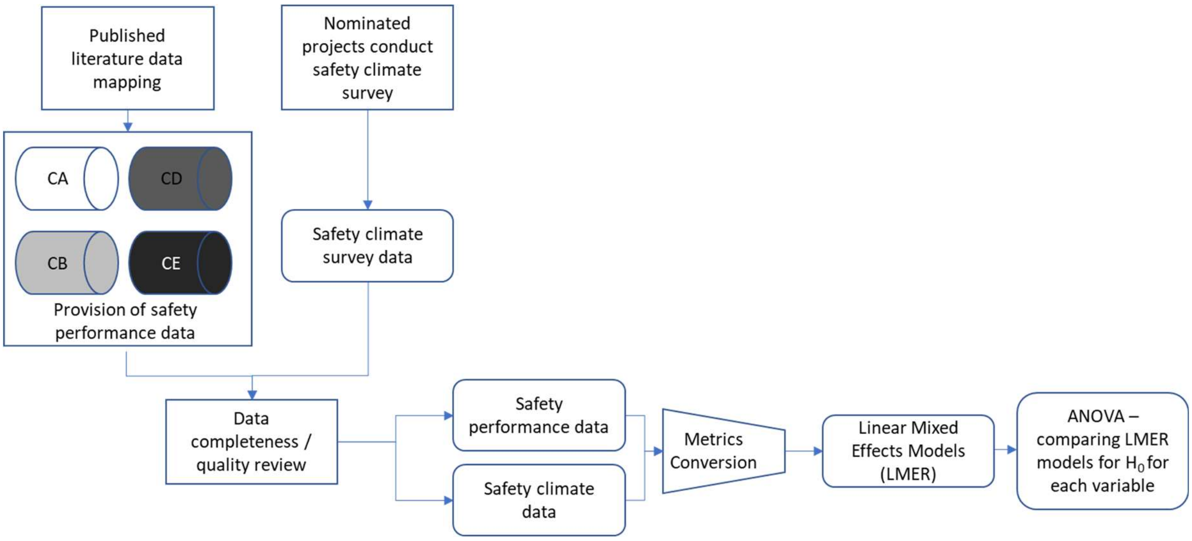


Figure 40 Planned Research Workflow

Participating construction organisations (Company A (CA), Company B (CB), Company D (CD) and Company E (CE), identified projects to implement the MAP program either part way through the existing projects or at commencement of new projects field activities. For a project to be considered all safety performance metrics had to be available for a minimum period of 12 months. The projects where the CCRM program (MAP) was not implemented were used as 'non-Map' control sites.

Where English was not the primary project language the MAP critical risks, controls and training material was translated into the primary language (e.g., Mongolian, Pidgin). The translation included repetitive process of having an interpreter translate the information and then back translated by another interpreter into English to obtain consistent interpretation of the intent of the material.

The data was analysed using R statistical package (R Core Team, 2020) applying exploratory analysis steps to understand the relationships and strength of relationships between the data set factors and the independent variables (Hyndman & Athanasopoulos, 2018). More information on the method used in each of the key steps shown in the workflow (Figure 40) are discussed in the next subsections.

6.4.1 Project Selection

Participating construction organisations identified projects to implement the MAP program either part way through the existing projects or at commencement of new projects field activities. For a project to be considered all safety performance metrics had to be available for a minimum period of 12 months. The projects where the CCRM program (MAP) was not implemented were used as 'non-Map' control sites.

Where English was not the primary project language the MAP critical risks, controls and training material was translated into the primary language (e.g., Mongolian, Pidgin). The translation included repetitive process of having an interpreter translate the information and then back translated by another interpreter into English to obtain consistent interpretation of the intent of the material.

6.4.2 Safety Performance

6.4.2.1 Leading and Lagging Measures

A range of leading and lagging metrics for construction projects (J. Hinze et al., 2013; Lingard et al., 2017; Sallas & Hallowell, 2016) were identified and evaluated against available data across all participating companies. Each of the participating projects provided a summary of available safety performance measures, identified the availability of raw data from which twelve measures including frontline risk management activities and incident metrics were selected based on the data available (Table 25). The participating organizations provided two safety performance data sets; incident events and counts of risk management activities. The data was reviewed for completeness and quality. Based on the methodology defined in Salas and Hallowell, (Salas & Hallowell, 2016) the monthly data was normalised for the project size by converting all measures into frequency rates (equation 1)

Frequency rate = Number of events or activities in period * 1,000,000/exposure hours in period. (1)

Table 25 Summary of Project Safety Performance Data and Risk Management Activities

Measure	Definition	Unit (monthly)
Personal Risk Assessments	Individual completing a task specific risk assessment	Count
Hazard Reports	Any person reporting a workplace hazard as an unsafe condition or unsafe act	Count
Supervisor Observations and Interventions	Supervisor having a safety conversation with an individual or team following an observation of work.	Count
Major Accident Prevention (MAP) Critical Control Checks	MAP Check – verification of CCs completed by supervisors	Count
Major Accident Prevention (MAP) Audits	Audit of MAP Check verifications to confirm CCs have been verified and the quality of verification is the standard required. Conducted by line managers, safety professionals	Count
Exposure hours	Hours worked on a project in a given time period.	Total hours worked
First aid injury incidents	Injuries not requiring medical intervention	Count

Measure	Definition	Unit (monthly)
Medical treatment incidents	All injuries required medical intervention (e.g., sutures, prescription medication)	Count
Restricted Work Case incidents	Medical cases where the injured person cannot return to their normal duties following medical treatment but are still fit to work in a limited capacity	Count
Lost Time Injury incidents	Injuries where the injured person is declared unfit for work by the treating physician. Minimum of one work shift or more.	Count
High Potential incidents / near misses	Incidents with the potential to result in a fatality or serious disabling injury however the severity was not realised.	Count
Total number of incidents	Total of all incidents reported on the project	Count
Incident frequency rates	Calculated field to normalise incident rates between different projects and / or organisations. Frequency rate = No of injuries in period * 1,000,000 / exposure hours in period	Frequency rate[c]

6.4.2.2 Linear Mixed Effects Regression Analysis

The Linear Mixed Effects Regression (LMER) analysis was selected to evaluate the fixed effect of the CCRM program across the range of performance variables being assessed. LMER provides a method of linear regression which tests fixed variables (e.g., MAP) for effect on the dependent variable (safety performance indicators) whilst accounting for other sources of variance (company, country, project), which are included as random effects. The series of LMER models enables the correlation between MAP and other safety performance measures be tested not only for significance (standard linear regression), but also estimate the type and size of the effect in combination with other safety performance activities and ensure the effect is not due to other confounding factors like company or country.

Three null hypotheses (H_0) are proposed to test the effect of MAP on safety performance. The presence or absence of MAP did not change the leading or lagging dependent variables and did not modify the effect (positive or negative) MAP had on the dependent variables and MAP affect is independent of the Company implementing MAP.

i. H_0: MAP ≠ lagging measures (injury or incident frequency rates)
    a. H_A: MAP > lagging measures (injury or incident frequency rates)
    b. H_B: MAP< lagging measures (injury or incident frequency rates)
ii. H_0: MAP ≠ leading measures (frontline risk management activities)
    c. H_C: MAP >leading measures (frontline risk management activities)
    d. H_D: MAP < leading measures (frontline risk management activities)

iii. H_0: MAP ≠ is not affected by company

   a. H_e: MAP <> affected by company

MAP and Company are used as independent fixed effects in testing of each safety performance variable. The mixed effects models included as random effects Projects, Country, or Resource Sector in which the construction project is being executed. Separate LMER models were run to assess the effect of MAP on each of the lead and lag variables.

The base model (Var_x.model1) which assesses the significance of the fixed effect variable (Var_y) on the dependent variable (Var_x) includes nested random effects of Factors 1 -3, is shown in (2).

Var_x.model1 <- lmer(Var_x ~Var_y + Var_z + (1|Factor1/Factor2), data = data_set) (2)

e.g. SUP_FR.model1 <-lmer(SUP_FR ~ CCRM + COMPANY +(1|Country / Project), data = safety_data)

The significance of variance due to each of the random factors was assessed by comparing the log likelihood of the full model (including all random effects) with that of a model that excluded that factor, using the anova(x) function in R.

The LMER analysis was conducted for all leading and lagging variables. The significance of the effect of the independent variables (Var_y, Var_z) was evaluated using an F-test, and was considered significant at *p=0.05.*

6.4.3 Safety Climate Survey

The survey commenced with seven demographic questions (company, project, date of survey, age range, gender, organisation type, role) to support differential analysis between demographic factors.

The Saunders et al [31] safety climate survey tool was selected as it had been developed for construction organizations and measured individual, team, supervisor, and management factors. The safety climate survey provided a point in time benchmarking tool measuring eleven (11) attributes of worker safety climate perceptions (Table 26) comprising 35 questions. The safety climate survey was structured to measure organization, team, and individual safety perceptions. Eleven questions, using a 5 point Likert scale (Table 26) and two questions of free text enquired about safety risks and safety improvements identified by participants. The survey was administered via an online form using Microsoft Forms® and in hard copy for field based personnel.

Table 26: Structure of Safety Perception Survey

Organizational Elements	Likert Scale Units – Group of Questions
Company (ORG Avg)	Management Commitment (MC Avg) Communication (COM Avg) Rules and Procedures (RUL Avg) Overall Safety Climate (SC_Avg)
Team (TEAM Avg)	Supportive Environment (SUP Avg) Supervisory Environment (VIS Avg) Workers Involvement (WI Avg)
Individual (IND Avg)	Personal Appreciation of Risk (PRA_Avg) Work Hazard Identification (HAZ Avg) Work Pressure (WKP Avg) Competence (CMP Avg)
Context Questions	Safety Risks Safety Improvements

Participants were recruited in two ways, attendance at a site safety meeting, and via an email distribution list provided by the organization. Participation in the survey was voluntary and anonymous with basic demographical information and response to questions collated into the MS Form® database for analysis. All participants were asked to provide consent on the survey forms consistent with the ethics requirements for the research and where consent was not provided to use the data, the information was excluded from the analysis. Incomplete hard copy forms were excluded from the survey results and not uploaded into Microsoft Forms® data set.

Site based surveys were facilitated by the organization, where the researcher (Selleck) attended the project work site, attended the weekly safety toolbox meeting with the workers, provided an overview of the survey aims, ethics being applied and handed out hard copy survey forms. Workers were provided time to complete the survey which were deposited by the participants anonymously in a box provided. The collection box remained available until the shift end. The process was administered to the cross shift a week later. Personnel with access to computers were emailed the Microsoft Forms® survey link to complete the survey within the two weeks of their roster, and a reminder was emailed on day 7 and day 13.

The Microsoft Forms® survey analytics was used for comparative analysis and to provide a report of the response summary to the participating company.

Each participant's Likert Scale scores were averaged using following formulas to transform data so comparative statistical analysis could be conducted on responses from the two sets of surveys.

Average Likert Scale Score (x) = sum (Qi score + Qii score +… Qn score) / n scores

Where: Qi = participant score for (i) Likert scale question, (3)

n= number of Likert questions within Likert Scale

(Minimum value = 0, Maximum value = 5)

Statistical analysis was conducted to highlight the significance of the relationship between variables including organisational elements and safety perception factors.

6.4.3.1 Safety Climate Survey Model:

The Safety Climate Survey statistical model tests each of the Likert Scale parameter to identify if there is a significant difference in the means due to the factors (Project, MAP, Organization, Gender, Age, Role Types). The model analysed for differences in means between MAP (implemented or not), projects, participant Companies (CA - CE), gender (male, female, non-disclosed), age groups (<18, 18- 29, 30 – 39, 40- 49, 50 – 59, 60 – 69, >69) and role types.

The null hypothesis assumes there is no significant variance in average safety climate scores when MAP is implemented on a project. The alternative hypothesis assesses if the presence or absence of MAP affects safety climate rating of the workforce and whether there is a positive (higher average score) or negative (lower average score) effect as:

- H_0: MAP < > average safety perception scores (Likert scale units)
    a. H_1: MAP > average safety perception scores (Likert scale units)
    b. H_2: MAP< average safety perception scores (Likert scale units)

The mixed effects models included as random effects Projects, Organization, Role, Gender, Age in which the construction project is being executed. Separate LMER models were run to assess the effect of MAP on each of the safety climate variables.

The significance of variance due to each of the random factors was assessed by comparing the log likelihood of the full model (including all random effects) with that of a model that excluded that factor, using the anova(x) function in R.

The base model (Var_x.model1) which assesses the significance of the fixed effect variable (Var_y) on the dependent variable (Var_x) includes random effects of Factors 1 -5.

Var_a.model1=lmer(Var_a ~MAP + (1|Factor 1) + (1|Factor 2)…….(1|$Factor_n$), data= data.set, REML = FALSE) (4)

e.g., CMP_model1 = lmer(CMP_FR ~ MAP + (1|Project) + (1|Organization) + (1|Role) + (1|Gender) + (1|Age), data = sc_data)

The LMER analysis was conducted for all safety climate variables. The significance of the effect of the independent variable (Var_y) was evaluated using an F-test and was considered significant at *p=0.05.*

6.4.4 Company Safety Maturity Assessment

Ten representatives (managers, safety professionals) from each participating company were nominated to undertake the safety maturity assessment. Each of the representatives were independently provided the Minerals Industry Risk Management (MIRM) safety maturity scale in the absence of a construction specific maturity model and via survey asked to rate the company safety maturity. The responses were collated, and a majority rating was accepted.

6.5 Results

6.5.1 Safety Performance

6.5.1.1 Selection of Participating Projects

Initially five companies with 45 projects were nominated for the 5 year research project. Due to the dynamic commercial environment within the construction industry several companies and projects withdrew from the study. Four projects withdrew as the client vetoed their construction contractor inclusion in the research, leaving 41 within the study. In addition, two companies had a change of ownership in the initial year, and one company suspended the project due to COVID-19 and did not resume. At the conclusion of the project, the results from two companies and 31 projects remained for safety performance statistical analysis (Table 27).

The two companies involved in the research had projects being undertaken in different socio-economic environments. Company CA projects were predominantly in 'first world countries or when in developing countries (e.g., PNG) were being undertaken for large scaled, mature clients requiring high safety standards. Company CE projects were undertaken in South Africa and Zambia with developing country economic issues and unskilled workforce drawn from local communities across a mix of tier 1 and tier 2 mining clients. Prior to participating in the research Company CE indicated it aimed to improve its management of fatality risk as an average of 3 fatality per year had occurred in the previous decade.

Table 27: Participating Project Summary

Project ID	**Country**	**Resource Sector**	**Scope**	**Exposure Hours**	**Duration (months)**	**Language**
CA_01	PNG	Defense	Marine infrastructure – Construct only	415 000	12	Pidgin
CA_02	Australia	O&G	Offshore Hook-up – Construct only	1 710 000	14	English
CA_03	Timor Leste	O&G	Offshore Hook-up – Construct only	937 000	26	English
CA_04	PNG	Energy	Power infrastructure - EPC	912 000	21	Pidgin
CA_05	Australia	Water	Infrastructure - EPC	66 100	16	English
CA_06	Australia	Energy	Power infrastructure - EPC	245 600	18	English
CA_07	Canada	O&G	Marine infrastructure - EPC	385 000	34	English
CA_08[b]	USA	O&G	Process infrastructure - EPC	2 308 000	36	English
CA_09	Australia	Mining	Mining infrastructure - EPC	1 010 000	33	English
CA_10	Australia	Mining	Mining infrastructure - EPC	1 137 000	28	English
CA_11	Australia	Transport	Road infrastructure – Construct only	90 500	13	English
CA_12	Australia	Mining	Process infrastructure – Procure & construct	210 000	17	English
CA_13	Australia	Water	Infrastructure - EPC	5 950 000	40	English
CA_14	PNG	Transport	Roads and infrastructure - EPC	536 000	16	Pidgin
CA_15	Australia	Mining	Rail infrastructure - EPC	1 190 000	22	English
CA_16	Australia	Transport	Road infrastructure – EPC	150 500	14	English
CA_17	Australia	Energy	Power infrastructure – EPC	410 300	17	English
CA_18	Australia	O&G	Process plant & infrastructure - EPC	780 000	21	English
CA_19	Mongolia	Mining	Surface infrastructure – EPC	1 907 000	21	Mongolian
CA_20	USA	O&G	Design & Construct	502 250	15	English

Project ID	Country	Resource Sector	Scope	Exposure Hours	Duration (months)	Language
CE_01	South Africa	Mining	Engineering services	1 510 000	26	English /Afrikaans
CE_02	South Africa	Mining	Infrastructure – construct only	3 482 000	12	English /Afrikaans
CE_03[b]	South Africa	Mining	Infrastructure & services	3 736 000	60	English /Afrikaans
CE_04[b]	Zambia	Mining	Infrastructure – construct only	1 076 000	48	English
CE_05	Zambia	Mining	Infrastructure – construct only	360 000	36	English
CE_06[b]	South Africa	Mining	Infrastructure – construct only	3 444 000	47	English /Afrikaans
CE_07	South Africa	Mining	Infrastructure – construct & services	740 000	40	English /Afrikaans
CE_08[b]	South Africa	Mining	Engineering services & construction	2 938 000	60	English /Afrikaans
CE-09[b]	South Africa	Mining	Infrastructure - Design & construction	7 557 000	60	English /Afrikaans
CE-10[b]	Zambia	Mining	Infrastructure - Design & construction	4 030 000	36	English
CE-11	South Africa	Mining	Infrastructure - Design & construction	153 000	15	English /Afrikaans

a) Five participating companies were labelled: CA, CB, CC, CD, CE. Project ID shows company ID followed by project number.

b) MAP implemented on existing projects – data includes months of Non-MAP and MAP data.

6.5.1.2 Reported Incident Events Summary

During the period of the study, no fatalities were reported for the projects involved in the study. A total of 7084 incident events were reported. A summary of the overall count of incident events by company is provided in (Table 28). Companies CD and CE did report one fatality respectively on projects not participating in the study. The total high potential events (n=112) represented 1.6% of the overall incident events which occurred during the study period, which is a limitation of measuring safety performance to assess effect of CCRM.

Table 28: Summary of Reporting Incident Events by Company

	Company CA	Company CE	Total Events
High Potential Events	48	42	90
Fatalities	0	0	0
Lost Time Incidents	5	49	54
Restricted Work Cases	19	15	34
Medical Treatment Cases	40	82	122
First Aid Injuries	724	98	822
Near Miss Events	389	3016	3505
All Incidents	3513	3302	6815

6.5.1.3 Demographic Summary

Company CA contributed the most projects (20) which were predominantly performed in Australia. Company CE contributed 11 projects mainly in South Africa. All countries except for Canada and Timor Leste had a minimum of two projects represented in the data (Figure 41).

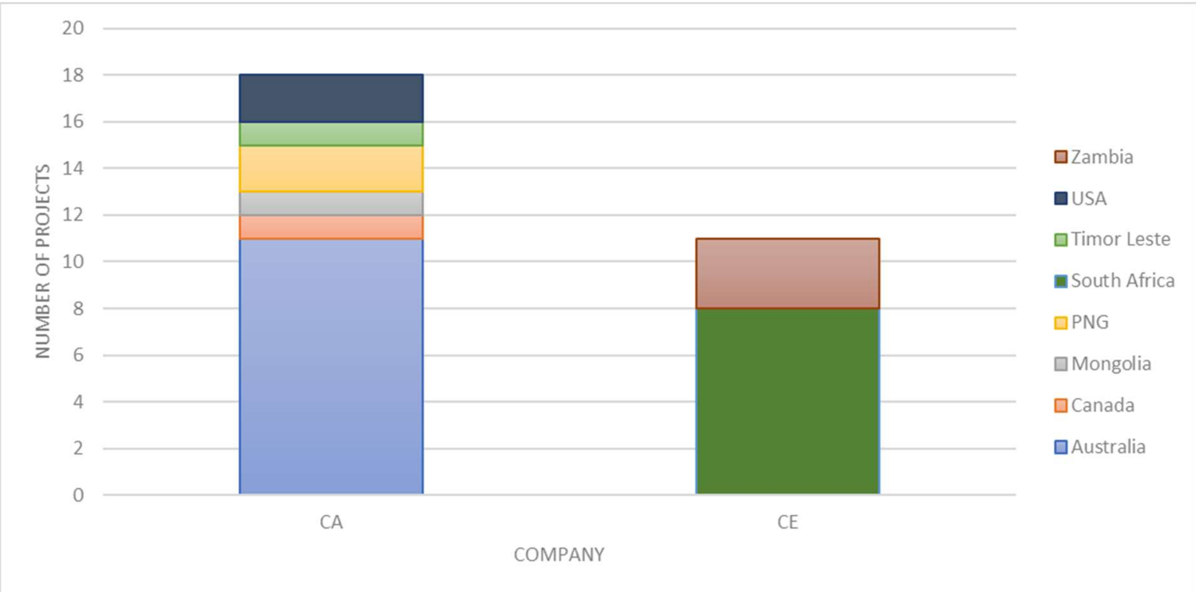


Figure 41: Participation by Company and Country

The study included construction projects across multiple resource sectors (Figure 42) with Company CA having projects in all six resource sectors and Company CE working in the mining sector. Except for the Transport and Defence sectors the research included multiple companies with representative projects.

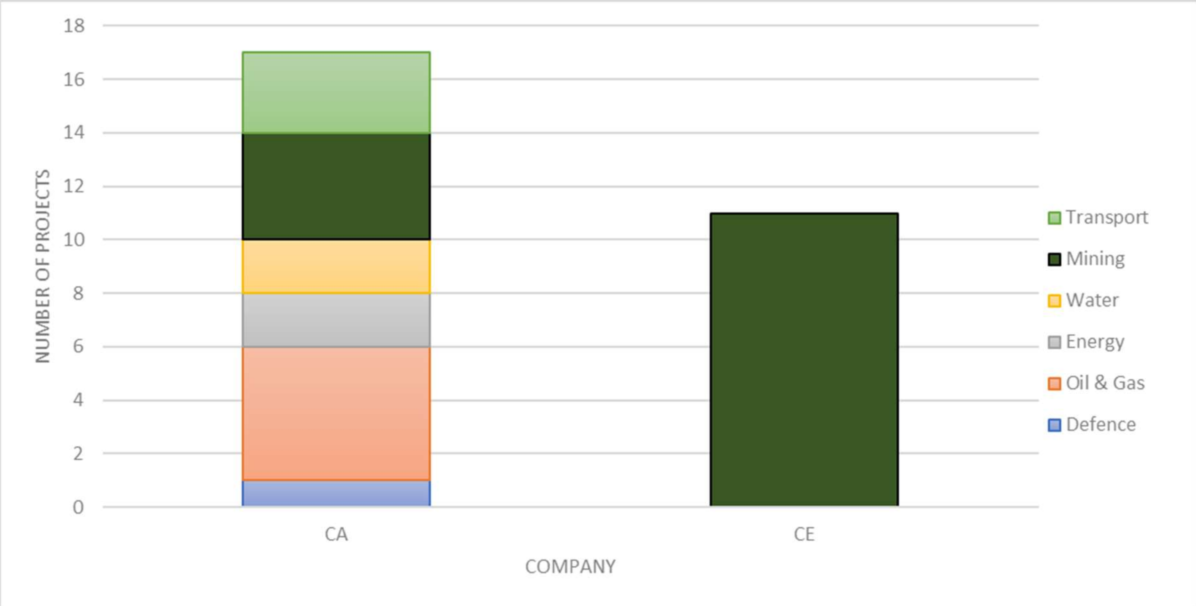


Figure 42: Company Participation by Resource Sector

In summary the research had representative projects from both companies and each sector however had limitations due to variability in the number of projects per company, country, and resource industry sectors which needed to be considered in the statistical analysis.

6.5.1.4 Exploratory Analysis

Variation in the project data sets occurs through different durations of projects (12 to 60 months), companies, locations, the type of project and the resource sector of the project. Principal Component Analysis (PCA) identified 93.5% of the variance within the data set was described by nine principal components attributed to five leading indicators and three lagging measures. The five leading indicators included personal risk assessment, hazard reporting, supervisor observation together with MAP checks and MAP audits. The lagging measures were a combination of all incidents, near miss and first aid incident frequency rates.

Correlation analysis was applied to identify variables of interest for regression modelling of three hypotheses:

i. H_0: MAP ≠ lagging measures (injury or incident frequency rates)
   a. H_A: MAP > lagging measures (injury or incident frequency rates)
   b. H_B: MAP< lagging measures (injury or incident frequency rates)
ii. H_0: MAP ≠ leading measures (frontline risk management activities)
   e. H_C: MAP >leading measures (frontline risk management activities)
   f. H_D: MAP < leading measures (frontline risk management activities)
iii. H_0: MAP ≠ is not affected by company.

a. H_e: MAP <> affected by company

The Pearson correlation method identified non-linear correlations which can be expected from a high number of zero values in variables, particularly incident frequency rates. The relationship between variables represents monotonic (non-linear) correlations which are better represented by Spearman rank correlations (Table 29)

The analysis identified moderate to high correlations between the safety measures:

- Hazard reporting frequency rate: SUP_FR (0.661), PRA_FR (0.780)
- Supervisor safety conversation frequency rate: PRA_FR (0.676)
- All incident frequency rate: NMFR (0.608)
- MAP Check frequency rate: MAPAS_FR (0.766)
- MAP Assurance frequency rate: HAZ_FR (0.620)

There were weak correlations between the safety measures:

- MAP Assurance frequency rate: PRA_FR (0.570)
- All incident frequency rate: FAI_FR (0.427)
- Lost time injury frequency rate: TRIFR (0.553)

The rate of MAP Checks and MAP Assurance activities positively influences frontline risk assessment processes (HAZ_FR, PRA_FR). The MAP Check or MAP assurance rates did not influence injury or incident rates. The correlation between LTIFR and TRIFR was expected as loss treatment injuries are a subset of the TRIF measure. The strong correlation between PRA_FR and HAZ_FR (0.712) occurs from conducting personal risk assessments (PRA) which results in the identification of hazards. Similarly conducting supervisor safety observations will also result in the identification of hazards and a moderate correlation between SUP_FR and HAZ_FR (0.676).

A previous study by the authors (Selleck et al., 2023a) identified a strong positive correlation between MAP Checks and supervisor safety observations was observed. The previous observation was derived from a single project analysis and reflected the practices on the project of conducting a supervisor safety conversation when conducting a MAP Check to reinforce the critical controls with the team involved. This is not evident in this more extensive study across multiple projects and across the different companies when random effects project and sector were considered.

Table 29 Correlation Matrix Across Performance Measures (Spearman Rank Correlation Method)

Correlation matrix showing Spearman's rank correlation r for safety performance measures									
Safety Performance Measure	LTIFR	TRIFR	NMFR	ALLIFR	FAI_FR	SUP_FR	HAZ_FR	PRA_FR	MAPCH_FR
LTIFR									
TRIFR	**0.553**								
NMFR	0.130	0.168							
ALLFR	0.128	0.252	**0.608**						
FAIFR	0.021	0.123	0.095	**0.427**					
SUP_FR	-0.181	-0.144	**-0.215**	**0.144**	**0.254**				
HAZ_FR	-0.144	-0.120	-0.199	**0.251**	**0.340**	**0.661**			
PRA_FR	-0.162	-0.162	-0.019	**0.312**	**0.370**	**0.676**	**0.780**		
MAPCH_FR	-0.107	-0.203	-0.089	**0.104**	**0.081**	**0.312**	**0.422**	**0.391**	
MAPAS_FR	-0.137	-0.137	-0.108	**0.197**	**0.205**	**0.438**	**0.620**	**0.570**	**0.766**

NOTE: **Bold text** denotes significant correlation at p=<0.05.

6.5.1.5 MAP Effect on Safety Performance (LMER) Analysis

The LMER regression analysis of the leading and lagging measures, summarised in Table 30, identified three variables where implementation of MAP had a significant effect: hazard observations (HAZ_FR), MAP check frequency rate (MAPCH-FR) and MAP assurance frequency rate (MAPAS-FR). It is expected the variables directly associated with the MAP program are significant as without the MAP program in use on the project the activities being measured are not conducted. The study did include some trials on 'non-MAP' projects usually for a three month period where MAP checks were undertaken, hence some MAP checks and MAP assurance results were recorded for non-MAP projects.

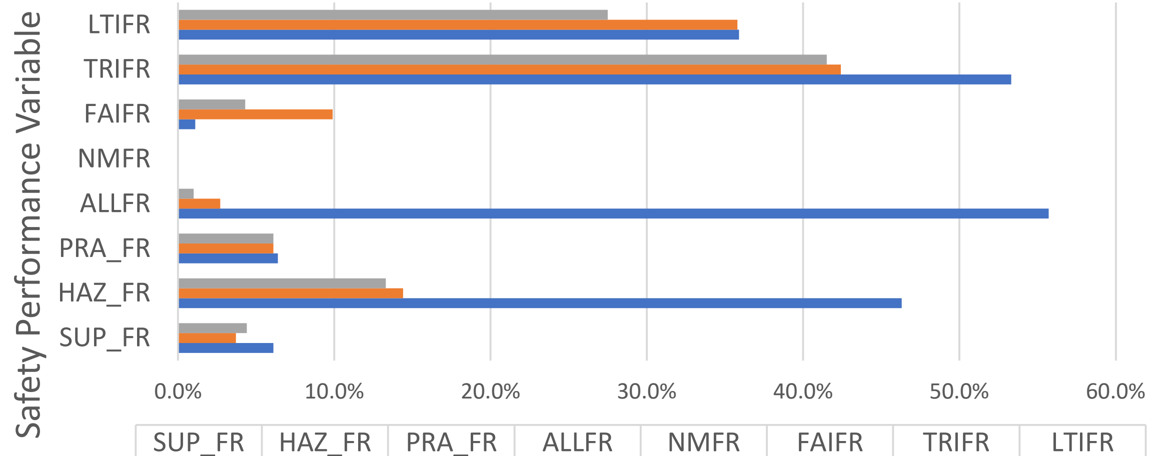
The results confirm the presence of the MAP program used on a project increases the frequency rate of hazard observations (1.10e+05, p=0.050) being reported independent of the company implementing the CCRM program. Therefore, the null hypothesis (ii) is rejected and based on the results hypothesis (i.e.) is accepted. The null hypotheses for (i) and (iii) are accepted, MAP was not affected by the Company implementing the project and did not have a significant direct effect on lagging safety performance measures.

The relationship between MAP activities, increase in hazard reporting and strong correlation with the other leading safety performance measures (SUP_FR, PRA_FR) indicates MAP is influencing other activities, not just hazard reporting.

Table 30: Effect of MAP on Safety Performance Measures

Safety Performance Measure	**Non-MAP estimate *(SE)***	**MAP Estimate *(SE)***	**(t) value**	**Pr(>|t|)**
HPIFR	1.11 (SE 0.69)	1.19 (SE 0.49)	0.11	0.912
LTIFR	-0.13 (SE 0.55)	0.15 (SE 0.38)	0.518	0.605
TRIFR	3.77 (SE 1.49)	1.52 (SE 1.05)	-1.512	0.131
NMFR	12.9 (SE 13.46)	23.7 (SE 22.2)	0.758	0.449
ALLFR	153.8 (SE 16.09)	147.1 (SE 46.8)	-0.418	0.679
FAIFR	28.01 (SE 2.88)	25.18 (SE 8.54)	-0.992	0.322
SUP-FR	5604 (SE 390)	5808 (SE 1332)	0.535	0.601
HAZ-FR	**1.01+05 (SE 4510)**	**1.10e+05 (SE 1.614e+04)**	**1.888**	**0.050**
PRA-FR	55845(SE 2372)	56951 (SE 8753)	0.466	0.641
MAPCH-FR	**694.6 (SE 99.7)**	**1169 (SE 309.6)**	**4.763**	**2.24E-06**
MAPAS-FR	**455.3 (SE 33.2)**	**538.2 (SE 118.7)**	**2.282**	**0.013**

The analysis identified that all factors included as random effects (Country, Sector) explained significant variance in safety performance measures. A summary of these factors and their contribution to the variance in each safety performance variable is shown in (Figure 43). The most significant factor was "Project" with substantial variance between projects in most of safety performance measures. Variance among countries and industry sectors was observed in leading measures and first aid injury frequency rates.



	SUP_FR	HAZ_FR	PRA_FR	ALLFR	NMFR	FAIFR	TRIFR	LTIFR
Country	4.4%	13.3%	6.1%	1.0%		4.3%	41.5%	27.5%
Sector	3.7%	14.4%	6.1%	2.7%		9.9%	42.4%	35.8%
Project	6.1%	46.3%	6.4%	55.7%		1.1%	53.3%	35.9%

Figure 43: Variance in Dependent Variables Explained by Each Random Effect

6.5.1.6 Company Effect on Safety Performance (LMER) Analysis

Significant variance in safety performance measures (*p* <0.05) between the two companies was identified including hazard reporting, lost time injury, total recordable injury, and near miss incident frequency rates (Table 31). Company CE had significantly higher incidence rates (LTIFR, TRIFR, HPIFR) and lower hazard reporting frequency rate compared to Company CA.

Table 31: Effect of Company on Safety Performance Measures

Safety Performance Measure	Company CA Estimate *(SE)*	Company CE estimate *(SE)*	(t) value	Pr(>|t|)
HPIFR	1.19 (SE 0.49)	2.08 (SE 0.72)	1.25	0.421
LTIFR	0.15 (SE 0.38)	2.20 (SE 0.49)	4.165	**3.43e-05**
TRIFR	1.52 (SE 1.05)	4.54 (SE 1.59)	2.854	**0.007**
NMFR	23.7 (SE 22.2)	107.0 (SE 37.1)	-2.262	**0.031**
ALLFR	147.1 (SE 46.8)	106.8 (SE 83.3)	-0.489	0.651
FAIFR	25.18 (SE 8.54)	48.93 (SE 16.5)	-1.438	0.244
SUP-FR	7486 (SE 1016)	2139 (SE 1773)	-3.016	0.147
HAZ-FR	1.10e+05 (SE 1.614e+04)	7700 (SE 2.92e+04)	3.505	**0.037**
PRA-FR	56951 (SE 8753)	2991 (SE 14710)	-3.668	0.1412
MAPCH-FR	1169 (SE 309.6)	507.9 (SE 525)	-1.258	0.332
MAPAS-FR	538.2 (SE 118.7)	82.9 (SE 199.6)	-2.282	0.174

6.5.1.7 MAP influence – Difference in Safety Performance Measures within Companies

Results from Companies CA and CE were analysed independently to assess the MAP influence on safety performance indicators within each company.

Table 32: Company CA - MAP Influence on Leading and Lagging Measures

Safety Performance Measure	**non-MAP**	**MAP Estimate *(SE)***	**Difference (%)**	**(t) value**	**Pr(>|t|)**
SUP_FR	7565 (SE 2021)	7776 (SE 964.0)	0.33%	8.371	0.917
HAZ_FR	11460 (SE 23811)	113349 (SE 16828)	**90.8%**	-4.279	**6.88E-05**
PRA_FR	65905 (SE 14065)	56779 (SE 10843)	-%13.8	0.649	0.516
ALLIFR	241.7 (SE 54.83)	142.2 (SE 42.96)	**-25.9%**	4.408	**1.44E-05**
NMFR	20.9 (SE 14.36)	19.8 (SE 6.20)	-5.4%	0.078	0.9379
HPIFR	4.24 (SE 1.202)	0.81 (SE 0.424)	**-80.8%**	2.860	**0.005**
FAIFR	42.6 (SE 13.61)	23.6 (SE 5.393)	-44.6%	1.397	0.165
TRIFR	3.90 (SE 1.656)	1.13 (SE 0.557)	-71.0%	1.678	0.105
LTIFR	0.917 (0.254)	0.020 (0.087)	**-97.8%**	3.654	**0.0002**

An increase in frequency of hazard reporting occurred in both companies consistent with the overall result (Tables 32 and 33). In Company CA projects with MAP had a reduction in frequency rate of lost time incidents (97.8% *p=0.*0002), high potential incidents (80.8%, *p=0.005*) and all incidents (25.9% *p=1.44E-05*). In Company CE, on MAP projects an increase in personal risk assessments (100.3%, *p=3.5E*-09) occurred in addition to the increase in hazard reporting frequency rate (67.9 *p=0.0001*). In contrast to Company CA, a reduction in incident frequency rates on MAP projects was not observed in Company CE.

Table 33: Company CE - MAP Influence on Leading and Lagging Measures

Safety Performance Measure	**non-MAP**	**MAP Estimate *(SE)***	**Difference (%)**	**(t) value**	**Pr(>|t|)**
SUP_FR	2116 (SE 220.3)	2174 (SE 619.5)	2.70%	-0.266	0.790
HAZ_FR	2893 (SE 508.7)	4858 (SE 1679)	**67.9%**	-3.867	**0.0001**
PRA_FR	1554 (SE 260.9)	3125 (SE 1214)	**100.3%**	-6.023	**3.5E-09**
ALLIFR	108.0 (17.44)	114.4 (SE 49.7)	169.97%	-0.364	0.716
NMFR	96.1 (SE 17.28)	103.4 (SE 48.57)	6.51%	-0.362	0.717
HPIFR	1.362 (SE 0.872)	2.39 (SE 0.578)	75.2%	-1.174	0.243
FAIFR	3.893 (SE 1.213)	3.10 (SE 1.088)	-20.4%	0.655	0.513
TRIFR	7.331 (SE 2.183)	5.88 (SE 2.421)	-19.7%	0.664	0.507

Safety Performance Measure	non-MAP	MAP Estimate *(SE)*	Difference (%)	(t) value	Pr(>|t|)
LTIFR	1.315 (SE 0.863)	1.859 (SE 0.803)	41.3%	-0.677	0.500

6.5.1.8 Hazard Observation Frequency Rate – All Projects

Higher levels of hazard reporting were observed where MAP was implemented on project with significant random effects between Project and Country factors (Figure 44 and Figure 45).

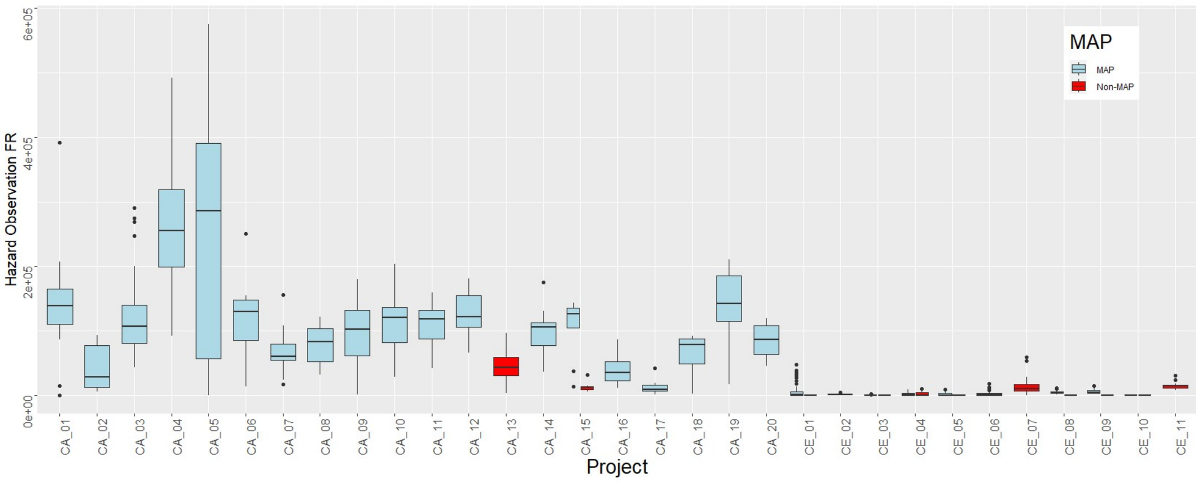


Figure 44: Hazard Observation Frequency Rate by Project

Developing countries (e.g., PNG, Timor Leste, Mongolia) have on average higher rates of hazard reporting than developed countries (e.g., Australia, Canada & USA), (Figure 45).

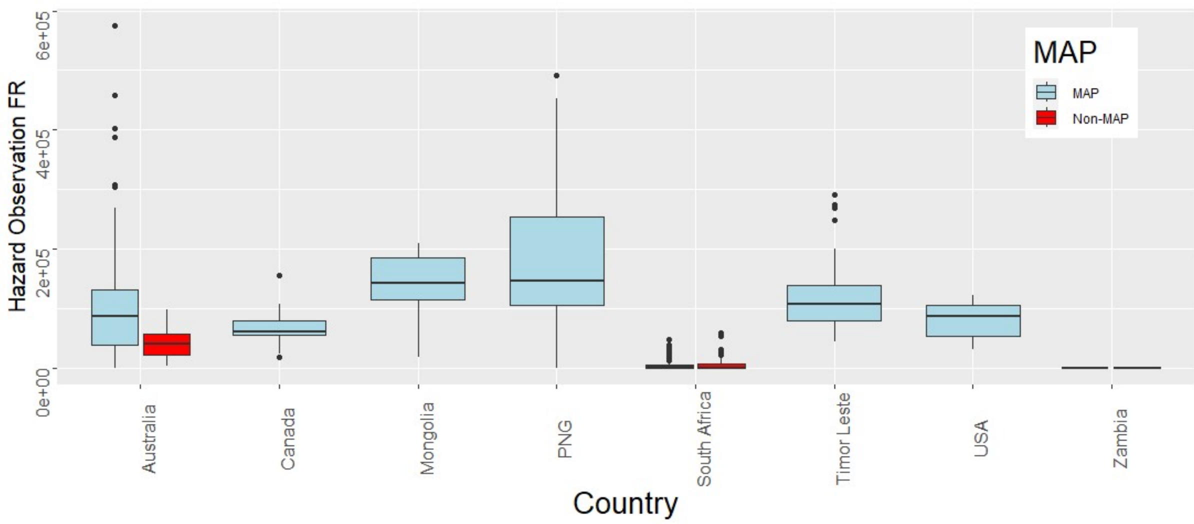


Figure 45: Hazard Observation Frequency Rate by Country

6.5.2 Safety Climate Survey

A total of six safety climate surveys were undertaken across four projects (CA-09, CA-10, CA-13, CA-15) representing construction projects based in Australia. The other company was unable to undertake the surveys due to logistical limitations and clients declining to allow the projects to participate. Two safety climate surveys were completed on projects (CA-09, CA-13 and CA-15) with CA-13 having not implemented MAP. Participation rates varied between 38.2% and 82.5% with project CA-09 having the highest participation rate (Table 34).

Project CA-13 was logistically difficult to present to the various workforces as the project sites were spread over multiple locations. The surveys on this project were conducted in the field with a focus on frontline workers and line management. Limited representation was obtained from office-based personnel.

Table 34: Safety Climate Survey Participation Rates

Project and Survey	**Total Participants**	**Project Participant Rate**
Project CA-09 – Survey A	66	82.5%
Project CA-09 – Survey B	97	57.1%
Project CA-05 – Survey C	57	66.3%
Project CA-15 – Survey D	96	51.8%
Project CA-15 – Survey E	70	78.6%
Project CA-20 – Survey F	146	38.2%
Project CA-20 – Survey G	280	44.7%
n=	812	

6.5.2.1 Demographics

The participation by age group was evenly distributed across both MAP and Non-MAP projects (Figure 46). MAP projects had 40.5% of the survey population with non-MAP projects 59.5%. No significant difference was identified in the age group distribution between projects (Figure 47) or between role types across the surveys (Figure 48).

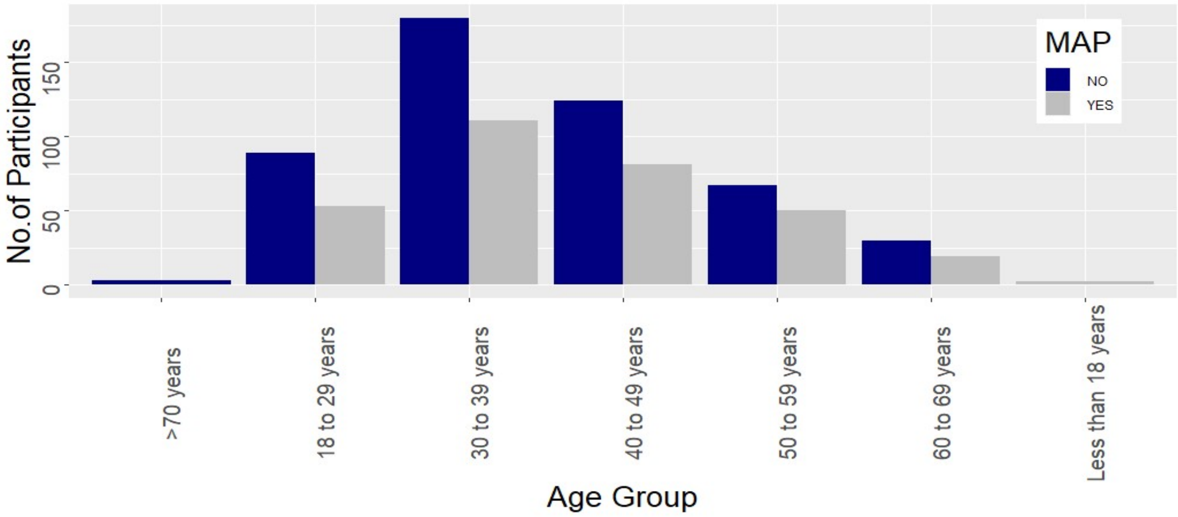


Figure 46: Participation by Age Group - MAP / Non-MAP projects

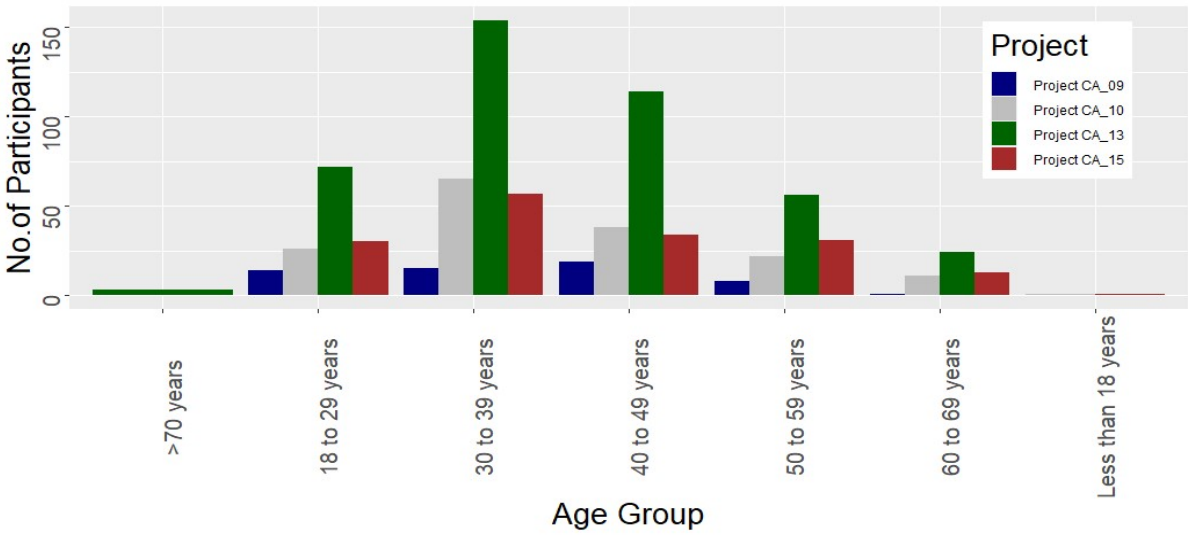


Figure 47: Participant Age Groups by Project Surveyed

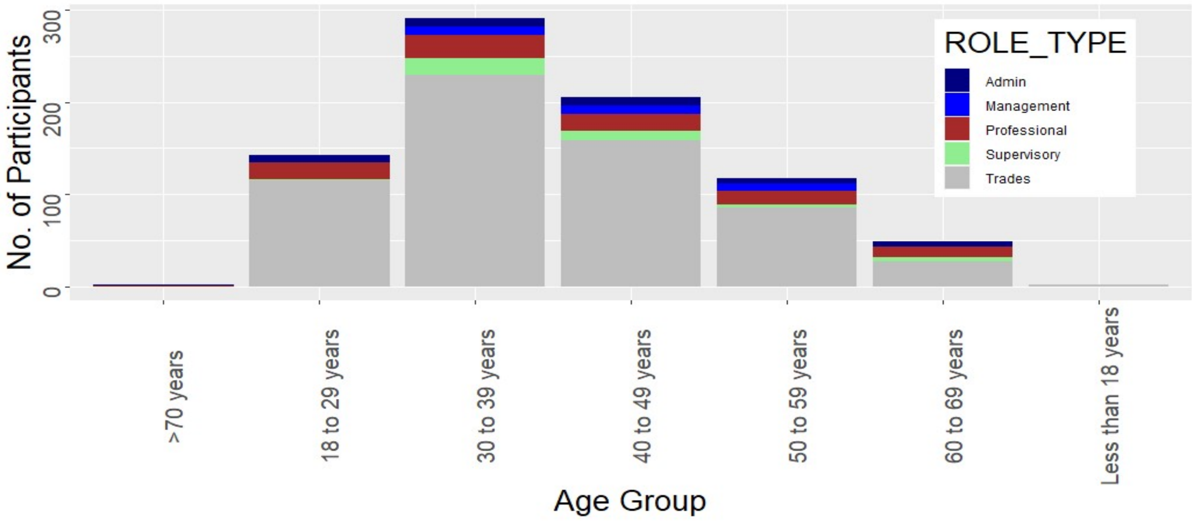


Figure 48: Age Distribution by Participant Role Type

6.5.2.2 Safety Climate Survey Differences on MAP Projects

The participant average score of the Likert scale items was plotted comparing MAP to Non-MAP results across the safety climate measures. Visual differences were identified for items measuring participant rating of safety competency (CMP_Avg), safety communication (COM_Avg), personal risk assessment (PRA_Avg) and overall organisation safety climate (ORG_Avg),(Table 35).

On MAP projects the average organisational (ORG_Avg), communication (COM_Avg) and competency (CMP_Avg) safety rating scores were ranked higher on the Likert scale (0-5) with 0 a low score and 5 a high score of safety rated perceptions. On non-MAP projects the personal risk average (PRA-Avg) scores were higher with a large proportion scoring the Likert items at the highest rank (5) available.

The participant average score of the Likert scale items was plotted comparing MAP to non-MAP results across the safety climate measures. Visual differences were identified for items measuring participant scoring of safety competency (CMP_Avg), safety communication (COM_Avg), personal risk assessment (PRA_Avg) and overall organisation safety climate (ORG_Avg).

Linear Mixed Effect Regression (LMER) models were fitted to all variables (Likert scale units) and the different organisational elements (organisation, team or individual). The LMER models included MAP and Project as fixed variables with organisation type, role type, gender, and age as random effects. The multiple regression model identified ‘role type’ was a subset of ‘organisation type’ which created a nested result when validated by mean differences and were treated as one nested factor in detailed LMER analysis. Analysis of variance (ANOVA) was conducted on each variable confirming MAP was significant on the safety communication (*p = 5.85e-11*), safety competency (*p=0.002*) and overall organisation (*p=2.11e-10*) safety perceptions (Table 35). All three variables had higher average safety rating scores on projects where MAP was implemented. Personal risk average (PRA_Avg) scores were significant (*p=0.1)* and the only variable with a negative effect (lower average score) on projects with MAP. The results confirm the presence of the MAP program on a project influenced safety climate rating enabling the rejection of the null *(H_0)* hypothesis.

Table 35: Safety Climate Analysis of Variance Summary (LMER model)

Safety Measure	MAP estimate *(SE)*	Non-MAP estimate *SE)*	(t) value	Pr(>|t|)
MC_Avg	4.00 (SE 0.12)	3.89 (SE 0.16)	0.987	0.335
COM_Avg	4.15 (SE 0.07)	3.72 (SE 0.43)	6.641	**5.85e-11**
RUL_Avg	3.78 (SE 0.10)	3.63 (SE 0.13)	1.593	0.136
SC_Avg	3.83 (SE 0.11)	3.70 (SE 0.14)	1.201	0.249
ORG_Avg	4.01 (SE 0.6)	3.64 (SE 0.10)	6.436	**2.11e-10**
SUP_Avg	3.68 (SE 0.08)	3.53 (SE 0.10)	1.828	0.88
VIS_Avg	4.07 (SE 0.06)	3.89 (SE 0.07)	1.508	0.132
WI_Avg	3.73 (SE 0.11)	3.71 (SE 0.17)	0.176	0.861
TEAM_Avg	3.81 (SE 0.07)	3.69 (SE 0.09)	1.886	0.112
PRA_Avg	4.34 (SE -0.04)	4.41 (SE 0.04)	-1.714	0.088
HAZ_Avg	3.82 (SE 0.11)	3.70 (SE 0.13)	1.13	0.272
WKP_Avg	3.90 (SE 0.11)	3.84 (SE 0.09)	0.574	0.581
CMP_Avg	4.06 (SE 0.05)	3.90 (SE 0.05)	3.188	**0.002**

NOTE: Correlation significance denoted by **Bold text** denotes significant correlation at p=<0.05.

The analysis identified MAP and Project were confounding factors with the potential variation between projects masking the direct effect of MAP on worker safety climate ratings. Further detailed analysis was conducted on Project CA15 which had two surveys completed, one prior to and one post MAP implementation. The Project specific results identified the Management Commitment (0.283, *p*=0.014), Safety Rules (0.205 p=0.034) and overall Organisation safety climate (0.201, p=0.036) scores increased after MAP was implemented on the project.

6.5.2.3 Communication Safety Perceptions

MAP implementation on a project positively influenced workforce rating of safety communication, shown in Figures 49 and 50. Comparing the random effect of factors associated with participants (project, organisation/role type, gender, age) the analysis identified the organisation type / role type contributed to the to the regression estimate (*Pr = 0.024 where*

Pr(>Chisq)). Labour hire workers (e.g., Trades organisation type) have a lower rating of safety communications compared to principal construction contractors and subcontractors (Figure 49 and 50).

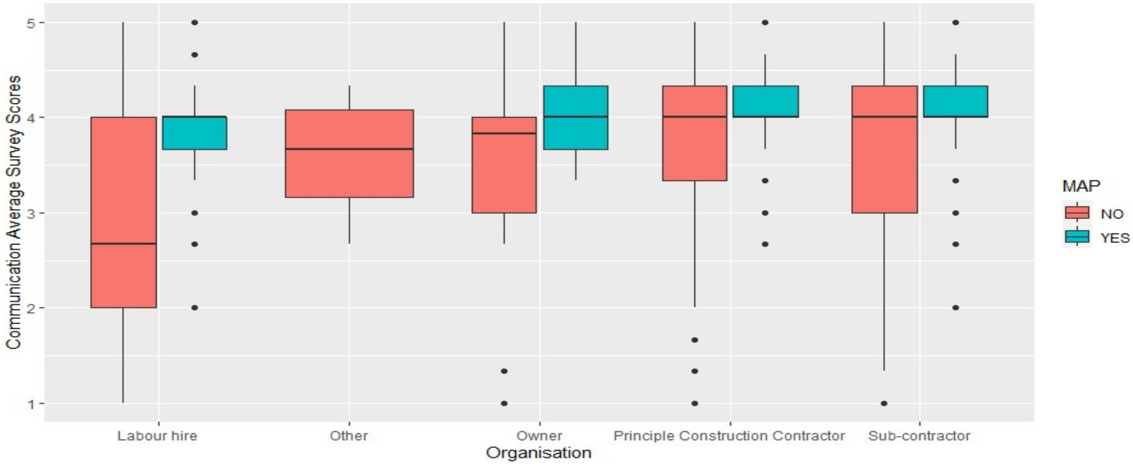


Figure 49: Average Safety Communication Scores by Organisation Type

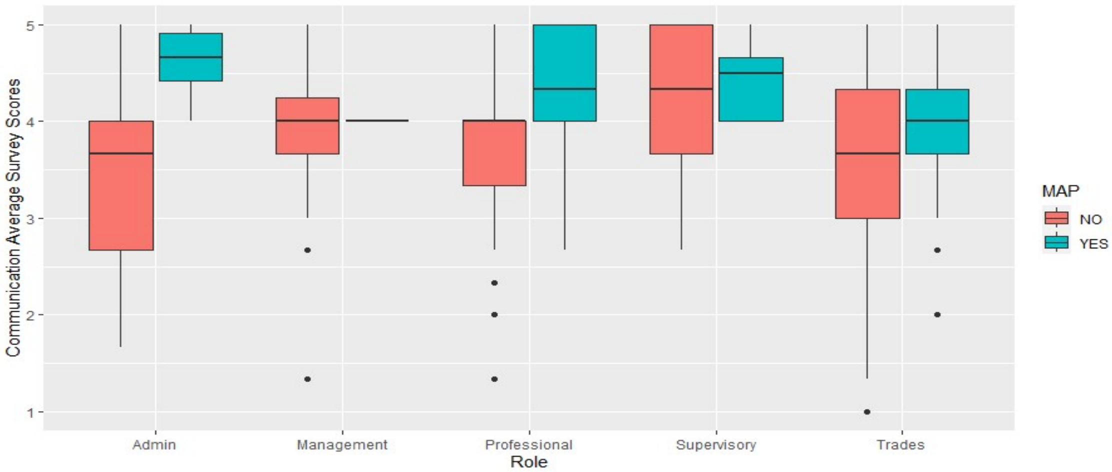


Figure 50: Average Safety Communication Scores by Role Type

6.5.2.4 Rating of Safety Competency

Workforce perceptions of competency as being important in construction safety were positively influenced when MAP was implemented on a project. The analysis identified that factors included as random effects (organisation / role) explained significant variance in safety performance measures. Supervisory roles and subcontractor organisations having higher safety competency perception scores (Figure 51 andFigure 52).

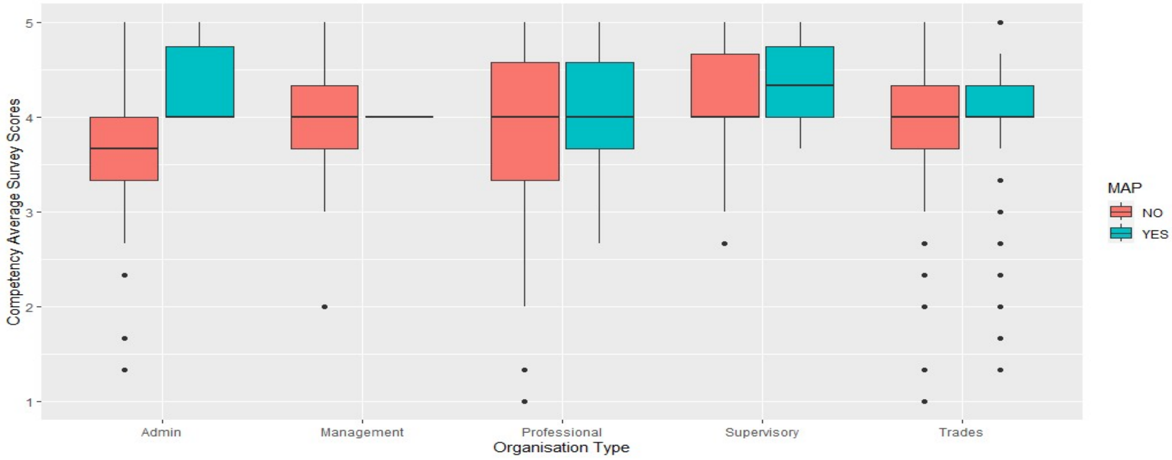


Figure 51: Average Safety Competency Perception Scores by Role Type

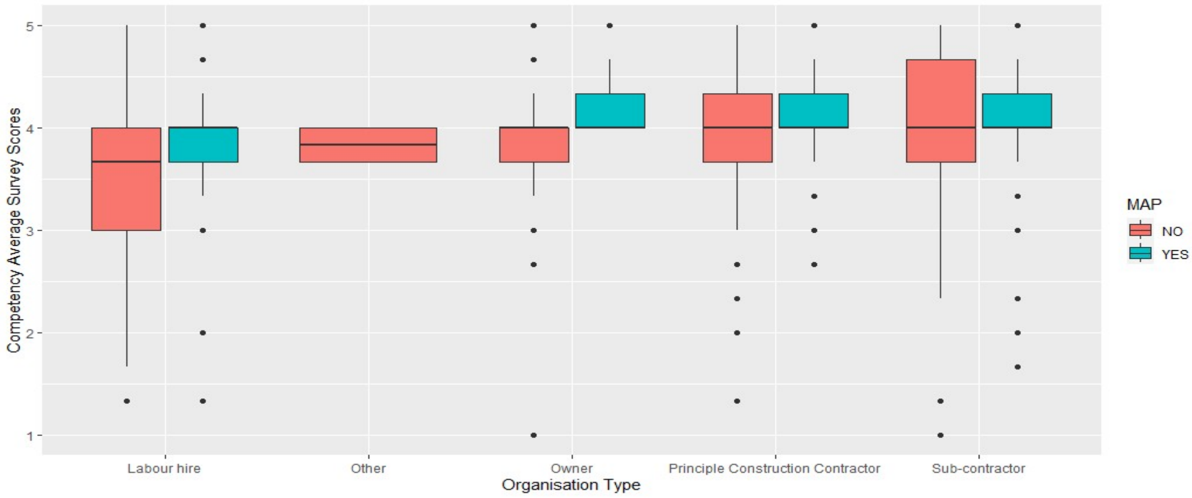


Figure 52: Average Safety Competency Scores by Organisation Type

6.5.2.5 Organisation Safety Perception

Overall organisation safety perceptions were positively influenced when MAP was implemented on a project scoring an estimated average of 3.70 *(pr=2.11e-10)*. Survey participants from Labour Hire organisations had the greatest variance between MAP and non-MAP projects, with subcontractor organisations overall having the highest ranking for organisational safety (Figure 53).

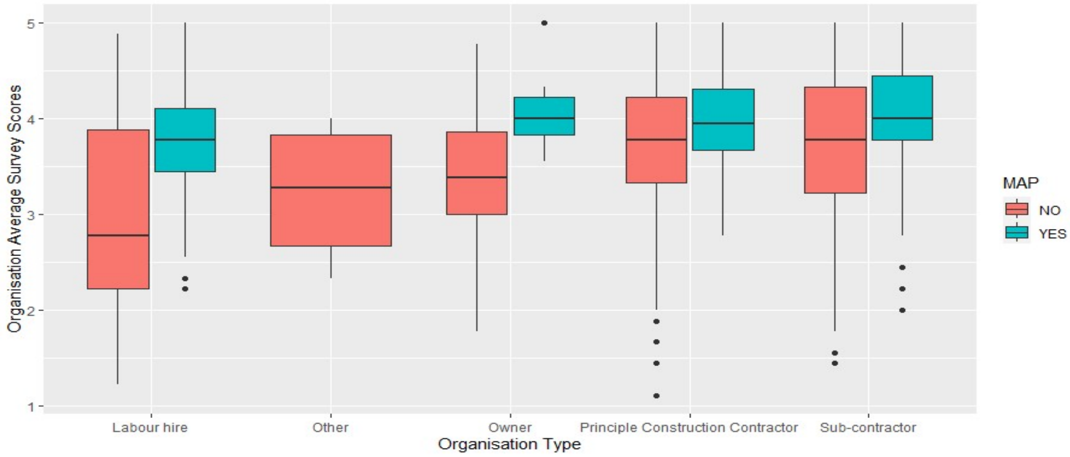


Figure 53: Average Organisation Safety by Organisation Type

In summary the CCRM program (MAP) influenced the perceived level of safety communication being undertaken on the projects, improved rating of safety competence across the workforce and the overall organisational safety across the project. Labour hire workers had lower safety ratings and subcontractors' higher safety ratings in all three safety climate measures.

6.5.3 Company Safety Maturity Assessment

Most nominated company representatives from Company CA identified the safety maturity as being 'Proactive' with only two responses at the lower 'Compliant' level. Company CE representatives held a more diverse view of the safety maturity of the company ranging from 'Vulnerable' to 'Compliant" reflecting the diversity of operations across the company. The consensus was Company CE was best described as having a 'Compliant' safety maturity level (Table 36).

Table 36: Safety Maturity Responses by Company

Participating Company	Minerals Industry Risk Management (MIRM) Maturity Levels				
	Vulnerable	Reactive	Compliant	Proactive	Resilient
Company CA			2	8	
Company CE	1	2	7		

6.6 Discussion

The research evaluated the influence a CCRM program (i.e., MAP) had on construction projects leading and lagging safety performance measures. The longitudinal study spanned five years across two construction companies, eight countries and was tested on thirty one projects. The control group for the study comprised five projects where MAP was not implemented (due to client or joint venture constraints) and a further nine projects where MAP was implemented during the execution phase of the project, i.e., the control group being overall 40% of the test population. Implementation of MAP during a project provided added rigour to the study as the same project, under the same management had safety performance assessed prior to and post MAP implementation. CCRM had a direct impact on safety performance in Company CA and indirectly, through an increase in risk management activity in both companies. The significant random effects on safety performance (company and project) identified CCRM effectiveness is influenced by company safety cultures, project safety climate in addition to the direct effect of the CCRM risk identification, training, communication, and verification activities.

The study is novel in the comprehensive validation of the same CCRM program across multiple countries, companies, and types of construction projects, enabling the comparative assessment of safety performance, organisational and cultural differences which are influenced by CCRM. Results from the research are unique as the analysis from practical application of CCRM identifies the influence CCRM has on construction safety performance (lead and lag) measures and inter-relationship with safety climate factors.

6.6.1 Has CCRM improved safety performance?

During the study, the construction companies involved did not experience any fatalities on the projects involved in the study. The use of CCRM achieved the objective to prevent fatalities for the organisation which had a history of annual fatality events prior to CCRM implementation. Through the five years of the study 1.6% of total incident events were related to potentially fatal incidents (i.e., high potential incidents) the target safety performance measure of CCRM. The high potential frequency rate (HPIFR) was higher on non-MAP (control) projects by an average of 25.6% however only Company CA had a significant reduction in HPIFR (80%) and lost time injuries (97%). By contrast Company CE had a different result with an increase in the rate of hazard reporting (68%) and personal risk assessments being conducted (100%). The effect on safety performance measures varied between the companies and across different projects.

Overall, the relatively small sample of high potential incidents within the data set is representative of the conundrum of direct measures of infrequent high consequence (e.g., fatal) events. The alternative is to consider the underlying assumptions of CCRM relative to existing frontline risk management activities and the safety environment these are being conducted.

CCRM comprises comprehensive risk analysis of major hazards (e.g., fatalities) in the form of material unwanted events (e.g., dropped objects), identification of the causes (hazards) and the controls to prevent the fatalities. CCRM then applies the rigour of high reliability organisations in the definition of Critical Controls including operational specification, then applying a verification process to ensure the CCs stay within tolerance limits (International Council on Mining and Metals (ICMM), 2015). The act of hazard identification underpins CCRM when applied in the field. Workers undertaking high risk tasks, (e.g., working at height where dropped objects could fall on others working below), need to identify the hazard and then apply the CC to the standard required to prevent a serious injury or fatality. This involves different cognitive processes including hazard identification, analysis of potential risk consequence (fatality) for the activity being undertaken, the motivation to implement CC's and verify the control is effective (A Albert et al., 2014; Liao et al., 2021; Pandit et al., 2019). The interaction between these processes was explored in the study and the effect observed in frontline risk management and supervision.

6.6.1.1 Influence of CCRM on Hazard and other risk management activities

Based on the premise higher level of safety risk improves hazard identification (Albert et al., 2020), CCRM which is designed to focus construction workers on high-risk activities, CCRM should improve hazard identification and result in increased levels of hazard reporting. The MAP program generated a 4.3% increase in overall hazard reporting on projects where MAP was applied. The hazard reporting was the result of the MAP specific activities and an increase in hazard reporting from the existing risk management programs. CCRM contributed to the increase in hazard reporting frequency rate which ranged from 40% (Company CA) to 89% (Company CE). However, the result is not a direct measure of safety, as it is measuring an increased level of participation in hazard reporting (an activity), not the actual management of risk (Smith, 2018).

The companies involved in the study were unable to differentiate between the types of hazards being reported, or the risks being assessed as the information was contained on the physical record and not digitally available for analysis.

Hazard reporting frequency rate as a leading measure had positive correlations with other frontline risk management activities including personal risk assessments (*r=0.712),* supervisor observations *(r=0.651)* and MAP assurance reviews *(r-0.560)*. All three programs are assessing work activities to identify hazards and compliance to the required controls and would result in the generation of a hazard report. The direct contribution MAP, as a CCRM program, had on hazard reporting was unclear due to limitations in the data collation. However, what is clear MAP did contribute to an overall increase in hazard reporting either directly from MAP Checks and / or MAP assurance reviews, or indirectly by either; increasing workers hazard awareness, or by improving supervisor risk management engagement which lead to improvements in control.

6.6.1.2 Role of Supervisors and Safety Observations

During the implementation of MAP on the projects in the study supervisors were provided training on the fatal risks, hazards, Critical Controls (CCs) and how to apply the MAP checks (Selleck et al., 2023a). The training was supplemented with infield coaching to ensure supervisors were competent in assessing high risk work and verification of CCs being implemented and effective. The training investment to improve supervisor risk competence is a fundamental component of CCRM (Grattan, 2018; Hardison et al., 2014; Hassall, 2017; Selleck et al., 2022a; Selleck, 2023b). Supervisors were responsible for undertaking MAP Checks and accounted for 95.1% of MAP Checks completed, with the remaining being undertaken by construction management and safety representatives.

Supervisors within construction projects hold a key responsibility to enforce compliance to safety standards and set the behaviour expectations of workers (Petitta et al., 2017; Saunders et al., 2017). It is reasonable to propose the increased level of risk competency of supervisors undertaking MAP checks would also apply to the daily supervisor observations being undertaken across all work scopes. The rate of supervisor observations did not significantly change between MAP and non-MAP projects however there were positive correlations between supervisor observations, hazard reports *(r=0.651)* and personal risk assessments *(r=0.597)*. Supervisors engaging the workforce through daily workplace safety interactions resulted in a positive relationship on the other frontline risk management programs and contribute to the increase in the observed hazard reporting (Selleck et al., 2023a).

The MAP assurance reviews were conducted as an 'audit' of the quality of the MAP checks against the CCs to provide a level of assurance regarding supervisor competency and execution of the MAP checks (Selleck et al., 2023a). A similar relationship to supervisor observations was identified for MAP assurance reviews *(HAZ_FR r=0.560, PRA_FR r=0.523).*

The frequency of frontline risk management activities (hazard reporting, personal risk assessment) was significantly influenced by CCRM; however, the relationship is complex involving organisation safety culture and is interrelated with supervisor and management safety engagements.

6.6.2 Influence of CCRM on Safety motivation and CC compliance

CCRM is designed to increase awareness of high consequence risks in an organisation and provide a mechanism to verify that CCs are implemented and effective. Hazard identification improves where a hazard is likely to impose a higher level of safety risk (Albert et al., 2020). The MAP program increased the profile of fatal risks and controls through the monthly fatal hazards assessments against planned activities, training of line supervision in CCs and verification which validated CCs in the field. Supervisors shared this knowledge and understanding through existing frontline risk management processes and directly with their workers during supervisor engagements. Safety climate modelling (Choudhry et al., 2009; Guo et al., 2016; Zhang et al., 2018) identified social support from supervisors improved worker safety knowledge and safety motivation which had direct correlations with safety participation (e.g., an increase in hazard reporting frequency) and safety compliance (e.g., implementation of CCs). An improvement in the implementation of CCs (compliance) would be expected to result in a reduction of HPIFR which was observed in Company CA, however not in Company CE, indicating other organisational factors have influenced the CCRM results.

6.6.3 CCRM influence within a mature safety culture.

CCRM introduced a change which was expected to enhance the company safety culture and improve safety performance (Hudson, 2001). The implementation of CCRM within the mature safety culture of Company CA resulted in the reduction in frequency of related events (HPIFR, LTIFR). A finding consistent with safety culture studies which identified higher levels of safety investment, safety culture or lower project hazard profiles have better safety performance (Al-Bayati, 2021; Feng et al., 2014; Stemn et al., 2019). However, the results were not universal across all Company CA projects as demonstrated by the significance of the random effect 'Project' on safety performance measures.

Company CA projects (CA-02, CA-16, CA-17 – see Figure 44) had low rates of hazard reporting and higher incidence rate which was inconsistent with the broader company results indicating other factors were influencing the results on these projects. All three projects were being executed in Australia with predominantly Australian labour with minimal difference in country related cultural factors affecting the risk management or safety performance results. Different levels of safety performance between construction projects occur due to safety cultural influences of project stakeholders (client, joint venture partners, subcontractors) creating a project safety climate which moderates the managing company safety culture (Neal et al., 2000; Pettita et al., 2017). Individual project safety climate, established by site management and leadership will modify overarching organisational safety culture including motivation, participation in safety risk management processes and compliance to safety standards (Glendon & Litherland, 2001; Neal et al., 2000; Pandit et al., 2019). To be effective CCRM requires robust risk management to identify fatal hazards, implement CCs and verify compliance to the standards required, the same organisational attributes influenced by safety climate.

During the study Company CA had a series of safety climate surveys completed on different projects and periodically on long term projects and it was used as the CCRM case study. The safety climate surveys together with safety performance leading indicators, provided insight into the cognitive processes which influenced by CCRM. The safety climate survey compliments the safety performance data as it provides context on the organisational factors influencing the CCRM results.

6.6.3.1 Safety Communication

A significant improvement (6.3%) in safety communication within MAP projects was identified through the surveys which is consistent with previous CCRM observations (Selleck et al., 2022b). The introduction of MAP processes required supervisors to engage workers during MAP checks on the critical controls (CCs) and other managers to discuss CCs with supervisors and workers during MAP assurance reviews. Both processes increased the level of safety communication occurring within a project where MAP was implemented.

By contrast none of the other safety climate measures directly relating to existing supervisor or management engagement was different between MAP and non-MAP projects. For example, leader led risk management engagements (e.g., supervisor observations) had not significantly changed after MAP implementation. Equally the measures directly relating to supervisory safety perceptions (Supportive Environment, Supervisory Environment, Worker Involvement) remained consistent between MAP and non-MAP projects (Table 35).

Gaps in the safety communication effectiveness between organisation types was identified with labour hire workers having a lower perception compared to principal contractors and subcontractors (Figure 49). The results indicate differences in contracting arrangements between labour hire and subcontractors influence the perception on effectiveness of safety communications. Labour hire workers are predominantly tradespersons on casual contracts, do not have company representatives on the project and are highly mobile working across multiple companies and / or projects annually. Subcontractors in contrast, are contracted as specialists for specific work scopes, have company site supervision and management engaged in the project, support the workers in applying the principal contractor safety requirements and have direct communication with the workers daily. Under MAP subcontractors are engaged to support the identification of fatal hazards for their work scopes, define CCs and verification specifications (Selleck et al., 2023a). Subsequently, subcontractors regularly engage with principal contractor representatives to align on safety standards and have a high level of safety ownership more likely to participate in communication activities (e.g., pre-start meetings, supervisor conversations) (Lingard & Oswald, 2020; Lingard et al., 2019).

6.6.3.2 CCRM influence on safety competence ratings

The safety climate surveys identified a significant increase in the overall safety competence ratings, and more specifically supervisor roles and subcontractor organisations. The purpose of CCRM is to improve fatal risk competence to prevent major unwanted events by focussing on risk treatment in the form of CCs (ICMM, 2015). MAP as a CCRM program applied during this study involved training in CCRM at multiple levels within a construction organisation with particular emphasis on field supervision. Supervisors developed competency in analysing work activities for fatal risks, application of CCs and assessing the implementation and effectiveness of CCs (Selleck et al., 2023a). Subcontractors were included in the development and validation of CC specifications for the specialist scopes of high risk work the subcontractor was undertaking.

6.6.3.3 CCRM influence on overall organisation safety ratings

On CCRM projects workers had a more positive rating of the organisation and the commitment to safe outcomes. The deep dive analysis into the safety climate survey on a project which introduced MAP mid execution identified significant changes in management commitment (0.283, p=0.014), safety rules (0.205 $p=0.034$) and overall organization safety climate (0.201, $p=0.036$). CCRM is dependent on management commitment to enforce ‘stop work authority’ when a CC is not implemented or effective (Selleck et al., 2023a). The requirement to ‘stop work’ when a gap in CC integrity is identified takes precedence over cost and schedule and the decision to stop work is invested in the frontline supervisors. This is a significant organisational shift in decision making from senior construction or project managers directing the progress of work to frontline supervision having a mandated authority to stop work regardless of the production or cost pressures. In projects which have successfully implemented a CCRM program like MAP, frontline supervisors are commended for exercising CC stop work which is perceived as management commitment to safety.

CCRM defines CCs as a formalized set of ‘safety rules’ which need to be complied with when high risk work is being conducted. Supervisors have clear CC specifications to be applied removing the ‘interpretation’ of safety rules often perceived as bending the rules or not consistently applying safety rules. In a dynamic construction environment clearly, defined CCs remove discretion in the application of the CC and are welcomed by supervisors to assist in their risk decision making. The improved perception of compliance with safety rules in MAP projects is consistent with CC decision making by supervisors.

6.6.4 CCRM influence within a less mature safety culture.

Company CE executes construction projects in South Africa and Zambia was perceived to have a ‘compliant’ safety maturity level as assessed by company management against the Minerals Industry Risk Management (MIRM) maturity scale (Foster & Hoult, 2013). ‘Compliant’ rated safety maturity cultures are compliance focussed, based on enforcing standards with limited worker engagement in proactive safety processes, reflected in low levels of near miss reporting, task observations or proactive hazard reporting. Compliance based safety cultures develop in organisations with low work ownership (limited worker engagement) and high safety climate, particularly where a new body of safety rules are introduced and effectively enforced (Zohar, 2008). Organisations with high safety climate improve worker ownership of safety increases individual and collective ‘safety citizenship’ resulting in better safety communication, hazard identification and taking responsibility to include others safety (Zohar, 2008; Neal et al., 2000; Petitta et al., 2017).

Application of CCRM resulted in an increase in existing hazard reporting frequency (68%) and personal risk assessment activities (100%). Changes in incident event frequency rates were not significant however the observed increase in hazard reporting frequency is consistent with Company CA together with the mechanisms of CCRM influence on hazard reporting. The increase in the rate of personal risk assessments indicates a shift in ‘ownership’ of safety as workers become more involved in personally managing their individual risks. The observed trend in CCRM projects of increased levels of incident frequency rates across near miss, high potential, and all incidents (Table 33) provide an indication the application of MAP processes has extended the worker ‘safety citizenship’ to improved event reporting and a potential shift in Company CE safety maturity towards a ‘Proactive’ level. However, in the absence of safety climate surveys or formal assessment of safety maturity post MAP implementation the effect of CCRM on safety maturity needs further study.

6.6.5 Limitations

The study was comprehensive, covered developing and developed countries, different client industries and across different contracting strategies which provide a good cross section of the construction industry across a five year period. However, there are a few limitations which need to be acknowledged. Firstly, the leading indicators between the companies varied in the forms being used at the project level, however all were applied consistently with the measure being assessed. Whilst a difference in safety culture maturity was identified at the company level, variation will exist at the project level which was not assessed within the study. Further research to explore critical risk maturity (Hassall & Joy, 2016) within the construction industry would further enhance organisations development of CCRM programs.

6.7 Conclusion

CCRM has direct and indirect effect on construction safety performance as measured through leading and lagging safety measures and safety climate perceptions.

CCRM applied on a construction project consistently improves hazard reporting frequency through CC verification and assurance processes or indirectly from improved critical risk awareness and competency. The increase in hazard reporting correlates with and complements existing frontline risk management practices including personal risk assessments and supervisor observations.

The influence of CCRM on safety performance varied between organisations (companies). In the more safety mature company CCRM reduced high potential incidents and serious lost time injury rates the target measures proving CCRM reduced project fatal events. The same effect was not observed on the less safety mature company where CCRM improved existing risk identification activities indicating a shift in safety maturity as workers increase ownership of safety. This was supported by an increase in incident frequency trends indicated a shift in safety maturity was occurring. Further investigation is required to explore this nuance of CCRM effects.

Within an organisation the effect of CCRM on safety performance varied by project but not by country indicating CCRM was affected by project safety climate and not by differences arising from nationality or societal cultural practices.

Safety climate surveys were used to compare safety factors affecting safety climate between control and MAP projects and within MAP projects to understand the behaviours and organisational dynamics being influenced by CCRM. Holistically MAP projects increased safety communication, safety competence and overall organisation safety ratings. The improvement in safety communication rating occurred directly due to the implementation of MAP and the new CC verification and assurance practices. Safety communication improved indirectly through supervisor observations as their risk competency and awareness improved. Similarly improved safety competence ratings were a direct reflection of the CCRM training and competency processes for senior management and frontline supervisory positions.

Significantly the overall organisation safety result when validated at a project level identified this was due to improvement in management commitment and safety rule compliance. A CCRM program when practically applied in the field is dependent on an effective "stop work authority" mandate when a CC is identified as substandard. The field verification of CCs is completed by frontline supervisors meaning the decision making authority shifts from senior construction managers when significant conflicts arise with production pressure due to cost or schedule. In projects which have successfully implemented a CCRM program like MAP, frontline supervisors are commended for exercising CC stop work which is perceived as management commitment to safety. Similarly, the clearly defined CCs remove discretion in the application of the CCs and is identified as improved compliance to safety rules.

In summary CCRM directly improves construction project safety performance by increasing the frequency of hazard reporting and indirectly complimenting existing risk management practices. CCRM improves fatal hazard awareness in day-to-day work practices and in safety mature organisations reduces high potential incidents. Organisational CCRM culture can be negatively moderated by project safety climate influenced by other stakeholders. Construction organisations considering CCRM programs like MAP will benefit from an overall improvement in project safety climate provided executive and senior management fully support the shift in organisational stop work decision making by frontline supervision.

6.8 Acknowledgements

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CHAPTER 7. CONCLUSION

In this chapter, the thesis overall summary is presented together with a summary of the research findings and assesses the extent to which they support the research questions and how they relate to existing research into construction fatality prevention strategies. The chapter critically reflects on the impact of the research, insights, and limitations of the research. The chapter brings together all the research findings and presents the conclusions with recommendations for construction organisations thinking of using a CCRM strategy like MAP and identifies areas for future research.

7.1. Thesis Summary

A disproportionate number of fatalities continue to occur in the construction industry from the due to common high-risk tasks being undertaken where the risks and controls are known, however the controls are not reliable. Current construction safety risk management strategies and practices have been inadequate in preventing fatalities in part due to the dynamic project work environment and complex management structures. This research presents an alternative fatality risk management strategy which applies the principles of Critical Control Risk Management (CCRM) for use by the construction industry. The objectives outline below set the framework for a series of studies to advance the research questions to improve the industry understanding of managing potentially fatal risks:

1. Evaluate current risk practices to identify an alternative risk management strategy to prevent construction fatalities (Part I – Literature Review).

2. Build a working CCRM program for the construction industry (Part II) considering the dynamic work and organisational environments and changing fatality risk profile through a project lifecycle.

3. Field test CCRM using action research and case studies to quantify CCRM contribution to safety performance and analyse CCRM control effectiveness to improve construction projects fatality risk (Part III); and

4. Develop a measure to assess the contribution of an alternative risk management strategy in managing field level fatality risks (Part IV - Critical Control Reliability).

5. Explore the relationship of CCRM on safety climate and organisational risk management through case studies, safety climate and risk maturity surveys to enable comparative analysis of the impact of CCM on different attributes of organisation risk (Part V).

set the framework for a series of studies to advance the research questions to improve the industry understanding of managing potentially fatal risks.

7.1.1. Research Question 1

Research Question 1: Can an alternative risk management strategy, when applied to known fatality risks, reduce the likelihood and severity of potentially fatal events in the construction industry?

This question was used to inform four studies and was the primary objective of the research. The literature review identified alternative risk management strategies used by other industries to manage fatal risks. The literature review identified gaps in current construction risk management strategies due to the inherent human and organisational factors, and the question formed the basis for the research activities to fill the gaps.

7.1.1.1. Alternative Industry Fatal Risk Management Strategies

The literature review identified current construction risk management deficiencies and compared two alternative fatal risk management strategies; safety case used in the hazardous facility and oil and gas industries; Critical Control Risk Management developed for the mining industry.

The construction industry relies on a layering of risk assessments or ‘defence in depth’ strategy which protects operations from single human error or technical fault (Reason, 2016). The strategy breaks down as it is used for all level of safety risks from high-risk tasks to housekeeping type hazards (Perlman et al., 2014b), and assumes all risks are managed to an acceptable level amidst the dynamic and complex construction project (Hallowell & Gambates, 2009). The risk management practices have become bureaucratic (Dekker, 2014) with documentation of the risk assessment process becoming more important than the relationship between the hazard and control (Smith, 2018).

The effectiveness of major hazard and frontline risk assessment programs is impacted by hazards not being recognised (Perlman et al., 2014b), inadequate use of stop work (Dekker, 2014) and risk tolerance by line management (Alarcón et al., 2016). Hazard identification, the fundamental basis for layered risk management strategy is inherently less effective in dynamic construction environment where the risk profile is constantly changing throughout the work shift (Bahn, 2013; Neitzel et al., 2013; Perlman et al., 2014b; Zhang et al., 2017). The effectiveness of controls (barriers) is reliant on the judgement and perceived severity of the hazards by the individual required to implement or action controls (Hopkins, 2011b). Equally, the decision making by supervision to ‘stop work’ based on the integrity of the controls will be shaped by their perception of risk in the absence of clear specifications (Hale & Swuste, 1998; Hayes, 2012).

Comparison of the safety case and CCRM risk management strategies identified similarities in the process to identify major accident events (e.g., Layer of Protection Analysis (LOPA) methodologies) and identify controls. The point of difference in CCRM was the expansion of basic risk management process by focussing on risk treatment through CCs and the verification and monitoring activities to maintain the integrity of the CCs (Hassall et al., 2015; ICMM, 2015).

The review concluded the construction industry, like the oil and gas industry previously, would benefit by adopting a shift in focus from risk assessment and the associated bureaucracy to risk treatment and control to prevent ongoing occurrence of fatality events across the industry. Design and implementation of a CCM approach would need to consider:

i. How the controls were developed to ensure the controls are practical
ii. Provide criteria to support effective frontline decision making that is directly relevant to the fatal hazards
iii. Adaptability of controls to multiple high-risk work activities
iv. Managing human factors which contribute to failure of critical controls, and
v. Different cultural factors between projects in developing countries (e.g., Hong Kong) and developed countries (e.g., Australia).

CCRM was selected as the alternative risk strategy for the further studies, as the methodology was potentially adaptable to the differences inherent in construction industry and managing the dynamic MAE risks within construction projects.

7.1.1.2. Development and Validation of Novel Construction CCRM program (Part II & III)

The study used a mixed method research process for the design, development, and validation testing of the new CCRM program. A six phase fatality prevention process, the Major Accident Prevention ('MAP') program was developed and validated over 18 months on a construction project in Australia. The objectives of the study were:

- Define a risk-based model to assist the management of construction fatality risk reduction.
- Describe and validate the steps required to implement the model on a construction site consistently throughout the project lifecycle.

- Conduct a pilot study to evaluate the performance of the new model relative to existing risk management processes and the human factors which contribute to the failure of controls.
- Conduct statistical evaluation of the potential impact on incident performance.

The study produced a comprehensive construction register of MAEs, associated CC specifications, training packages for line management and supervisors and the methodology to verify CCs in the field as part of ‘normal’ business. Action research, initially using the panel of experts and then feedback from the case study pilot program participants was used to improve the program and supporting tools. CCRM (ICMM, 2015) provided guidance on the generic development of MAP, however novel processes were developed to manage the constantly changing construction risk profile (MAE Risk profile), field verification process and the framework enabling a shift in organization decision making power through the stop work authority.

The study confirmed the CCRM strategy can be applied in practice in construction. The steps of the MAP program outlined the process for implementation and provided the system for the project leadership and line supervision to apply the tools. The MAP program was adaptable to the project lifecycle as the CC verification effort changed throughout the project as the work scope (activities) or MAE Risk profile changed.

The Major Accident Prevention (MAP) program is an alternative risk based Critical Control Risk Management (CCRM) model and implementation methodology. It was shown to effectively manage construction MAE hazards through rules based critical control management applied using high reliability organisational principles.

The MAE risk profiling process MAP adapted well to the dynamic construction environment and provided a practical platform to update MAE risks and management of Critical Control (CC) field verifications.

The MAP program provided a practical solution to manage a complex interface of high-risk tasks by limiting the number of controls and improving the specificity of control statements. The process of defining CCs for each MAE hazard reduced the overall number and complexity of controls front line leaders needed to focus their attention on.

The specificity of the CC statements aided front line leaders and supervisors to quickly assess if the CC was implemented as designed and within control tolerance limits. This resulted in the efficient assessment of CCs for high-risk tasks across multiple MAE hazards.

Supervisors were able to plan and prepare for high-risk work as part of the standard pre-work activities reinforced using the MAE verification as a communication tool during pre-task risk reviews to raise awareness of the MAE hazards and the CCs.

The MAP program resulted in a shift in decision making authority from executive to front line leaders by mandating frontline leaders were fully authorised and required to ‘stop work’ when CCs were not implemented or effective. The shift in decision making authority together with the comprehensive training in CC specifications increased the confidence of frontline leaders to manage high risk activities and act to ‘stop work’ in the absence of CCs. The organisational impact of the shift in decision making authority was not investigated in the study, with further research required to understand how MAP and CC ‘stop work’ impacts safety leadership and project safety climate within a construction organisation.

The MAP program does not operate in isolation to existing construction risk management processes, and in the absence of MAE events on the pilot project was found to enhance field risk management programs (i.e., hazard reporting, supervisor engagements) and has a relationship in reducing first aid events. The interrelationship between MAP and other risk management programs used in construction organisations was both positive and perplexing as MAP contributed to higher frequency of some activities but depressed the use of personal risk assessments by work team members.

The MAP program will benefit construction organisation willing to adopt a CCRM approach to managing fatality risks. The MAE risk profiling process efficiently review high risk work and is supported by practical application through field verification of CCs. Further understanding is required on the human factors affecting CC reliability and how the MAE model will respond to changing construction methodologies. Equally getting the CC’s ‘right’ and the relationship the MAP program has on safety performance and performance of existing risk management processes needs further study.

7.1.1.3. Has CCRM improved safety performance (Part III)

The Pilot Study project did not have any MAE events and no significant correlation between CC verification and MAE’s events was identified.

The high correlation between MAP Check rate and frontline risk assessment processes (HAZOB, SOI) indicates MAP Checks contribute to improving the rate of frontline hazard identification and control. The confounding factor is the negative influence MAP Checks had on Personal Risk Assessment (PRA_FR). PRAs are personal task based hazard assessment conducted by individual workers prior to commencing the task. Verification of Critical Controls managed by a personal safety CCRM program are common contributory factors in lower consequence events (Bellamy, 2015). By applying MAP Checks line supervisors also verified the common controls which prevented minor injuries and incidents.

MAP Checks are supervisor led and include interactions with their work team to conduct verifications which potentially replaces individual task risk assessments and reducing the rate of PRA's being recorded. It is unclear if the relationship between MAP_CH and PRA rates is due to changes in the criteria for completion of PRAs on the project, limitations due to the size of the data sample or another factor. Further research is required to explore the MAP, existing risk programs (PRA, HAZOB, SOI) relationship on safety performance.

The premise in developing the MAP program is through systematic identification of MAE hazards and application of CCs with specific 'control limits' will result in improved risk-based decision making within a project and reduce incidents, particularly MAEs (Grill et al., 2017). Apart from the weak correlation between first aid injuries and MAP Assurance rate [r= -0.589] it was unclear if implementation of MAP in the case study reduced the frequency of incident events.

Measuring construction safety performance given the decentralised organisation structure is complex (Woolley et al., 2020) as leading indicators are interrelated and not always directly related to lagging indicators of incident or injury performance (Lingard et al., 2017; Shohet et al., 2018). Analysis of the case study data indicated MAP verifications improve hazard identification by increasing the rate of other frontline risk assessments, however provided limited information on incident prevention. Further investigation is required to explore the relationship between MAP Checks, risk management processes and incident prevention.

7.1.1.4. Critical Control Reliability Factors (Part IV)

The study answered questions on the reliability of CCs raised by construction executives and site management during the development of the MAP program and conducting the pilot case study. Implementing and maintaining MAP is a significant investment in time, resources, and cost all of which are significantly constrained in the construction environment (Woolley et al., 2020). Senior managers want assurance the investment in MAP delivers safety improvements, which in the absence of incidents is difficult to quantify. Construction organizations participating in the research questioned the validity of MAP to prevent potentially fatal accidents, specifically how does the organization know effort is invested in the 'right' CCs.

The study addressed the following questions:

i. How do we know the CCs developed in the MAP program are the “right” controls to prevent fatality events in the construction industry?
ii. Construction CCs rely heavily on human actions, what performance factors affect the reliability of critical controls?

The study used a focus panel of experts to assess CC reliability factors (implementation, effectiveness) of 160 historic fatality and serious injury events, which occurred over ten years in four participating construction companies. Events for working at height, mobile plant and equipment, stored energy and lifting operations MAE hazard categories were assessed.

The study was able to validate CCs identified in MAP applicable to each of the events would have prevented the events occurrence. The study identified gaps in the existing CC standards which were not initially defined in MAP and were subsequently used to update MAP CCs as part of the continuous improvement process.

The study provided insight into the individual and organizational factors which potentially impact the reliability of CCs. Human performance factors including hazard identification, personal decision making and competency were common findings in the investigation reports analysed. Worker competency was attributed to inexperience or lack of training, or the lack of competency to assess, adapt and apply CC to the work activity being conducted.

In complex construction environments individuals need to be adaptive in the application of the CC to the situation not just follow a black and white ‘rule’. It is the competency to apply CCs to the work environment individuals need to develop which informs their decision to stop work when the ‘rule’ is found not to apply to the situation. In the absence of an organization providing clear direction regarding CC deviations, failures will occur as workers influenced by their own risk perceptions will decide on how and whether to apply the CC and to what standard. The human performance factors can be addressed by the organization improving worker competency to assess and apply CCs across all high-risk tasks and, critically the actions and / or behaviour of competent supervisors to verify CC implementation and effectiveness for the given task being undertaken.

Organisational factors also contributed to the reliability of CCs. Supervisors having reacted to changes in construction schedule, materials, labour resourcing failed to undertake the CC activities including job planning, risk assessments or communicating the risks and CCs to the work team.

7.1.2. Research Question 2

Research Question 2: What effect will implementation of a CCRM strategy in the construction industry have on existing risk management processes, safety performance and human factors which influence safety performance?

The question recognises the CCRM program MAP does not operate in isolation and will interface with existing risk management practices within a project. The question seeks a deeper understanding the contribution CCRM has in preventing fatality events and identifying the factors which influence the effectiveness of the program. Two studies were conducted to investigate the research question: an initial single project case study and a five year longitudinal study of 31 international projects to validate the initial case study.

7.1.2.1. Case Study: Comparing Pre and Post COVID-19 influence on Safety.

This study tested the full interaction of MAP with existing risk management practices under realistic construction conditions (pre COVID-19) and under disruptive conditions (post COVID-19). The study introduced safety culture affects by considering the relationship between safety climate and safety performance as a methodology to describe the effects of changes (COVID-19, Project Manager) had on overall safety performance and CCRM.

The study demonstrated a relationship between MAP activities and existing risk management practices does exist, with MAP activities being influenced by supervisor observations, and MAP positively influencing hazard reporting, whilst having a negative impact on personal risk assessments. Supervisor activity was identified as having influence on safety performance through direct and indirect processes. The supervisor role is pivotal on a construction project as it directly influences work group safety attitudes and risk taking behaviour (Clarke, 2000) resulting in a reduction in injuries (Saunders et al., 2017).

Safety performance measured as total incident rate initially improved in response to COVID-19 due to heightened risk awareness across the workforce, a finding common with other initial COVID-19 studies (Almohassen et al., 2022; Alsharef et al., 2021; Pamidimukkala & Kermanshachi, 2021; Stiles et al., 2021). In response to COVID-19 supervisor observation rate initially increased which was associated with increase in other risk management activities including MAP verifications, however after the initial disruption, the supervisor observation rates reduced to below pre-COVID-19 rates. The decentralization of construction organizations (Lingard et al., 2017) with management control at site directed through the Project Manager and supervisors has meant front line leaders have a direct influence of on safety performance (Guzman et al., 2022). However, the result was transient as frontline risk management activities, (i.e., hazard reporting, personal risk assessments, supervisor observations, MAP checks) reduced over time under the influence of COVID-19 and did not improve until a change of Project Manager occurred.

The study identified the effect of leadership and power of setting a positive safety climate to increase worker motivation, participation in risk management processes and compliance to safety requirements. The safety climate on a project is perceived differently by different organizations working with the site environment or by different age groups. The dynamics with the construction site organizations collectively shape the safety climate on site with the subcontractors having a more direct relationship with their worker generating a more positive safety climate than the principal contractor. Younger members of a construction workforce perceive the safety climate more negatively than older workforce members.

In summary the case study confirmed safety performance and existing risk management practices were influenced by MAP. The study confirmed the importance of site leaders in setting the safety climate identified in previous research [32,40] further longitudinal research is needed to validate the interrelationships identified as changes introduced by COVID-19 are not typical on construction projects.

7.1.2.2. Longitudinal Study: Critical Control Risk Management (CCRM) – Does it contribute to construction safety performance?

Findings from the longitudinal study demonstrated CCRM has direct and indirect effect on construction safety performance as measured through leading and lagging safety measures and safety climate perceptions.

CCRM applied on a construction project consistently improves hazard reporting frequency through CC verification and assurance processes or indirectly from improved critical risk awareness and competency. The increase in hazard reporting correlates with and complements existing frontline risk management practices including personal risk assessments and supervisor observations.

The influence of CCRM on safety performance varied between organisations (companies). In the more safety mature company CCRM reduced high potential incidents and serious lost time injury rates the target measures proving CCRM reduced project fatal events. The same effect was not observed on the less safety mature company where CCRM improved existing risk identification activities indicating a shift in safety maturity as workers increase ownership of safety. This was supported by an increase in incident frequency trends indicated a shift in safety maturity was occurring. Further investigation is required to explore this nuance of CCRM effects.

In summary CCRM directly improves construction project safety performance by increasing the frequency of hazard reporting and indirectly complimenting existing risk management practices. CCRM improves fatal hazard awareness in day-to-day work practices and in safety mature organisations reduces high potential incidents. Construction organisations considering CCRM programs like MAP will benefit from an overall improvement in safety culture and project safety climate provided executive and senior management fully support the shift in organisational stop work decision making by frontline supervision.

7.1.3. Research Question 3

Research Question 3: Are there safety cultural influences or inter-country cultural variations that impact the effectiveness of a construction CCRM strategy?

This question examined CCRM and the effects of differences in safety culture between companies, countries or within organizations which influence safety performance. The research question informed the cultural factors to be considered in the CCRM longitudinal study demonstrating safety culture and risk maturity influence the safety climate and CCRM safety performance within the construction industry.

7.1.3.1. Cultural influence across different countries

Developing countries (e.g., PNG, Timor Leste, Mongolia) have on average higher rates of hazard reporting than developed countries (e.g., Australia, Canada & USA) in response to MAP. However, the result was not consistent across all developing countries with variation occurring between projects. A potential theory for further investigation is the result is related to safety risk maturity of organisations as outline in the section below.

7.1.3.2. Influence of Organization Safety Risk Maturity

MAP introduced a change which was expected to enhance the company safety culture and improve safety performance (Hudson, 2001). The implementation of MAP within the mature safety culture of Company CA resulted in the reduction in frequency of related events (HPIFR, LTIFR). A finding consistent with safety culture studies which identified higher levels of safety investment, safety culture or lower project hazard profiles have better safety performance (Al-Bayati, 2021; Feng et al., 2014; Stemn et al., 2019). However, the results were not universal across all Company CA projects as demonstrated by the significance of the random effect ‘Project’ on safety performance measures.

The company with a 'compliant' level of risk maturity (Foster & Hoult, 2013) the response to MAP resulted in significant increase in hazard reporting and personal risk assessment frequency rates. 'Compliant' rated risk maturity cultures are compliance focussed, based on enforcing standards with limited worker engagement in proactive safety processes, reflected in low levels of near miss reporting, task observations or proactive hazard reporting. Compliance based safety cultures develop in organisations with low work ownership (limited worker engagement) and high safety climate, particularly where a new body of safety rules are introduced and effectively enforced (Zohar, 2008). Organisations with higher safety climate improve worker ownership of safety with an increase in individual and collective 'safety citizenship' resulting in better safety communication, hazard identification and taking responsibility to include others safety (Zohar, 2008; Neal et al., 2000; Petitta et al., 2017) as evident in the response to MAP implementation.

7.1.3.3. Influence of Project Safety Climate

Safety climate surveys were used to compare safety perceptions between control and MAP projects and within MAP projects to understand the behaviours and organisational dynamics being influenced by CCRM. Holistically MAP projects increased safety communication, safety competence and overall organisation safety perceptions.

A significant improvement (6.3%) in safety communication within MAP projects was identified through the surveys which is consistent with previous CCRM observations (Selleck et al., 2022b). The introduction of MAP processes required supervisors to engage workers during MAP checks on the critical controls (CCs) and other managers to discuss CCs with supervisors and workers during MAP assurance reviews. Both processes increased the level of safety communication occurring within a project where MAP was implemented. Gaps in the safety communication effectiveness between organisation types was identified with labour hire workers having a lower perception compared to principal contractors and subcontractors. The differences in safety communication perceptions reflect the level of safety ownership within the organisational group. Under MAP subcontractors are engaged to support the identification of fatal hazards for their work scopes, define CCs and verification specifications (Selleck et al., 2023a). Subsequently, subcontractors regularly engage with principal contractor representatives to align on safety standards and have a high level of safety ownership more likely to participate in communication activities (e.g., pre-start meetings, supervisor conversations) (Lingard & Oswald, 2020; Lingard et al., 2019).

The safety climate surveys identified a significant increase in the overall safety competence perceptions, and more specifically supervisor roles and subcontractor organisations. The purpose of CCRM is to improve fatal risk competence to prevent major unwanted events by focussing on risk treatment in the form of CCs (ICMM, 2015). MAP as a CCRM program applied during this study involved training in CCRM at multiple levels within a construction organisation with particular emphasis on field supervision. Supervisors developed competency in analysing work activities for fatal risks, application of CCs and assessing the implementation and effectiveness of CCs (Selleck et al., 2023a). Subcontractors were included in the development and validation of CC specifications for the specialist scopes of high risk work the subcontractor was undertaking.

On CCRM projects workers had a more positive perception of the organisation and the commitment to safe outcomes. The deep dive analysis into the safety climate survey on a project which introduced MAP mid execution identified significant changes in management commitment (0.283, p=0.014), safety rules (0.205 $p=0.034$) and overall organization safety climate (0.201, $p=0.036$). CCRM is dependent on management commitment to enforce ‘stop work authority’ when a CC is not implemented or effective (Selleck et al., 2023a). The requirement to ‘stop work’ when a gap in CC integrity is identified takes precedence over cost and schedule and the decision to stop work is invested in the frontline supervisors. This is a significant organisational shift in decision making from senior construction or project managers directing the progress of work to frontline supervision having a mandated authority to stop work regardless of the production or cost pressures.

Individual project safety climate, established by site management and leadership will modify overarching organisational safety culture including motivation, participation in safety risk management processes and compliance to safety standards (Glendon & Litherland, 2001; Neal et al., 2000; Pandit et al., 2019). To be effective CCRM requires robust risk management to identify fatal hazards, implement CCs and verify compliance to the standards required, the same organisational attributes influenced by safety climate and project leaders. Further research into the influence of the various construction contracting strategies and composition of managing organisations (Woolley et al., 2020) has on CCRM will benefit construction organisations implementing CCRM programs.

7.2. Significance and Contribution of the Study

7.2.1. CCRM in the Construction Industry

CCRM programs like MAP positively influence construction safety performance and in safety risk mature organisations significantly reduce the potential for fatal incidents. Construction organisations that have less risk mature workforce (e.g., developing countries) will benefit from CCRM in the improvement of existing safety risk management practices (hazard identification) and workers taking ownership of hazards.

CCRM is a major investment in time and cost for construction organisations to develop to meet business requirements, implement and maintain. The research conducted demonstrates both direct and indirect safety benefits of implementing CCRM including the fundamental objective of CCRM to prevent worker fatalities including:

- CCRM verifications improve hazard identification by increasing the rate of other frontline risk assessment practices.
- CCRM activities improve safety climate factors associated with safety competence, risk awareness, safety communications which influence worker participation and compliance.
- The integrity and reliability of CCs is influenced by worker and supervisor competency in the interpretation and application of CCs to the work situation and discipline to stop work where CCs are found to be unreliable.

The study benefits construction organizations applying CCs as a risk management tool as the results confirm the applicability of CCs for the MAE hazards analysed and highlights the factors which need to be considered when implementing a CC program. The success of CCRM within a construction organisation is dependent upon the factors which affect the identification of MAEs, reliability of CCs and engagement by supervisors and workers in the program. The successful implement a CCRM program like MAP will include the following:

- Consistent application of MAE hazard risk profile to establish the plan for MAE verifications in each period (monthly)
- Invest in CCRM training to develop risk competency in frontline supervisors.
- Conducting MAP CC verifications – has the required CCs been implemented and is it effective as defined in the CC specification, i.e., is the CC reliable?
- Senior construction management holding project managers accountable to conduct MAP activities.
- Empowering frontline supervisors to ‘stop work’ regardless of cost, schedule pressures when a CC is not reliable.
- Communication of MAE hazards and actions taken during project communication meetings.

The discipline and risk maturity required to effectively implement a CCRM program within a construction organisation cannot be understated as indicated in observations made across other industries (Hassall, 2017a; IOGP, 2013a).

Monitoring project safety climate to detect changes in safety perceptions which affect programs like CCRM will benefit construction organisations and provide opportunities for early intervention to correct misalignment with the organisation CCRM requirements.

7.2.2. Research Contribution to Safety Risk Management

7.2.2.1. Risk Management in Dynamic Work Environments

The CCRM program does not operate in isolation to existing construction risk management processes. The research explored the interrelationship of the existing risk management practices whilst introducing CCRM. The research established CCRM enhances hazard reporting across both mature and immature risk management organisations. This is a significant finding as hazard identification which is integral to effective risk management programs is known to be unreliable and highly variable within construction sites (Albert, 2017; Abbas, 2018, Carter 2006). Contributing to the improvement in hazard reporting was supervisor engagement of workers when conducting CC verifications (Chapter 6).

CCRM has a significant impact in preventing serious injuries (e.g., lost time injures 97.8% $p=0.0002$) and high potential incidents (e.g., MAE related 80.8% $p=0.005$) within risk mature organisations. The reduction in incident rates was achieved across the risk mature organisation projects regardless of where the work was being performed demonstrating a risk resilience within the organisation could be achieved. However, the same organisation had projects being undertaken in joint venture arrangements where the CCRM was not implemented in part due to the contracting arrangements (Chapter 6).

In less risk mature organisations CCRM correlated with an increase in hazard reporting (67.9%) and personal risk assessments (100.3%) but did have the same effect in preventing incidents. The results indicate organisations on the lower end of risk maturity have found it more difficult in the application of CCRM due to their overall understanding of risk management. The effect of risk maturity and CCRM needs further exploration.

7.2.2.2. Organisational Dynamics and Safety Risk Management

The study provided insight into the individual and organisational factors which potentially impact the reliability of CCs. Human performance factors including hazard identification, personal decision making, and competency were common findings in the investigation reports analysed. Worker competency was attributed to inexperience or lack of training, or the lack of competency to assess, adapt and apply CC to the work activity being conducted.

A significant aspect of the research was the insights into organisational dynamics and shifts which occurred when CCRM was implemented within an organisation. The principles defining acceptable CCRM behaviours (Chapter 3) including front line supervisors' authority to 'stop work' when CCs were not reliable had was a major shift in organisational decision making. The shift in decision making authority together with the comprehensive training in CC specifications increased the confidence of frontline leaders to manage high risk activities and act to 'stop work' in the absence of CCs. Throughout the research frontline supervisors were pivotal to improving CC reliability through their directions and influence on safety climate factors (Chapter 5 and 6).

7.2.2.3. Personal Safety – Critical Control Reliability

The study on reliability of CCs (Chapter 4) explored the reliability of CCs and the common factors which affect implementation and effectiveness. Human performance factors including hazard identification, personal decision making, and competency were identified. Worker competency was attributed to inexperience or lack of training, or the lack of competency to assess, adapt and apply CC to the work activity being conducted. The effectiveness of supervision reacting to changes in construction schedule, materials, labour resourcing was identified where supervisors failed to undertake the CC activities including job planning, risk assessments or communicating the risks and CCs to the work team. The research identified the reliability of CCs relies on organisational processes to ensure supervision and workers are trained and competent in the application of CCs, direction is provided to manage deviations and management oversight to ensure implementation and quality is maintained.

7.2.3. Action Research and Industry Collaboration

The pragmatic methodology applied through action and mixed method research was conducted in collaboration with construction companies. Collaboration with the participating companies enabled the research to analyse fatality risk management problems, develop and trial solutions whilst testing validity of the solutions within the social context of construction projects. The research benefited from input from industry expertise in developing potential solutions, trialling within construction projects and feedback from participants undertaking CCRM activities. The participating construction organisations benefitted from application of the solutions in real time and throughout the research were able to take the findings and progress improvements in managing of fatal risks.

The risk for the research is the potential introduction of bias which was managed through the design of each study and overall, by the depth and breadth of the longitudinal study detailed in Chapter 6.

A final note the construction organisations involved in the research have continued to implement MAP as their CCRM program and continue to use for all new projects where they are principal contractor with the endorsement of the client organisations.

7.2.4. Research Methods

Where fatal risks associated with work activities are known the study developing the CCRM construction methodology (Chapter 3) through action research developed a risk profiling methodology to assess fatal risks based on planned work activities. The risk profile addressed the complexity of construction project lifecycles which are dynamic as the program of work progresses and the risk profile changes week to week. The value in the risk profile method was perceived by site managers and supervisors in the efficiency of completing a rigorous review of planned work which established the CC verification plan for the upcoming month.

The study on control reliability (Chapter 4) presented a novel use of bowties to illustrate the results of the control reliability analysis. The use of the bowtie enables organisations to clearly identify gaps in control pathways and the reliability of the controls being tested across the organisation. Organisations benefit by being able to focus resources on gaps or specific reliability factors for the weak controls. The methodology provides a way of evaluating and testing controls to identify weakness in the reliability (implementation and effectiveness) of the controls and fatal risks on construction sites.

7.3. Conclusion

The studies completed address a critical gap in current construction risk management practices which have proven to be inadequate in preventing fatalities from common high-risk tasks with known controls. The results of the studies presented in this dissertation build a body of knowledge and working methodology for the design, implementation, and maintenance of an alternative risk management strategy (CCRM) to prevent fatalities in the construction industry. A recurring finding throughout the research is the successful implementation of the CCRM program is dependent upon management commitment at all levels of the organisation to proactively support the consistent and systematic verification of CCs in the field. One of the benefits of the MAP program as designed through the research is the positive influence on safety climate the CC activities promote within a project increasing worker risk awareness, motivation, participation, and compliance to safety risk management in general.

CHAPTER 8. LIMITATIONS AND FUTURE RESEARCH

8.1 Study limitations and opportunities for future research

Each of the individual studies had limitations which are worth noting. Many of the limitations also provide an opportunity for further research.

8.1.1 Developing a novel CCRM program – Major Accident Prevention (MAP)

Limitations

The use of action research methodology in the development of each of the MAP tools and processes applied consensus decision making within the research focus groups. Consensus decision making can introduce ‘group think’ dynamics which can result in reduction in alternative solutions being suggested or ignoring novel perspectives. The inherent bias was offset by practical field application with independent construction personnel to provide constructive feedback which was incorporated into the tools or process and retested.

The organisation power shift in decision making by empowering supervisors to ‘stop work’ when CCs were not implemented or effective was not foreseen in the design of the initial study. The shift in decision making authority together with the comprehensive training in CC specifications increased the confidence of frontline leaders to manage high risk activities and act to ‘stop work’ in the absence of CCs. The organisational impact of the shift in decision making authority was not investigated in the study, with further research required to understand how MAP and CC ‘stop work’ impacts safety leadership and project safety climate within a construction organisation.

The MAP program does not operate in isolation to existing construction risk management processes, and in the absence of MAE events on the pilot project was found to enhance field risk management programs (i.e., hazard reporting, supervisor engagements) and has a relationship in reducing first aid events. The interrelationship between MAP and other risk management programs used in construction organisations was both positive and perplexing as MAP contributed to higher frequency of some activities but depressed the use of personal risk assessments by work team members.

Further Research Opportunities

Further understanding of the interrelationship between MAP and other risk management programs used in construction organisations is required to understand MAP influence on safety performance – does it directly prevent fatalities, or does it contribute to the prevention of fatalities? What behaviours are modified in the use of all the risk assessment programs when a CCRM program is implemented?

Further understanding is required on the human factors affecting CC reliability and how the MAE model will respond to changing construction methodologies?

Equally getting the CC's 'right' and the relationship the MAP program has on safety performance and performance of existing risk management processes needs further study.

8.1.2 Critical Control Reliability

Limitations

The methodology relied on a data base of historical fatal and serious incidents tother with detailed investigation reports in sufficient event number to assess CC reliability. The data limited the analysis to four hazard categories and did not cover all construction high-risk activities. Identifying and obtaining access to alternative data sets would be required to extend the research to a broader range of MAE hazards.

The calculation for control reliability level is biased and over represents the failure rate as the assessment was conducted on incident events with known control failures and does not represent every time a Critical Control was challenged when executing work.

Equally, the study did not assess various cultural factors (e.g., language, religion, societal structures) and commercial and delivery strategies (e.g., self-perform, subcontractor, joint ventures) which potentially impact control of construction project fatal hazards.

Further Research Opportunities

The construction industry captures in hard copy the detailed information in risk assessment forms to extend to broaden the control reliability calculations to assess every time a CC was challenged within the project. The data recorded on the hard copy forms would need to be captured digitally (through direct entry into a risk application and / or capture using Optical Character Recognition (OCR) software to undertake further analysis. The development of an algorithm to monitor CC reliability would provide construction organisations specific CCRM leading indicators.

The effect of the commercial mechanism for construction contracts and the type of organisation structure managing a construction contract will create different cultures from parent companies. Further understanding of the influence of these factors on CCRM will assist construction managers moderate negative cultural or organisation influences.

8.1.3 COVID-19 Influence on Safety Performance

Limitations

The study was limited to one construction project operating under fly in: fly out manning in remote Western Australia with personnel experiencing long periods of isolation physically away from immediate personal support networks. Managed under joint venture management structures with stringent client COVID-19 imperatives which constantly changed, a level of misalignment occurred between organizations not usually present within a construction project.

Under the unique circumstances the aspects directly related to participation rates (high rates) and misaligned safety perceptions between organizations, these should not be extrapolated as typical construction project work arrangements.

The safety climate survey used was modelled and validated through research (Guo et al., 2016; Saunders et al., 2017) to test inter-organization and supervisor level safety climate factors, while the safety climate measures were sensitive enough to detect differences in real test situations further validation across multiple case study sites is needed.

COVID-19 was a significant disruptive event and while being a focus of the study also introduced a potential bias in perceptions relevant to management commitment as organization management were not able to have a present on the work site.

Further Research Opportunities

While the study confirmed the importance of site leaders in setting the safety climate identified in previous research (Kapp, 2012; Zohar, 2002) further longitudinal research is needed to validate the interrelationships identified. Further research to across multiple projects is needed to test the safety performance and validate safety climate results from this one case study.

8.1.4 Longitudinal Study: Critical Control Risk Management (CCRM)

Limitations

The study was comprehensive, covered developing and developed countries, different client industries and across different contracting strategies which provide a good cross section of the construction industry across a five year period. However, the leading indicators between the companies varied in the forms being used at the project level, however all were applied consistently with the measure being assessed.

Whilst a difference in safety culture maturity was identified at the company level, variation will exist at the project level which was not assessed within the study.

Further Research Opportunities

Further research to explore critical risk maturity (Hassall & Joy, 2016) within the construction industry would further enhance organisations development of CCRM programs.

8.2 Critical Reflection

The research was conducted under a critical realism ontology which considered the real construction environment from different social perspectives and interactions when designing each supporting study. However, as the research progressed under the social constructionist epistemology the research perspective narrowed as the MAP program was further developed and then used as a test platform in assessing CCRM. Action research methodology was used throughout the various studies as each concept or approach was developed and validated through field application. The risk is applying action research is a level of researcher bias is introduced, which has been balanced by statistical rigour and the comprehensive longitudinal study across multiple organisations outside of the researchers influence.

The research confirmed an alternative risk strategy in the form CCRM applied through the MAP program in risk mature organisations can prevent potentially fatal events from occurring. To prevent fatalities using CCRM the conditions outlined in Section 7.1.4 must occur including the shift in stop work decision making authority to frontline supervisors who are critical actors in the CCRM program.

The MAP program is one methodology to apply CCRM in the construction industry. However, the register of MAE hazards, bowtie analysis and determination of CCs has proven to be adaptable across multiple organisations, companies, and international project implementation. The MAE hazard development methodology has proven to be repeatable. Throughout the duration of the research the methodology in developing MAE hazard bowties and CCs has been extended to further high-risk activities with the research team having now developed 63 separate MAE hazards and associated CCs.

No discernible difference due to translation of MAP tools including CC checklists into Mongolian or Pidgin (PNG) was identified. Equally with the associated

The study has contributed to the body of knowledge available to construction industry as the MAE bowties and CCs have been defined and can be made available upon request. The research has developed a working understanding of the inter-dependence of leading and lagging indicators together with safety climate perceptions held by workers and the influence of MAP activities. Construction managers and safety professionals detecting a change in one indicator (e.g., reduction in supervisor observations) can predict the effect the change will have on other risk management activities (MAP checks) and be able to intervene before a worker is exposed to potentially fatal energies as a CC has failed.

APPENDICES

Appendix A: Construction Activities and Definitions

Activity	Definition (activity scope)
Activity 1: Logistics – personnel / materials / equipment	Movement of personnel, materials, equipment and supplies to, from and around Company and non-Company sites for business purposes
Activity 2 - Site Establishment / Demobilisation	Design and construction and setup of commercial, industrial, residential or office buildings including site preparation; power, water, sewage or communication services; industrial fit-outs (cranes, exhaust systems, machinery).
Activity 3 - Earthworks / siteworks / road / rail	Design, construction, site preparation, installation and completion of bulk earthworks for facilities, structures and linear infrastructure including MOF facilities; roads, pavement, rail, power/coms transmission infrastructure.
Activity 4 - Structural, Mechanical, Piping (Including tanks)	Design, construction and installation of facilities and structures including process systems, storage tanks, stick build structures, machinery, communications towers. Includes Structural, Mechanical and Piping activities related to Hook-up, Operations & Maintenance tasks.
Activity 5 - Electrical, Communication, Instrument Installation	Installation and fit out of communications, instrumentation and control systems in a building, plant or facility. Includes Electrical, Communication and Instrument Installation activities related to Hook-up, Operations & Maintenance tasks.
Activity 6 - Pipelines construction - (onshore / offshore)	Design, construction, installation of pipelines including buried, surface laid and suspended/elevated pipes.
Activity 7 - Jetty / MOF Installation - including piling / dredging / marine works	Design, construction, installation and fit-out of jetties and MOFs, including bulk earthworks, in or immediately adjacent to any waterway.
Activity 8 - Fabrication	Fabrication, casting and manufacture in Company and non-Company locations including international suppliers including access to from and around that facility. Includes Fabrication activities related to Hook-up, Operations & Maintenance tasks.
Activity 9 - Tunnelling / Underground excavation	A tunnel or underground excavation including the construction of shafts, risers, drives, stopes, material passes and cut and cover excavations. Includes use of tunnel boring, airleg, shaft boring and mechanised mining methodologies.
Activity 10 - Pre-commissioning / Commissioning	Process Functional Testing, Fire & Gas Testing, ESD Testing, Mechanical running, High Pressure Leak Testing, Inerting with N_2, Catalyst Loading, Introduction of Fuel Gas, Commissioning Utilities, Commissioning Flare, Compressor runs on Nitrogen or possibly air. Energizing equipment.
Activity 11 - Survey / Inspection Services	Survey and inspection services requiring access to supplier facilities, inspection and testing at non-Clough and international locations; access to remote locations and activities where a Clough person is required to work alone. Includes Survey / Inspection activities related to Operations & Maintenance tasks.
Activity 12 - Forestry	The felling, clearing, hauling (skidding), sawmilling, loading and transport of timber including use of chainsaws, cherry pickers, dozer chains, explosives as methods to fell trees.

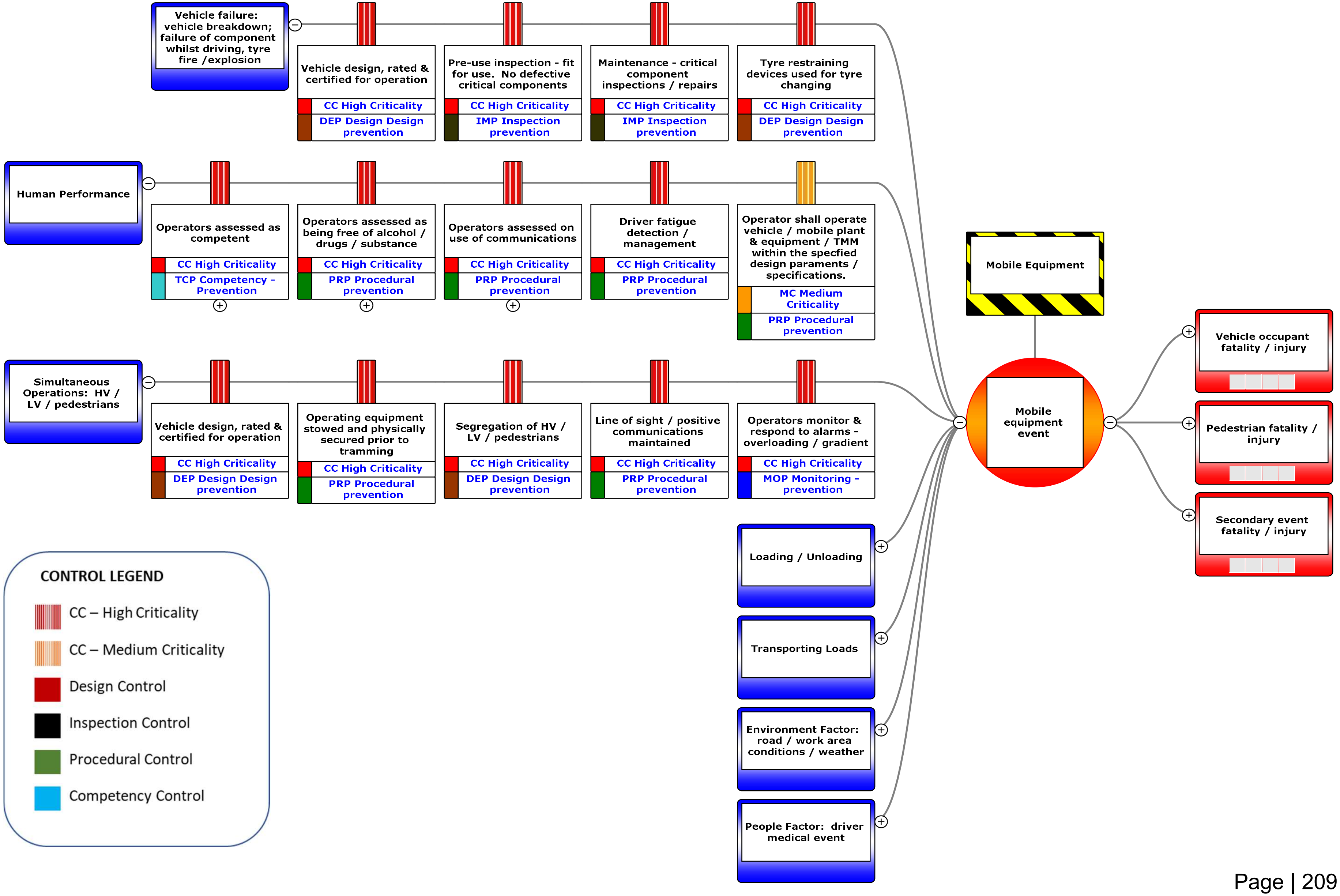
Appendix B: Summary of Fatality related Major Accident Event (MAE) Categories and MAE Hazard Scenarios

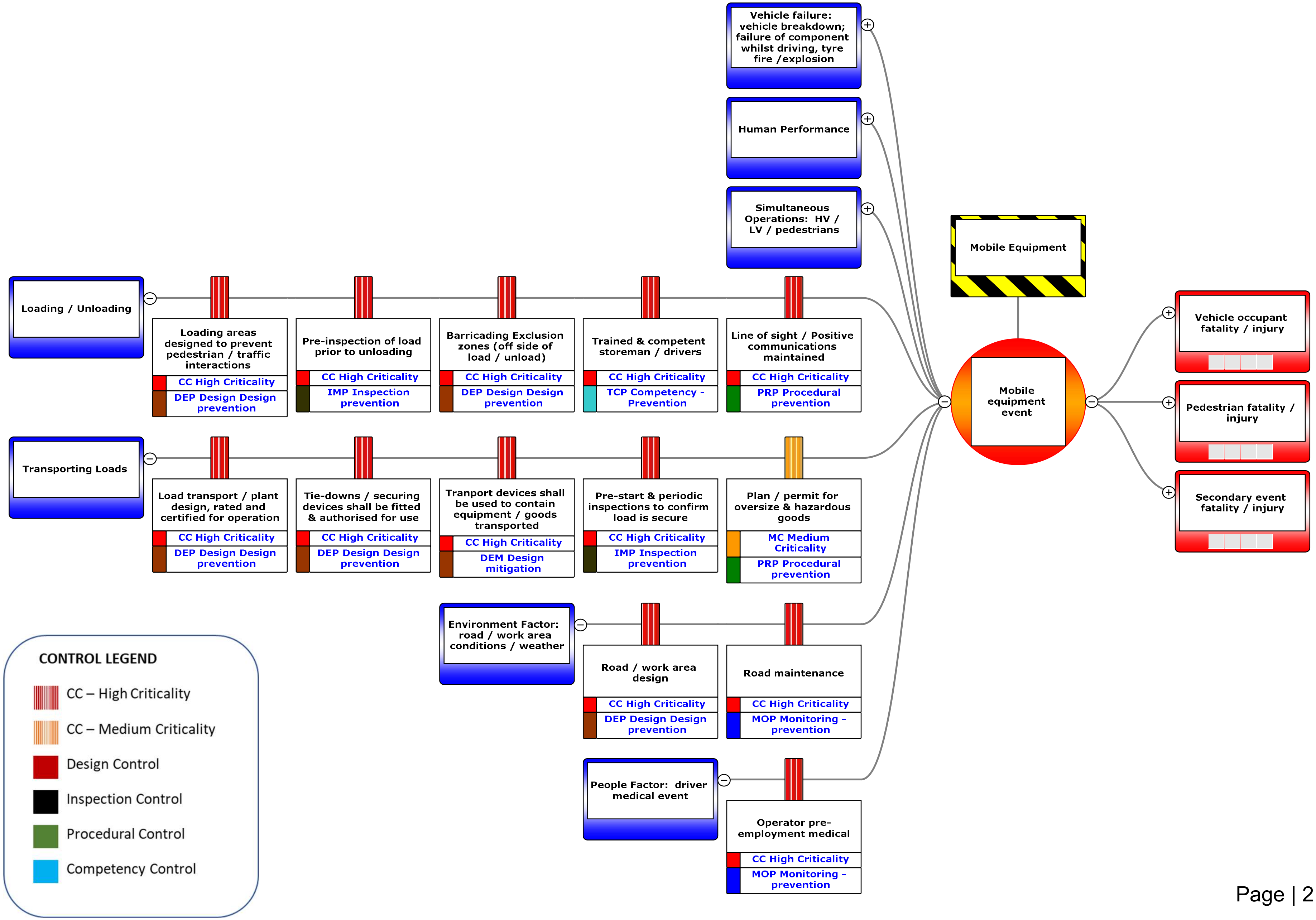
MAE Category	MAE Scenarios
Use of Air Transport	Travel using air transport – crash from flying in a fixed wing / helicopter event, fall from, depressurisation, medical or security event during travel.
Working in a Confined Space	Working in a confined space – insufficient oxygen, fumes / gas stored within a confined space, gasses entrained in fluids (H2s), work generating gasses (e.g., painting, welding fumes), hot work causing fire / explosion, hypo / hyperthermia
	Working within a contaminated atmosphere – working with a dedicated air supply in known toxic or oxygen deficient atmosphere in confined space.
Excavating or Penetrating a Surface	Striking a live service – gas / power / hydraulic pipe or cable during excavation or penetration activities, striking overhead power lines or other services
	Collapse of ground – into / around excavation inundating workers (soil, slope, groundwater, flooding, erosion)
	Unsafe atmosphere in excavation – use of chemicals, hydrocarbons generating fumes or reactive gas generating ground (e.g., H_2S).
Fire and / or Explosion	Unplanned detonation of explosives – during use, transport, storage or handling
	Hot work – thermal cutting, welding, grinding, heating with an open flame
	Hot work in potential explosive atmosphere – flammable process / hydrocarbon storage, venting or other release
	Loss of containment of Flammable Substances – during use, transport, transfer, storage or handling
Hazardous Substances	Loss of containment of hazardous substances – during transport and storage of bulk / containerised hazardous substances via leaks, collision, or corrosion of vessels, loading / unloading or overfilling
	Handling and use of hazardous substances – contract through skin, or inhalation of toxic gases / fumes.
Use of Land Transport	Vehicle component failure whilst driving on site / off site – loss of steering, brakes, wheel / tyre failure
	Loss of control of vehicle – driver error leading to vehicle collision, rollover or other accident on site / off site: fatigue, under influence of alcohol or drugs, concentration lapse, speeding, unfamiliar road rules / customs / vehicle type, driver medical event.
	Unsecured loads – loads fall during loading, transport, unloading
	Driving on site – heavy vehicle / light vehicle / pedestrian / fixed equipment collisions, site conditions leading to collision or rollover, uncontrolled release of high tyre pressures, vehicle tyre fires, adverse weather

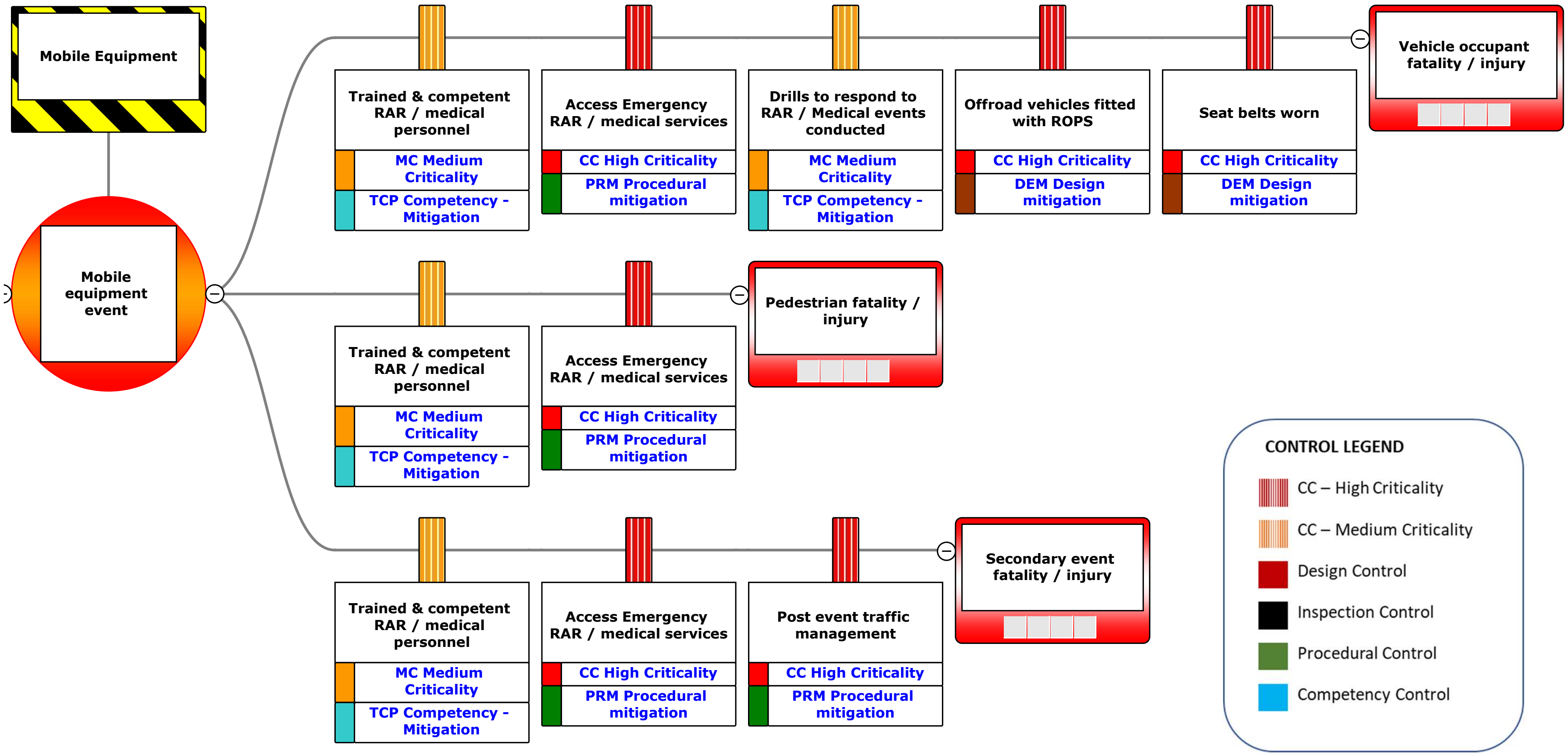
MAE Category	MAE Scenarios
Lifting Operations	Crane / lifting device instability – load / centre of gravity shifts, over capacity / range, failure of ground or supporting infrastructure, marine vessel instability, strong winds.
	Lift contact with structure / asset / powerline / live services – load or crane snagging or striking ancillary equipment, services, structures, or buildings.
	Moving / swinging loads – swinging loads or moving crane parts contacting personnel involved in the lift, including lifts to / from an unstable vessel.
	Dropped load – dropped load, loose objects, debris or falling parts.
Marine Operations	Working over water – personnel working near open edges, working on temporary / fixed platforms over water
	Drop / Fall from Personnel Transfer basket – use of lifting device / crane suspended transfer baskets with potential for basked to be dropped, personnel fall from or trapped under transfer basket.
	Marine personnel transfer failure – vessel to vessel, use of tender / crew boat, vessel to /from shore, structure, or jetty; gangway transfers
	Vessel collision / grounding – multiple vessel operations in same area; use of tender vessels for transfers or mooring operations; civilian or other vessel interaction when operating or in transit; grounding or vessel collision with submerged or surface structure, drifting / mooring / propulsion failure
	Vessel instability / taking on water – watertight integrity failure' vessel ballast / stability system failure; vessel overload / tippling, jack up barge lifting failure
	Mooring line / anchor handline failure – personnel struck / caught by mooring line or anchor during mooring operations.
	Divers in the water – dropped objects, air supply restriction / contamination, attack by shark / crocodile, diving 'bends' hazards.
Stored Energy	Uncontrolled electrical energy release
	Uncontrolled release from Pressurised Systems: personnel struck by debris, concussed by uncontrolled release of pressurised fluids / gases pressurised within tanks, pipes (temporary or permanent)
	Uncontrolled release of Physical energy from structure / equipment – personnel struck by, entangled within a structure / equipment from uncontrolled release of physical energy from structural failure / demolition, tension in lines and pipes, from push/pull/twisting/ expansion energies
	Uncontrolled release of mechanical energy from equipment - personnel struck by, entangled within a structure / equipment from uncontrolled release of mechanical energy including springs, fly wheels, pistons, motors, conveyors, rotating parts and tools.
	Manual tree felling – manual felling of trees / cutting of logs, falling trees, limbs or debris; deadfall; rolling / falling logs on the ground; struck by chainsaw blade.

MAE Category	MAE Scenarios
Working at Height	Fall through or from a platform or structure – grating, work platform, floor / roof access, manhole, voids, wharves / jetties, natural rock faces.
	Fall down – access and egress from fixed and mobile plant / vessels, stairs / ladders / unstable ground.
	Fall from scaffold – erection / dismantling of scaffolding, working from scaffold, scaffold collapse.
	Fall from mobile work platform – failure of / fall out of EWP, scissor lift, temporary mobile platform
	Working from man cage – man cage drops, or personnel fall out of man cage / work basket.
	Fall from height during rope access activities
	Dropped objects – dropped tools / materials whilst working at height.

Appendix C: Case Study - Mobile Equipment Bowtie Analysis

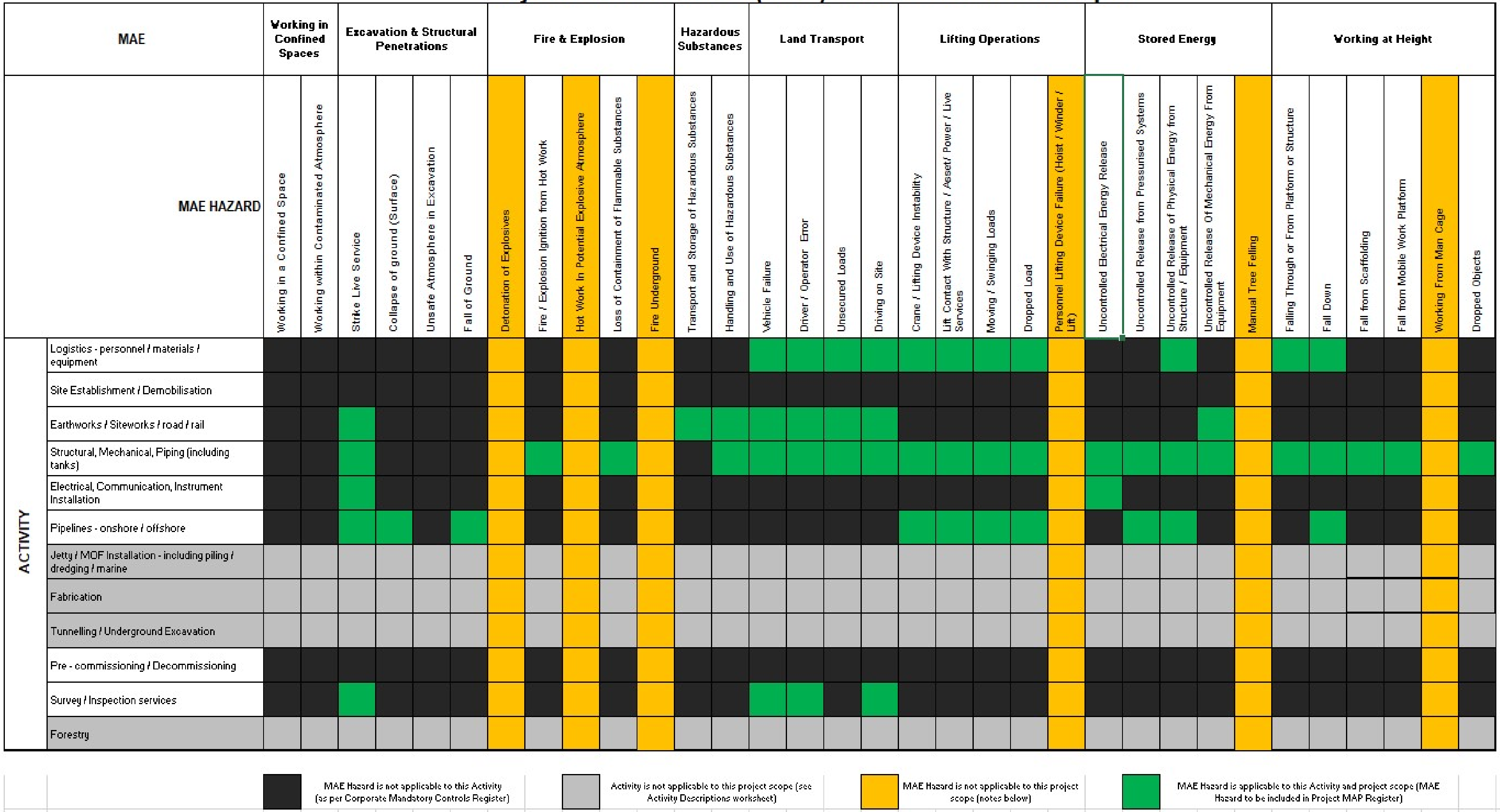



Vehicle failure: vehicle breakdown; failure of component whilst driving, tyre fire /explosion
Human Performance
Simultaneous Operations: HV / LV / pedestrians
Mobile Equipment
Loading / Unloading
Loading areas designed to prevent pedestrian / traffic interactions
CC High Criticality
DEP Design Design prevention
Pre-inspection of load prior to unloading
CC High Criticality
IMP Inspection prevention
Barricading Exclusion zones (off side of load / unload)
CC High Criticality
DEP Design Design prevention
Trained & competent storeman / drivers
CC High Criticality
TCP Competency - Prevention
Line of sight / Positive communications maintained
CC High Criticality
PRP Procedural prevention
Mobile equipment event
Vehicle occupant fatality / injury
Pedestrian fatality / injury
Secondary event fatality / injury
Transporting Loads
Load transport / plant design, rated and certified for operation
CC High Criticality
DEP Design Design prevention
Tie-downs / securing devices shall be fitted & authorised for use
CC High Criticality
DEP Design Design prevention
Tranport devices shall be used to contain equipment / goods transported
CC High Criticality
DEM Design mitigation
Pre-start & periodic inspections to confirm load is secure
CC High Criticality
IMP Inspection prevention
Plan / permit for oversize & hazardous goods
MC Medium Criticality
PRP Procedural prevention
Environment Factor: road / work area conditions / weather
Road / work area design
CC High Criticality
DEP Design Design prevention
Road maintenance
CC High Criticality
MOP Monitoring - prevention
People Factor: driver medical event
Operator pre-employment medical
CC High Criticality
MOP Monitoring - prevention
CONTROL LEGEND
CC – High Criticality
CC – Medium Criticality
Design Control
Inspection Control
Procedural Control
Competency Control

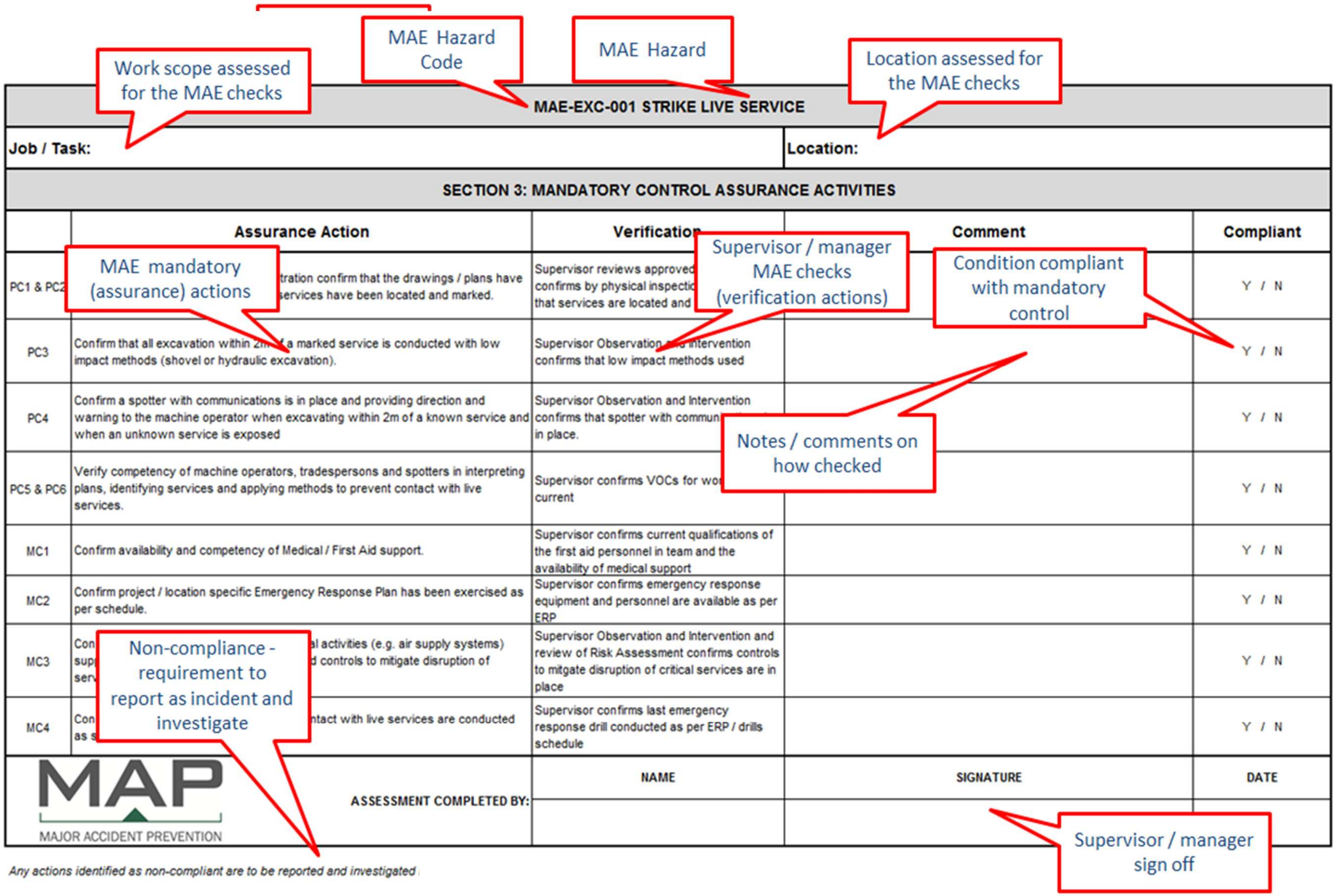

Mobile Equipment
Mobile equipment event
Trained & competent RAR / medical personnel
MC Medium Criticality
TCP Competency - Mitigation
Access Emergency RAR / medical services
CC High Criticality
PRM Procedural mitigation
Drills to respond to RAR / Medical events conducted
MC Medium Criticality
TCP Competency - Mitigation
Offroad vehicles fitted with ROPS
CC High Criticality
DEM Design mitigation
Seat belts worn
CC High Criticality
DEM Design mitigation
Vehicle occupant fatality / injury
Trained & competent RAR / medical personnel
MC Medium Criticality
TCP Competency - Mitigation
Access Emergency RAR / medical services
CC High Criticality
PRM Procedural mitigation
Pedestrian fatality / injury
Trained & competent RAR / medical personnel
MC Medium Criticality
TCP Competency - Mitigation
Access Emergency RAR / medical services
CC High Criticality
PRM Procedural mitigation
Post event traffic management
CC High Criticality
PRM Procedural mitigation
Secondary event fatality / injury
CONTROL LEGEND
CC – High Criticality
CC – Medium Criticality
Design Control
Inspection Control
Procedural Control
Competency Control

Appendix D: MAP Risk Profile – Case Study Example

Major Accident Event (MAE) Hazard Profile - Example



Appendix E: MAP Checklist Highlighting Design Features



MAE-EXC-001 STRIKE LIVE SERVICE				
Job / Task:			Location:	
SECTION 3: MANDATORY CONTROL ASSURANCE ACTIVITIES				
	Assurance Action	Verification	Comment	Compliant
PC1 & PC2	…tration confirm that the drawings / plans have … services have been located and marked.	Supervisor reviews approved … confirms by physical inspectio… that services are located and …		Y / N
PC3	Confirm that all excavation within 2m of a marked service is conducted with low impact methods (shovel or hydraulic excavation).	Supervisor Observation and Intervention confirms that low impact methods used		Y / N
PC4	Confirm a spotter with communications is in place and providing direction and warning to the machine operator when excavating within 2m of a known service and when an unknown service is exposed	Supervisor Observation and Intervention confirms that spotter with communi… in place.		Y / N
PC5 & PC6	Verify competency of machine operators, tradespersons and spotters in interpreting plans, identifying services and applying methods to prevent contact with live services.	Supervisor confirms VOCs for wo… current		Y / N
MC1	Confirm availability and competency of Medical / First Aid support.	Supervisor confirms current qualifications of the first aid personnel in team and the availability of medical support		Y / N
MC2	Confirm project / location specific Emergency Response Plan has been exercised as per schedule.	Supervisor confirms emergency response equipment and personnel are available as per ERP		Y / N
MC3	Con… sup… ser… …l activities (e.g. air supply systems) …d controls to mitigate disruption of	Supervisor Observation and Intervention and review of Risk Assessment confirms controls to mitigate disruption of critical services are in place		Y / N
MC4	Con… as s… …tact with live services are conducted	Supervisor confirms last emergency response drill conducted as per ERP / drills schedule		Y / N
MAP MAJOR ACCIDENT PREVENTION	ASSESSMENT COMPLETED BY:	NAME	SIGNATURE	DATE

Any actions identified as non-compliant are to be reported and investigated

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