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

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

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ABSTRACT

Despite developments in the prevention of fatalities in the construction industry, fatalities resulting from well-known hazards continue at an unacceptable rate. Construction fatality prevention literature describes risk management techniques to provide 'early warning' of potential events. In dynamic construction project environments, these 'early warnings' are missed resulting in serious and fatal events. Critical Control Risk Management (CCRM) provides an alternative strategy to prevent fatal events in the construction industry. However, no research exists that explores the application of CCRM to actual construction projects. This study aims to design, develop, and validate a construction fatality prevention program using CCRM principles through mixed method research. A six-phase fatality prevention process, the Major Accident Prevention ('MAP') program was developed and validated over 18 months on an Australian construction project. The MAP program provided a practical approach to risk management which significantly enhanced frontline risk management practices. Modelling of performance indicators identified first aid injuries and hazard reporting were the most significant measures which correlated with supervisor observations, and personal risk assessments MAP activities. A weak correlation between MAP activities and first aid injuries was identified (0.528p = <0.05) with further statistical analysis limited by the small sample size. A key attribute of the MAP program was the risk profiling planning tool which provided a four week look ahead on the fatal risks, allowing management to focus effort on verifying relevant critical controls in the field. The findings of this study aim to help construction organizations develop and implement fatal risk prevention programs.

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.[1] 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 1.

Research into accident prevention has identified multiple factors and safety controls to prevent incidents from occurring (Zhang et al. 2019; Mohammadi, Tavakolan, and Khosravi 2018; Bellamy 2015). Construction specific studies have analysed incidents to identify causation factors (S. Chi et al. 2015; Betsis et al. 2019; Winge, Albrechtsen, and Mostue 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.[2] 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 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

Abbreviations: MAP, Major Accident Prevention; CCRM, Critical Control Risk Management; HRO, High Reliability Organisations.

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Table 1
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

control was inadequate (Dodshon and Hassall 2017; Bellamy 2015; Lingard et al. 2021). A better understanding of the reasons why the controls are unreliable is required when considering alternative risk control strategies.

Hopkins (2011) 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 more likely to act and intervene when controls deviated from the limits even when under production pressure.

Our review, Selleck and Cattani (Selleck and Cattani, 2019), concluded that the construction industry "would benefit by adopting a shift in focus from risk assessment and the associated bureaucracy, to 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.

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) 2015b). 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 Karl and 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 (International Council for Metals and Mining (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.

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) (International Standardization Organization (ISO) 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" (International Organisation for Standardization, 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 and 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 and Cattani, 2019). Albert and Pandit (2020a) 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:

1. reduce human error associated with hazard identification;
2. reduce complexity of the layered risk management process by focussing on risk treatment (I.e., controls);
3. improve the specification of controls to enable consistent decision making on the implementation and effectiveness of controls; and
4. 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 (International Council for Metals and Mining (ICMM), 2015b, International Council on Mining and Metals (ICMM), 2015a). 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). 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.

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 (Selleck and Cattani, 2019; Albert and Pandit 2020a).

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. 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 Fig. 1 and summarized in Table 2. 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 bow-ties and alignment on controls.

Table 2
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 A, Appendix B, Appendix 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

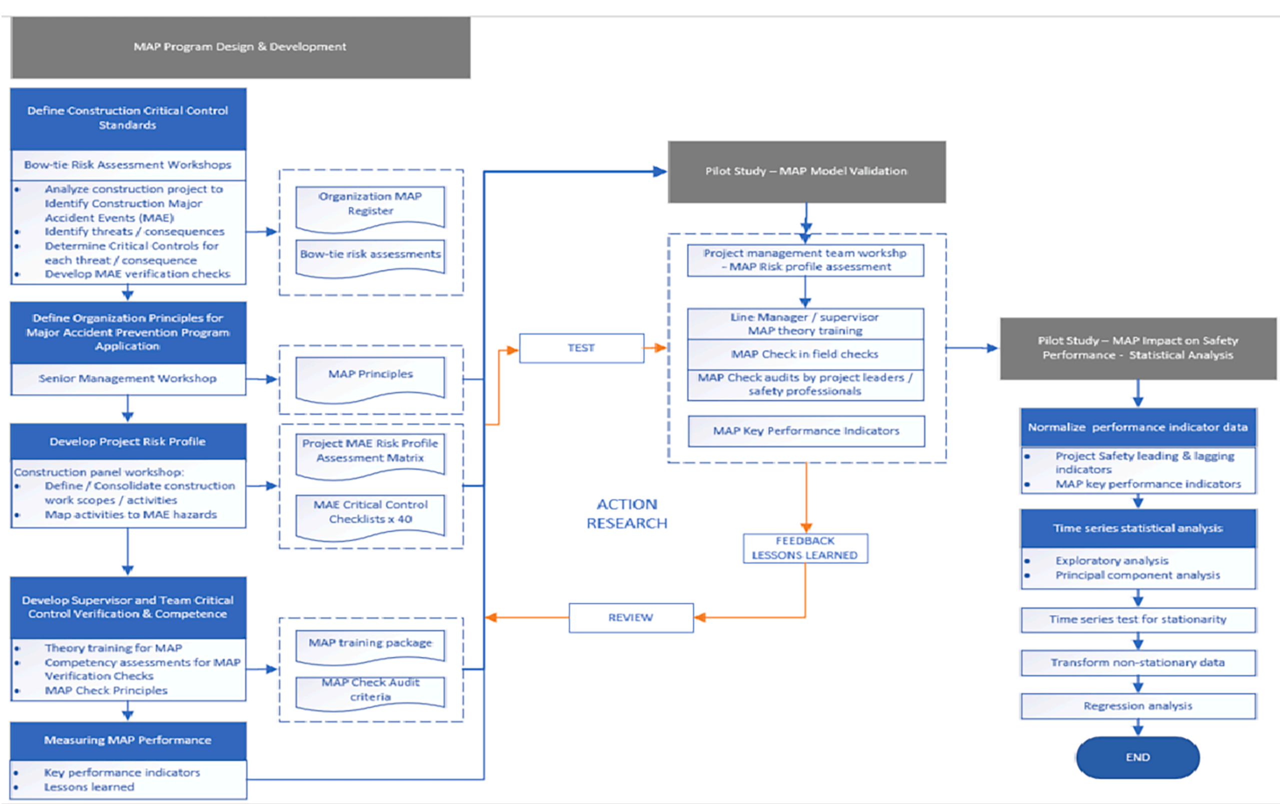

Fig. 1. Research framework by phase.

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.

3.1. Major Accident prevention model

The Major Accident Prevention (MAP) program was developed by adapting the safety case and the ICMM (2015b) CCRM models to manage known personal safety fatalities experienced in the construction industry. The MAP program builds on the process outlined in the ICMM (2015a) 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 (Fig. 2) 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.

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 and 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 (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.

3.2. MAP program design, development and tools

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 3.

To gain the detailed understanding, a panel of construction experts 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. The panel conducted bow-tie analysis following the

Table 3
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 (2015b) 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
MAE Category	Grouping of common MAE Scenarios – e.g. Working at Height

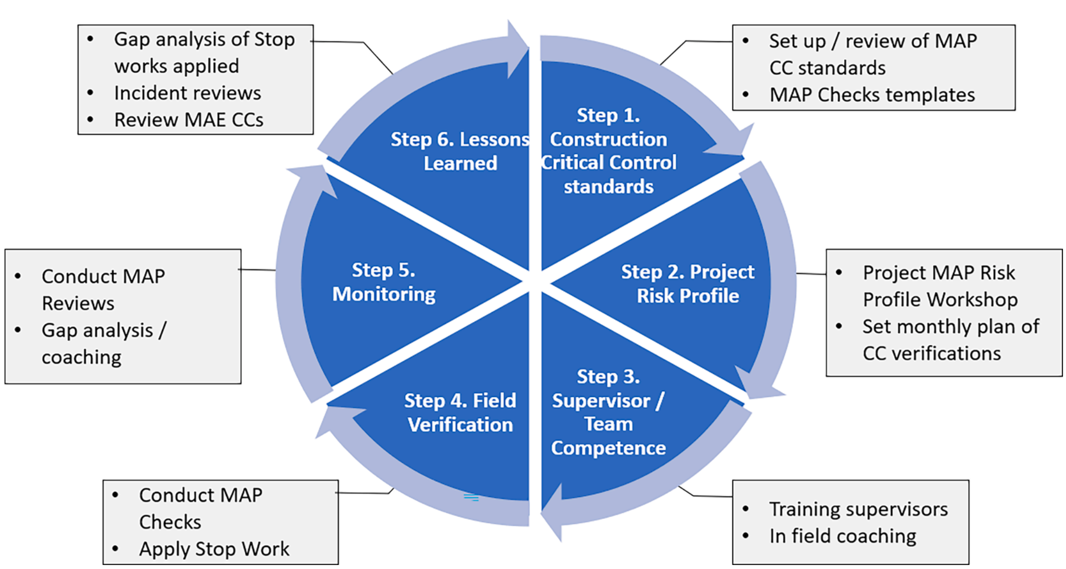

Fig. 2. Construction industry - major accident prevention model.

methodology detailed in ICMM (2015b) through a series of bow-tie risk assessment workshops averaging 4 h 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.

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 (International Association of Oil Gas Producers (OGP), 2012; Safer Together 2016) and mechanism of fatal incidents as threats (Safe Work Australia, 2018a; Chi et al. 2015). 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 panel analyzed 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 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 bow-ties 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 bow-tie 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 (Safe Work Australia 2015, Safe Work Australia, 2018a; Commission for Occupational Health and Safety (WA), 2004; Safe Work 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.

Identifying Threat / Consequence Critical Controls.

'Critical controls' were determined based on criteria adapted from Hassall et al., (2015) and International Council for Metals and Mining (ICMM), (2015b). 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.

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 panel proposed the design of the Project MAP Risk Profile (Section 3.2.3) as a method to address these limitations.

Design of MAP Verification Checklists.

The use of safety checklists provides a systematic method for application by workers and reduces errors due to oversight (Hopkins 2011; Hale and Borys 2013) or gaps in hazard recognition (Albert et al. 2020b); (Carter and Smith 2006; Bahn 2013). 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 (Loosemore and Malouf 2019; Langford et al. 2000), which is shaped by the emotional and cognitive engagement of workforce applying the safety practice (Rich, et al. 2010; Wachter and 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.

3.2.2. *Defining organisational principles for implementation of the MAP program*

A two-hour engagement workshop was held with Senior Management (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 should MAP checks 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 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.

3.2.3. *Developing the project risk Profile*

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 (Fig. 3). 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 (Fig. 3).

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

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.

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. A group consisting of subject matter 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).

3.2.4. *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 and 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).

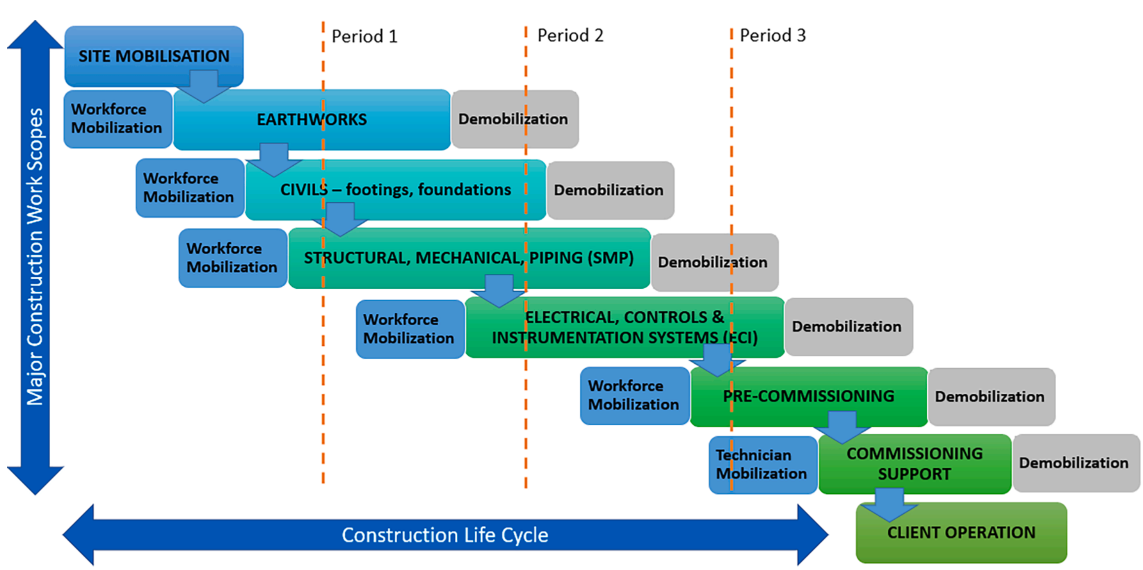

Fig. 3. Construction project life cycle – post mobilisation (Adapted from (Luo et al. 2017)).

- 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).

3.2.5. 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, 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.

3.2.6. Measuring MAP performance

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:
  - o Planned MAP checks versus actual conducted in the period (weekly)
  - o Planned MAP assurance reviews versus actual conducted in the period (weekly)
- Risk exposure: Critical controls failure rate – number of controls failed / controls applied

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 4). 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.

3.4. 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. The lead and lag variables (Table 5) 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 (Sallas and Hallowell 2016).

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 and 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 5.

The time series variables were tested for stationarity using the Kwiatkowski, 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 and Athanasopoulos 2018). Logarithmic and average mean differences transformation processes were applied to the data and retested for stationarity.

4. Results

4.1. Step 1 & 2: Defining project critical controls through the risk profile

The pilot study conducted the Risk Profile workshop to determine

Table 4
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 sub-contractors
Workhours	634,700 with 220 persons on site at peak
Duration	Total: 32 months. On site: 20 months

Table 5
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

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 (Fig. 4). 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.

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.

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 (Fig. 5). 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, Fig. 5.

"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.

4.4. Step 5: Monitoring

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

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

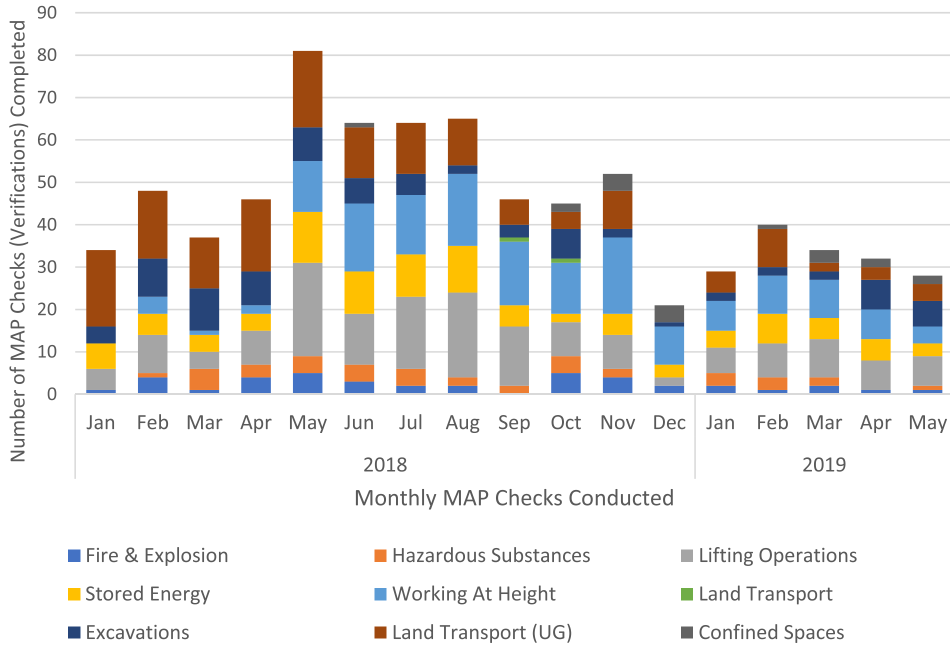

Fig. 4. MAP checks completed by MAE hazard category.

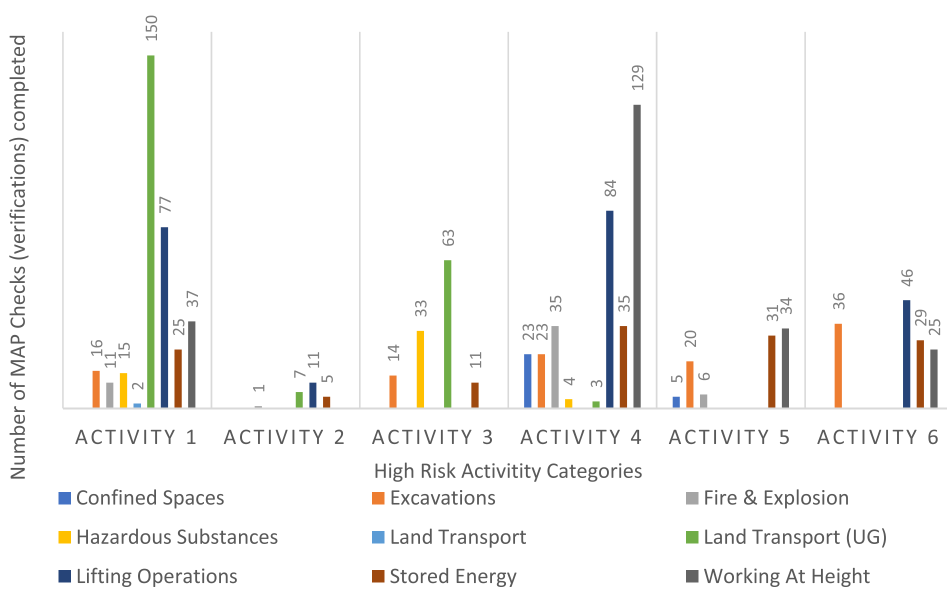

Fig. 5. MAP checks by activity for duration of case study.

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 (Fig. 6). 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.

4.5. *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

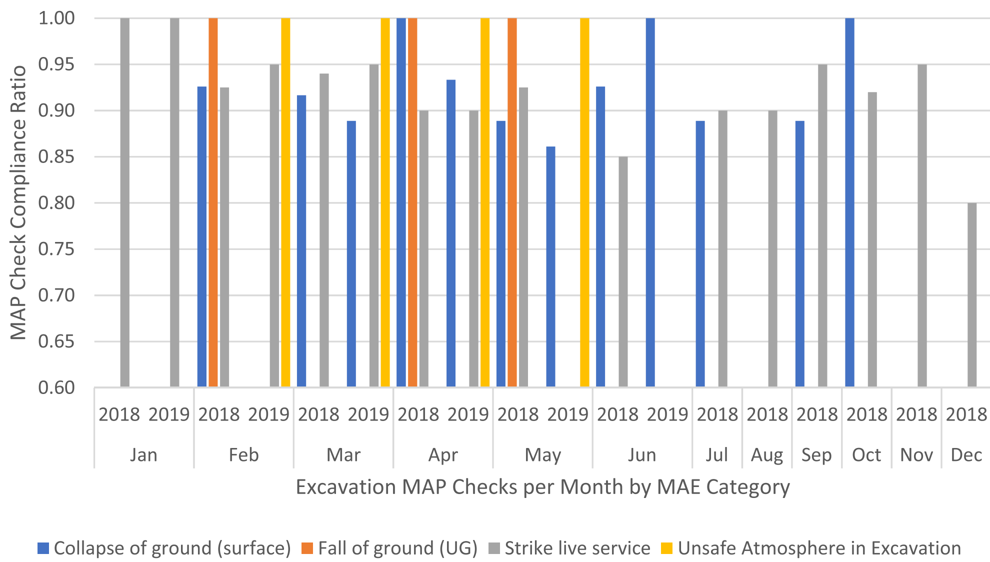

Fig. 6. Excavation activities - MAE's critical control compliance rate.

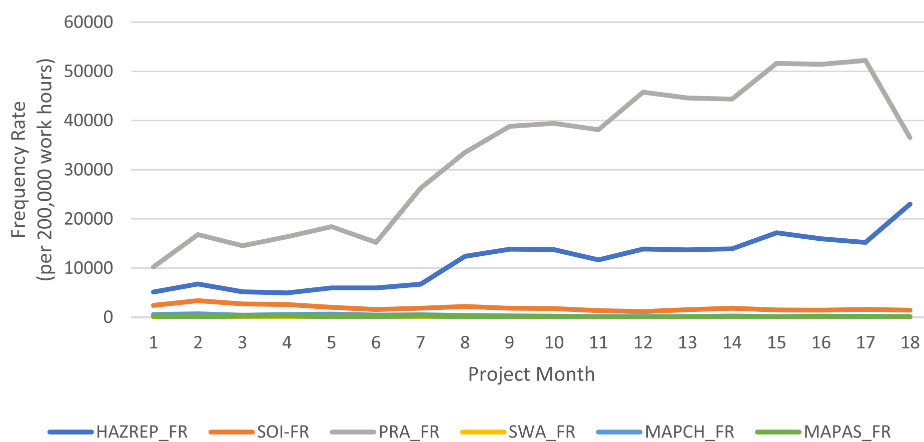

Fig. 7a. Performance trends of project leading indicators.

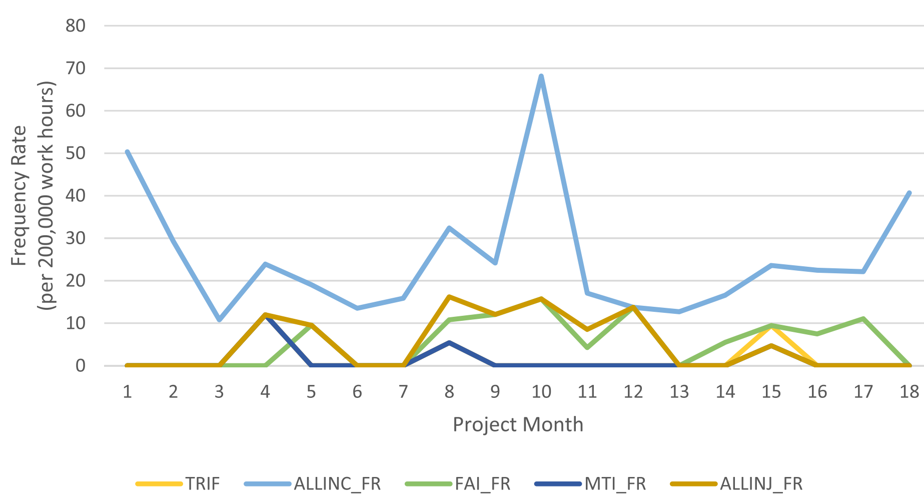

Fig. 8b. Performance trends of project lagging indicators.

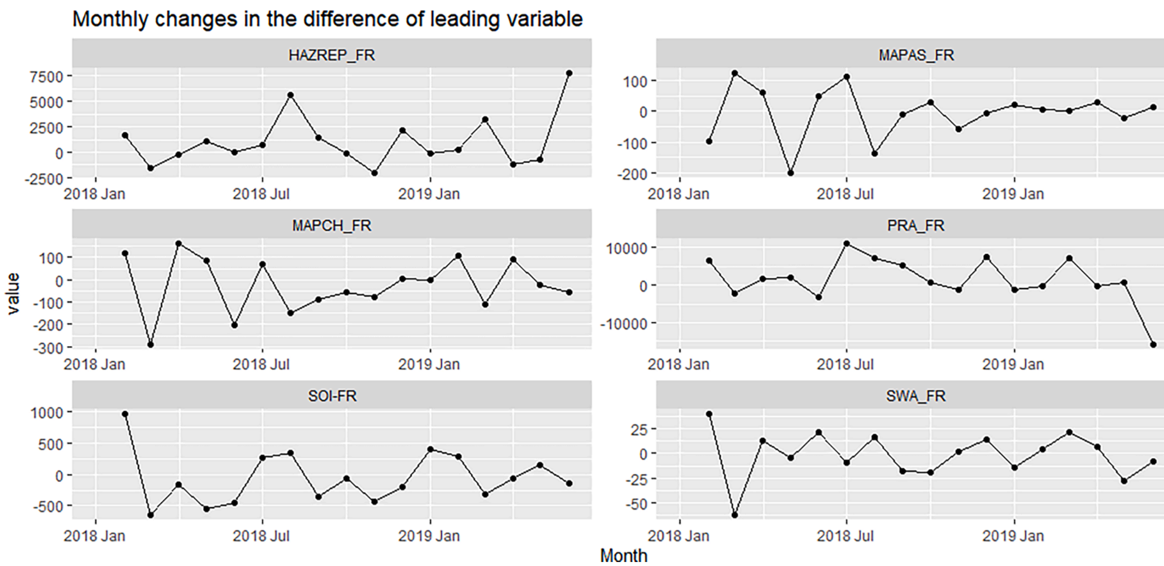

Fig. 9a. Monthly changes in the difference of each leading variable.

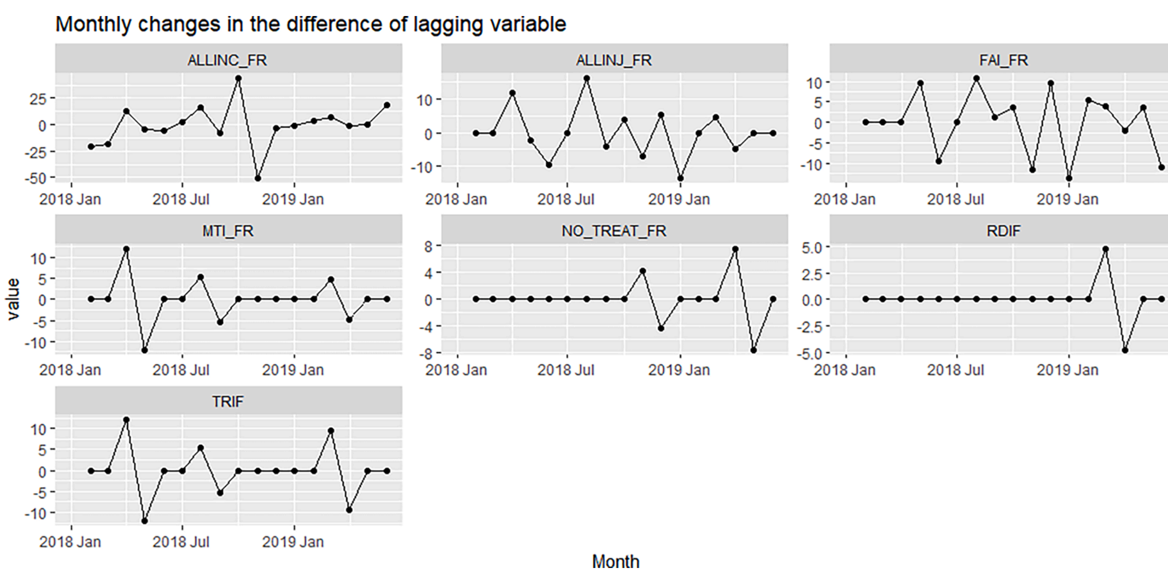

Fig. 10b. Monthly changes in the difference of each lagging variable.

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.

4.6. MAP contribution to safety – relationship analysis

Time series plots (Fig 7, Fig 8) 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.

Comparison of the difference between the monthly values for each variable (Fig 9, Fig 10) 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.

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 6). The statistical model was applied across all eleven variables defined in

Table 6
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

Table 7
Correlation matrix across performance measures.

	TRIF	ALLINC_FR	FAI_FR	MTI_FR	ALLINJ_FR	HAZREP_FR	SOI_FR	PRA_FR	SWA_FR	MAPCH_FR	MAPAS_FR
TRIF		0.004	0.003	**0.955**	0.350	0.055	0.168	0.023	0.155	0.080	0.345
ALLINC_FR	0.004		0.250	0.016	0.284	0.179	0.144	0.064	0.016	0.034	0.066
FAI_FR	0.003	0.250		0.063	**0.670**	0.409	0.401	**0.585**	0.077	0.410	**0.528**
MTI_FR	**0.955**	0.016	0.063		0.407	0.162	0.255	0.140	0.127	0.185	0.451
ALLINJ_FR	0.350	0.284	**0.670**	0.408		0.031	0.094	0.093	0.062	0.093	0.143
HAZREP_FR	0.055	0.179	0.409	0.162	0.031		**0.645**	**0.840**	0.251	**0.857**	**0.586**
SOI_FR	0.168	0.144	0.401	0.255	0.094	**0.645**		**0.713**	0.432	**0.789**	0.490
PRA_FR	0.023	0.064	**0.585**	0.140	0.093	**0.840**	**0.713**		0.207	**0.857**	**0.612**
SWA_FR	0.155	0.016	0.077	0.127	0.062	0.251	0.432	0.207		0.465	0.024
MAPCH_FR	0.080	0.034	0.410	0.185	0.093	**0.857**	**0.789**	**0.857**	0.465		0.530
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.

Table 5, with 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.

Correlation analysis (Table 7) 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.

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 Kwiatkowski, 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 kpss_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.

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.

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 min 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 (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.

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.

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 (2015b) 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 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.

6. 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 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. Acknowledgements.

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CRediT authorship contribution statement

Roberta Selleck: . **Marcus Cattani:** Writing – review & editing, Supervision, Conceptualization. **Maureen Hassall:** Writing – review & editing, Supervision, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data is confidential but may be available upon request and permission of the participating companies.

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
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

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MAE Category	MAE Scenarios
	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.
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.

Appendix D

MAP Risk Profile – Case Study Example.

Appendix E

MAP Checklist Highlighting Design Features.

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