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Determining the Effectiveness of Critical Controls in Construction Projects

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Abstract

Across the global construction industry, fatalities continue to occur from high-risk activities where the risk controls have been defined, however were unreliable. In the mining industry, Critical Control Risk Management has provided positive results in reducing major accidents, which raises the question, could the Critical Control approach reduce the fatality rate in the construction industry? This study analysed 10 years of serious and fatal incident investigation reports from four international construction companies to i) assess the reliability of their Critical Controls (CCs) and ii) assess the factors which affect the reliability of CCs. The results show the reliability of CCs, measured by implementation and effectiveness, averaged just 42%. Human performance factors including risk identification, decision-making and competency together with supervision, job planning, communication organisational factors were identified as affecting the reliability of CCs. The study used bow-tie diagrams with real event data to find the actual CC effectiveness. This gave actionable findings directly related to individual CCs enabling the participating organisation to focus resources on improving specific verification processes. The results confirm the applicability of CCs for the Major Accident Event hazards analysed and highlights further review is required of the factors which need to be considered when implementing a CC program. This paper details our methodology and results, to assist others apply CCs as a risk management tool.

Introduction

Accident prevention research has identified complex models of accident causation [1] identifying multiple factors and numerous safety controls [2, 3] to prevent incidents from recurring. However, within the construction industry serious and fatal incidents continue to result from recurring causes [4]. Construction industry fatalities result from high-risk work activities (e.g., operating heavy plant and machinery, lifting using cranes, working at height) where the interaction between human factors and the activity give 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 [5, 6].

Human actions and interventions can introduce errors through variability of hazard identification and assessment within dynamic construction environments [7, 8] with workers identifying on average only 53% of fatal hazards in the workplace [9]. In addition, human factors affect the compliance to critical controls [10], risk tolerance [11] and decision-making [12] all of which influence the efficacy of control implementation and effectiveness. Selleck & Cattani [13] 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

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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 [14]. The bow-tie method is often used to facilitate the identification of controls for an unwanted event. The bow-tie method was developed by joining fault tree and event tree (cause and consequences) surrounding an unwanted event [15]. The bow-tie 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 [15-18]. 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 [5]. However, an underlying factor is the influence of human action and organisational factors which affect the reliability of the barrier [5, 19-21].

The reliability of control barriers is influenced by organisational psychological mechanisms like confirmation-bias, normalisation of warnings, consensus mode decision making and group think which occurs within work teams and across organisations [19]. Reliability of barriers are also affected by human factors (e.g., competence) and human actions in the detection of threats or changes in the barrier functionality, diagnose what action is required and then act [20, 22]. Construction accident causation analysis [21] identified worker actions are heavily influenced by supervision and risk management through the planning and risk control at different levels across the organisation, emphasising the need for a holistic approach to managing fatal risks and use of barriers.

The safety barrier methodology has been applied in the mining industry through Critical Control Risk Management (CCRM). CCRM is focussed on risk treatment by specifying and verifying implementation and effectiveness of critical controls (barriers) in a model addressing organisational and inherent human factors using the principals of High Reliability Organisations [23, 24]. An adaptation of CCRM was piloted on an Australian construction project [25] however further understanding of Critical Control reliability was identified.

For construction organisations to invest in the development and implementation of a safety barrier approach like 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?) and how will the reliability of the controls be measured? Hassall et. al. [26] in a study on selection and optimisation of risk controls identified control performance is the product of *reliability* of 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 1). When considered in the context of construction fatalities, regulators across multiple jurisdictions reported between 85% to 90% of fatalities are events occurring from common high-risk activities where controls which prevent the incident are defined within organisation safety management systems, but still result in single to two person fatalities [4, 27, 28]. Based on the construction industry fatality events continue to be caused from the same high-risk activities and hazards, construction fatalities are the result of failures in control *reliability* and less from novel or abnormal situations where are not defined or are *inadequate* in preventing the novel events.

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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 minimise exposure to a threat of mitigate consequence severity [26]. Measuring effectiveness of risk controls can apply quantitative [6, 29], semi-quantitative [5, 21, 30, 31] and qualitative processes [26] 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 number of occasions the control was challenged [31], i.e.:

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

However, the performance of risk controls when being considered within a safety barrier program by a construction organisation, the implementation and / or availability of the control needs to be assessed together with the adequacy of the control [26].

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 [32]. 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 [33]. 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 [21].

This study explores critical control effectiveness through analysis of historical fatality and serious event investigations across four construction organisations to understand historical performance of critical controls. The study aims to:

i. Evaluate if known critical controls as documented within existing high risk activity performance standards and organisational specifications address known construction safety risks; and

ii. Identify performance factors which affect the reliability of critical controls to assist in the implementation of safety barrier programs within construction organisations.

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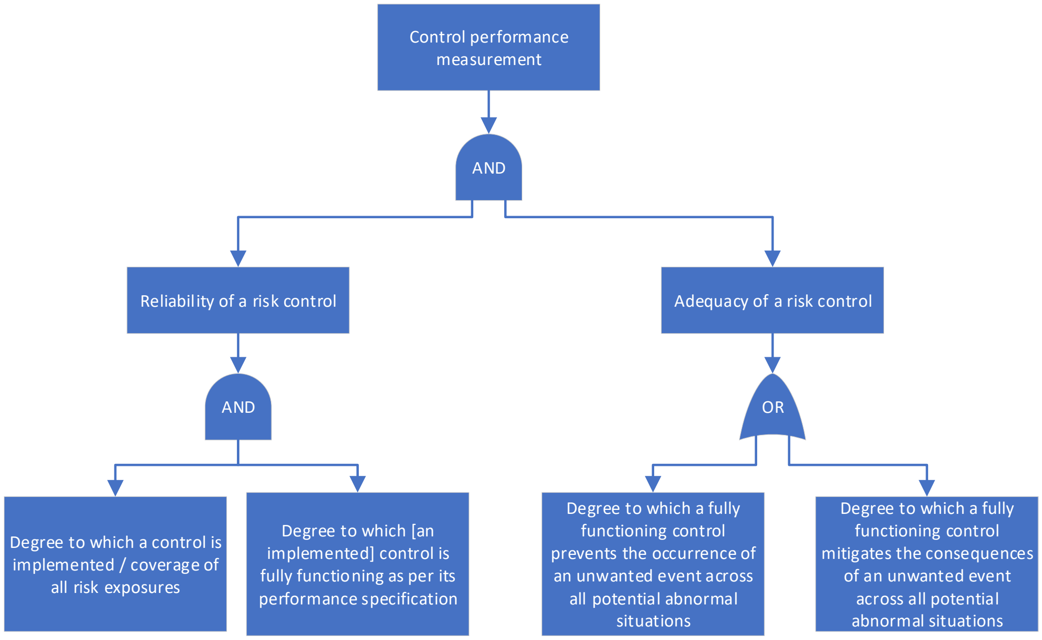
Figure 1: Measuring Control Performance[1]



Methodology

Incident investigation reports from serious and fatal incidents which occurred over a 10 year period (2010 to 2020) from four construction companies based in Australia, South Africa, Canada, and USA were collated 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') hazard, applicable controls, and causal factors. If the investigation report details were insufficient it 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' experience) including competence in incident investigation, which enabled the analysis of the incident investigation reports. The HSE professionals were assigned a MAE category and assessed all incident events from all four companies applicable to the category. 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. A workshop was conducted following the completion of all analysis where the outcomes were reviewed from each event and focus group members challenging the assessment rating until consensus was reached.

Critical Control Categorisation 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 2 event classification method). Each applicable CC was assessed to:

i. determine if CC had been implemented (yes / no), and,

[1] Visual representation of Control Performance Measurement as derived from Hassall et. al. 2015 [27]

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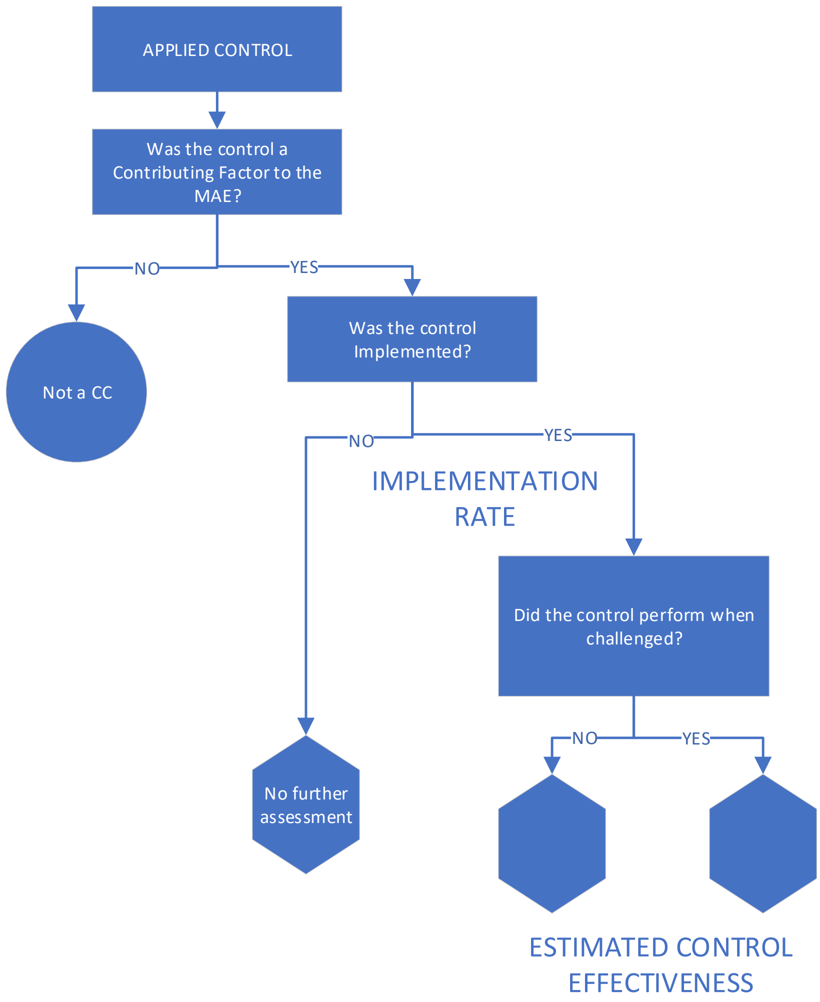
ii. had the CC performed as required, i.e., was it adequate to prevent events using a rating of good, needs improvement or inadequate.

The assessment also identified gaps in the MAP model of CCs and noted improvements required in existing CC specifications. The assessment details were recorded in an online Microsoft Form® database stored in a secure site.

Figure 2: Process for Assessing Control Effectiveness



Calculating Control Effectiveness

Two values were calculated from the CC assessment and converted into percentage values:

Implementation ratio = $\dfrac{\textit{number of times the CC was implemented} \times 100}{\textit{Number of occasions the control was challenged}}$

CC effectiveness = $\dfrac{\textit{number of times the CC was rated adequate (i.e., good)}^{2} \times 100}{\textit{Number of occasions the control was implemented}}$

Critical control effectiveness percentages were mapped against the MAE hazard Bow-tie. The mapping of the result from applying real data calculations for individual critical control effectiveness

[2] Derived from Hassall et. al. 2015 [27]

to the bowtie is a novel extension of bow-tie analysis that visually highlighted control gaps, and provided feedback on the performance of control pathways and improvements required in the verification processes.

Failure Rate by CC Hierarchy of Control Type

CC effectiveness ratings were compared by hierarchy of control type of CC for each MAE category to review the effectiveness of CC type.

Observations on critical control gaps and improvements were collated and provided to the participating organisations.

Results

A total of 186 serious and fatal event investigation reports were 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 1), 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 1: Number of L4/L5 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 representing 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 2).

Table 2: Data Analysed by MAE Category

High Risk Activity	Number of Events Analysed	% 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

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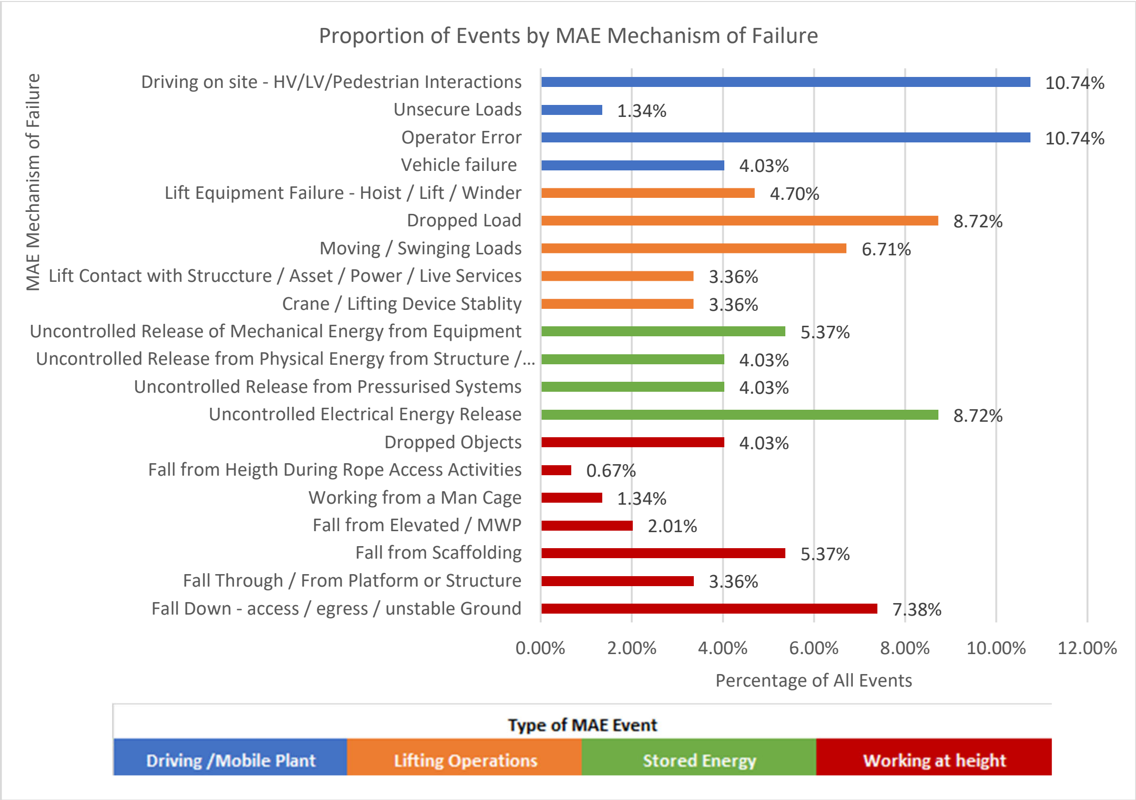
The most frequent MAE Hazards included 'driving interactions and operator error', 'lifting operations - dropped load', 'uncontrolled electrical energy release' and 'falls due to access / egress from plant or unstable ground' (Figure 3).

Figure 3: Proportion of Events by MAE Hazard



Critical Control Performance Measures

Implementation of CC across all MAE Categories was analysed at an average 57% with a standard deviation of +/- 35.5%, indicating considerable variation in the implementation of CCs. Effectiveness of the CC when implemented averaged 41.2% with a standard deviation of +/- 38.6% which means of the CCs implemented were on average to be effective only 41% of the time (Figure 4).

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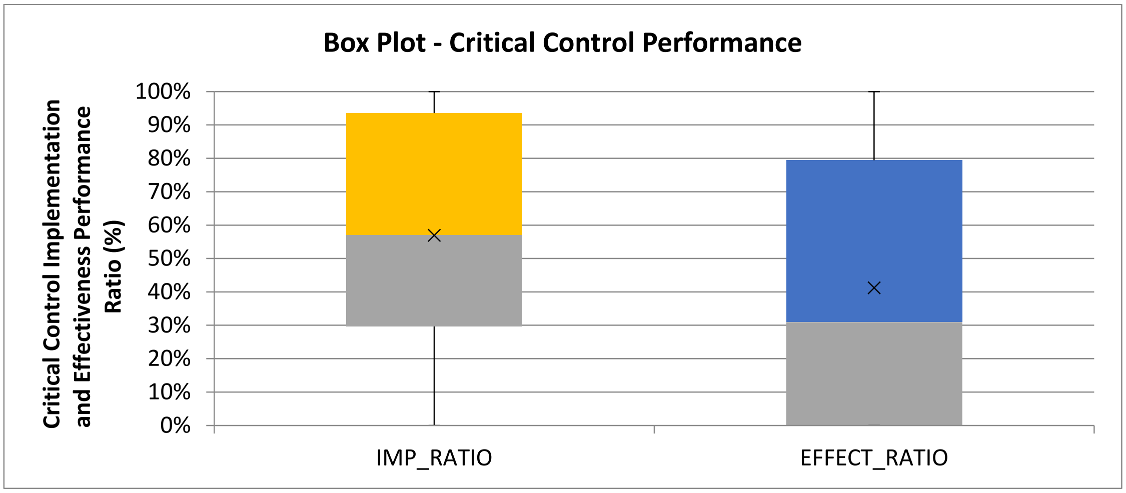
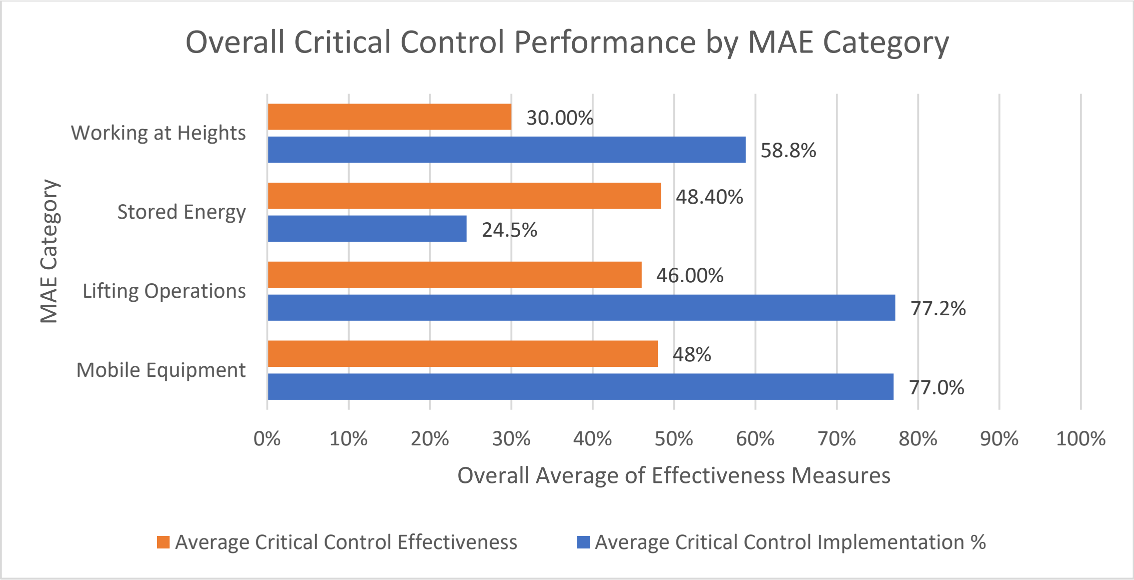
Figure 4: Statistical Comparison of Control Performance Measures



Comparison of CC performance measures (implementation, effectiveness) by MAE Category (Figure 5) identified Mobile Equipment (77%) and Lifting Operations (77.2%) have 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 category.

Figure 5: Overall Critical Control Performance by MAE Category



Comparison of CC by the hierarchy of control types identified Engineering controls had the strongest rate of implementation (73.3%) with the other control types ranging between 46.7% to 53.6%. Engineering and administrative procedural CCs had similar effectiveness ratings at 47.6% and 45.5% with the rest performing between 34.5% and 35.9%.

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 type across the MAE categories the Stored Energy CCs have a consistently lower rate of implementation yet deliver a higher rate of effectiveness (Figure 6).

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. 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 pressurised systems to be within design and test limits).

Implementation of administrative type controls (e.g., competency) in the Mobile Plant & Equipment was 97.0% and Lifting Operations 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 & Equipment only 62.5% of the time.

A total of 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 CCs could also be contributory factors in the MAE incidents.

Lifting Operations

Lifting Operations MAE Hazards had the strongest level of implementation of CCs with 15 of the 32 CCs having a greater than 80% implementation rate with an overall average of 77.2% (Figure 7).

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 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 were available to complete lifts.

The effectiveness of lifting operation CCs has an overall average of 46% with five CC being 100% effective with six CC being 0% effective (Figure 7). 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 have compromised CC prevention pathways with two or more CC effectiveness being compromised by having a 50% or lower failure rate when the control is implemented (Figure 9).

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 8) marginally behind Lifting Operations (Figure 5).

CCs which managed *Operator Error* Hazards had strong implementation average at 85% with the two lower implementation rates (67%) associated with *operating within vehicles specifications* and *driving off road with roll-over protection.* The weakest level of CC implementation (47%) was *heavy vehicles or plant operators not responding to alarms.*

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The CC implementation and effectiveness ratings for 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 CC associated with emergency response drills being 100% effective and two CC (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 8).

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- 33.3% (Figure 8).

Three of the four Mobile Plant & Equipment MAE hazards have compromised CC prevention pathways with two or more CC effectiveness being compromised by having a 50% or lower failure rate when the control is implemented.

Stored Energy

A total of 36 major accident events were analysed 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 issuing of permits without full validation ("we needed to get the permit issued as work had already been held up") or isolation placed on wrong system ("crew were waiting to start").

An average 4.4% of events analysed identified the critical controls were not implemented as the primary failure. Failure to apply isolations and / or exclusion zones were identified as a common failure across all Stored Energy MAEs (Figure 9).

Working at Height

A total of 36 major accident events were analysed for associated with working at height. 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 operations assessments.

An average of 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, inadequate job planning were identified as a common failure across all Working at Height MAE's (Figure10).

Table 3: Identified Improvements and Gaps in Critical Controls by MAE Category

	Identified CC Performance Improvements	Identified Gaps in CC Specifications
Lifting	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)	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.

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	Identified CC Performance Improvements	Identified Gaps in CC Specifications
	Communication between crane operators and riggers Competency of crane operators / riggers used for the task being performed	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-energised 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

Figure 6: Hierarchy of Control Performance by MAE Category

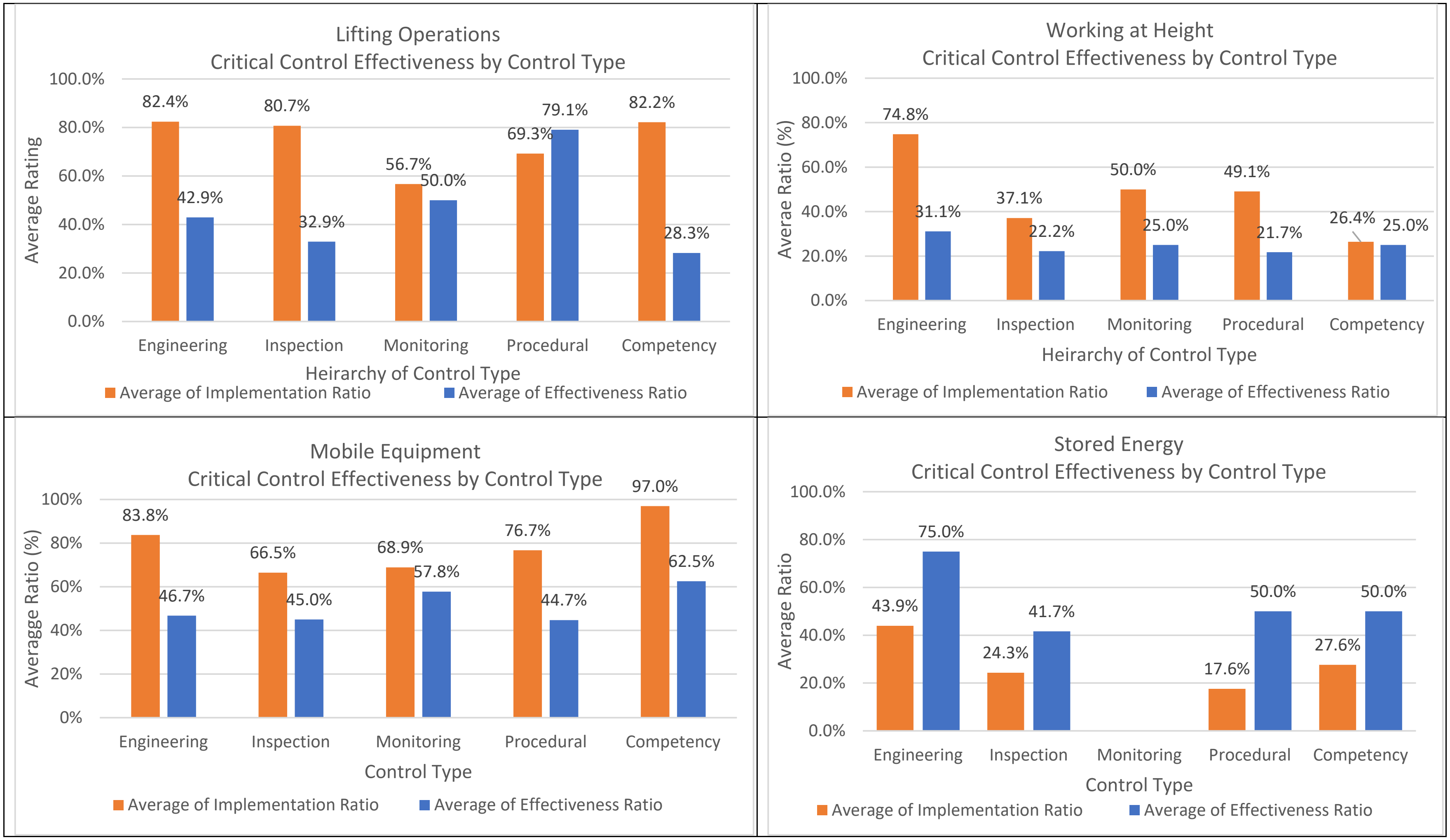

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Figure 7: Lifting Operations – Critical Control Effectiveness

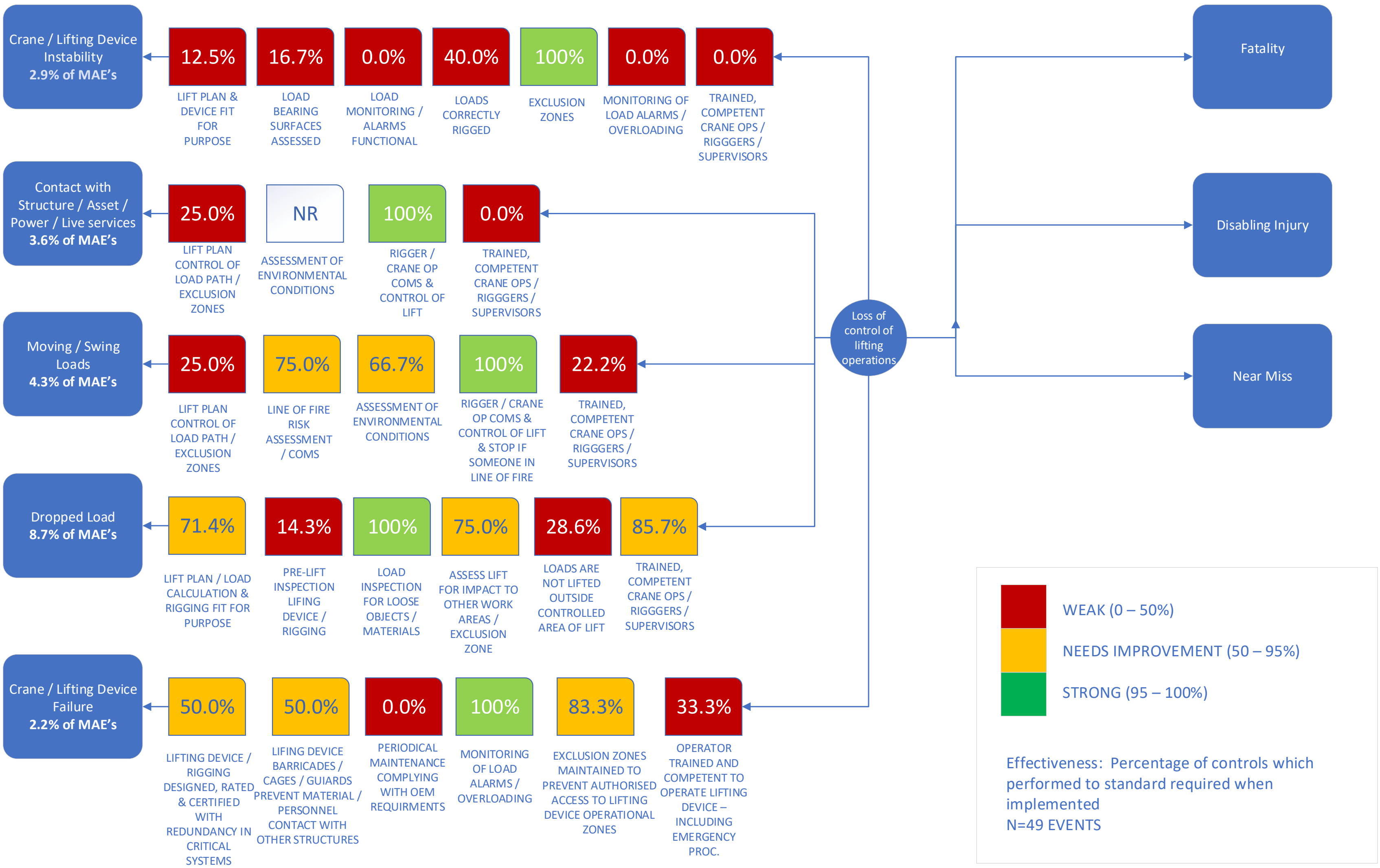

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Figure 8: Mobile Plant & Equipment – Critical Control Reliability

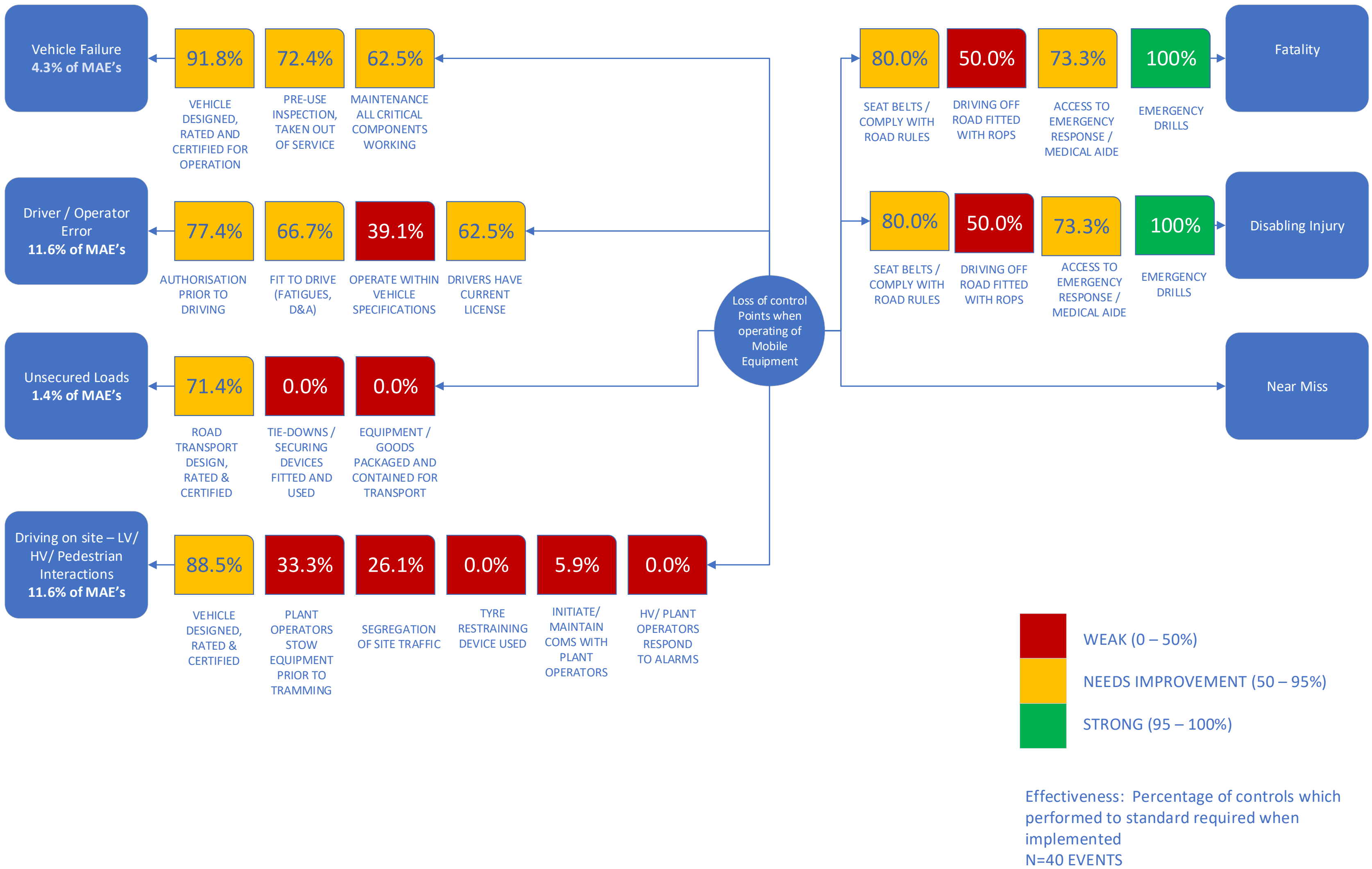

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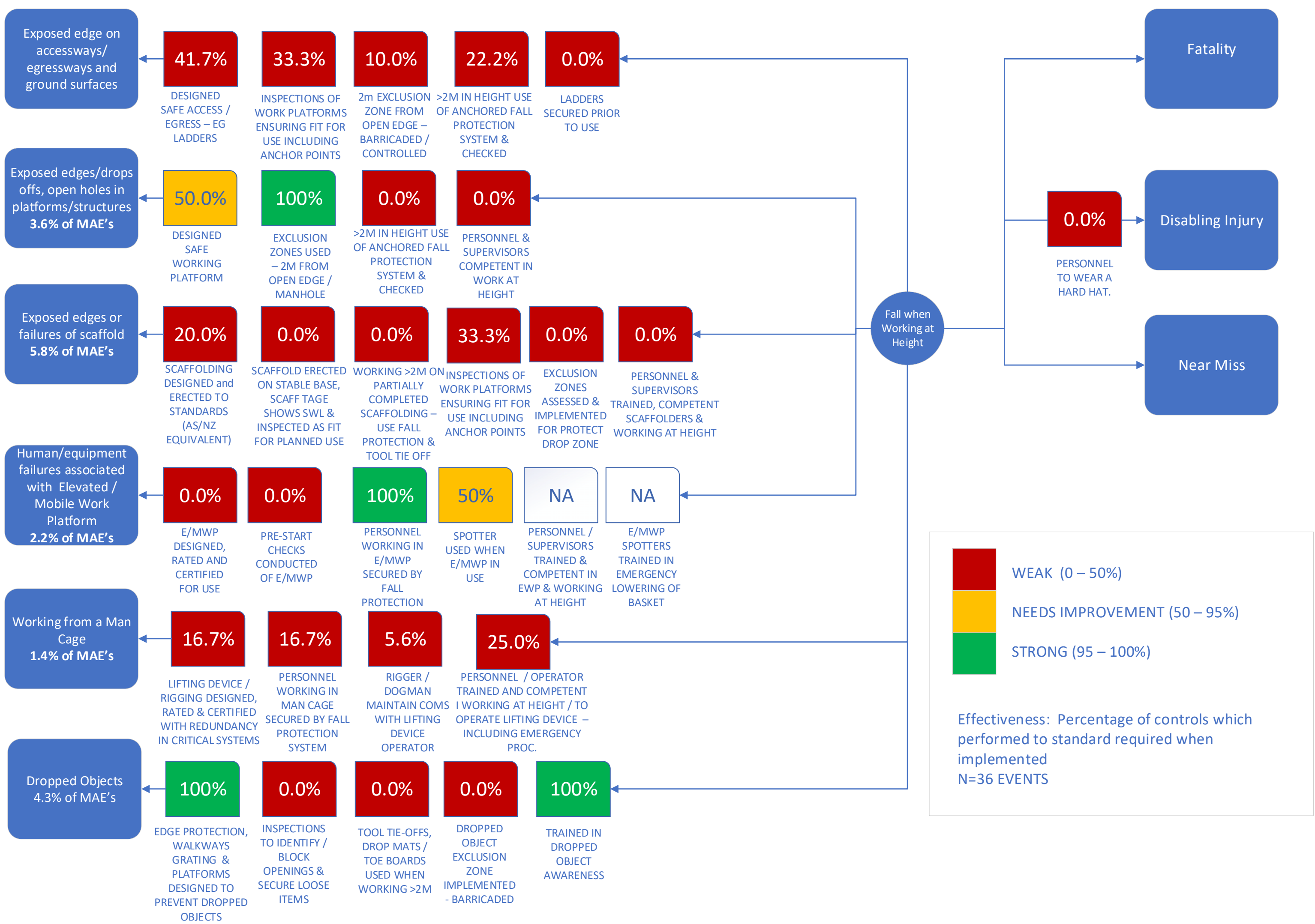
Figure 9: Stored Energy – Critical Control Reliability

Figure 10: Working at Height – Critical Control Relability



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Discussion

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

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 organisations 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 had been reviewed by internal construction and safety professionals however no definitive review against major incident events had been conducted and the organisations continued to experience significant incidents post the implementation of the CC verification process. The study confirmed all 119 CCs being applied by the organisations were valid with a further 7 CCs being recommended. The additional 7 CCs were recommended for MAE hazards where the threat had not been identified (e.g., loading / unloading from haulage vehicles) or there were gaps in the control specification.

The type of CCs 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 of procedural, administrative and training associated with the 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 not effective in preventing the release of hazardous energies. The CCs rated 'weak' (<50% effectiveness) were considered unreliable as they failed more times than the CC was effective. The ratings (weak, needs improvement, strong) highlight where construction organisations need to prioritise action to improve implementation and the quality of the CC being considered. The ratings also inform where CC verification programs need to prioritise organisational effort to validate CC effectiveness. In the case of Working at Height events (Figure 15) three of the control pathways (i.e., falling down, working from scaffolding, working from man cage) identified each Critical Controls as being weakly implemented or not effective. For example, Falling from Scaffold identified three Critical Controls were implemented: design of the scaffold, inspections on standard of scaffold being built, and scaffold foundation inspections, however only the design Critical Control was assessed as being only 20% effective. Similarly, when assessed in the overall context of the study, the Critical Controls which had a high reliance on human performance (e.g., operating plant and vehicles, inspections, maintaining exclusion zones) had a higher rate of failure (Figure 6) which aligns to hierarchy of control principles [21]. Human performance factors which affect either the implementation or quality of the Critical Control, including decisions to intervene when a Critical Control is not performing as specified, need further consideration.

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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 so arguably should have the best Critical Control performance. Comparing hierarchy of Critical Control type across the MAE categories the Stored Energy Critical Controls have a consistently lower rate of implementation yet deliver a higher rate of effectiveness (Figure 7). All four Stored Energy MAE hazards had a minimum of two Critical Controls assessed as having a 100% effectiveness rating (Figure 13). These Critical Controls were engineering and inspection type controls and whilst overall more effective in the absence of other Critical Controls (i.e., those relying on human performance) the incident events still occurred.

Human Performance Factors

The eighteen (18) recommendations on improving implementation of CCs (Table 3) provide insight into the type of human performance factors affecting CC implementation and effectiveness.

The *failure to recognise hazards* was identified across multiple incidents particularly when working in and around mobile plant where personnel were working in blind spots (reversing plant), in the line of fire (swinging loads), during loading and unloading of equipment and materials and working above others. Failure to recognise 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 [22]. The analysis identified multiple MAE incidents where an erosion of 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 normalised through repetition or familiarity (e.g., continuously working around mobile plant, working on scaffolding) workers are de-sensitised to the risk exposure and become 'complacent' [19]. 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.

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 3). 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 which have not been applied to the standard required, is more complex. Worker competency is linked to their ability to either adapt the standards to the diversity of the reality being experienced, or decide to stop work and seek clarification from supervision and management [34]. In both options the CC system must provide direction on how to manage deviations [34] as major incident investigation studies have identified deviations from controls [rules / barriers] are inevitable in high-risk industries, including construction [11, 35-37]. 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 [12].

Critical Control implementation was also affected by 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 3). Individual risk-based decision making in the application of CCs [rules and / or barriers] is influenced by a complex interface of personal, work team, organisational and psychological factors [12, 19, 34]. Further investigation into individual's decision making and the impact on CC implementation and effectiveness would benefit construction organisations looking to improve CC reliability.

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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 [38-40] both factors were identified as being inadequate and contributed to the events analysed. Winge [41] identified immediate supervision was 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 [42]. The delays result in perceived production pressure to 'get the job done' means work teams and supervisors become focused on task completion and fail to recognise changes in the work environment or hazards [7] or continue to work in the absence of effective safety supervision [41]. Where production pressure adversely affects safety performance through compression of work schedules [39, 42, 43] or rework from poor quality of execution [44] this also impacts performance of control barriers which rely on human action [5].

By focussing on CCs construction organisations become more resilient as risk assessment is integrated into all systems, the verification process identifies and eliminates problems before they occur [45]. The study used historical incident data where the risk maturity of the participant organisations were reactive or at best risk compliant [45]. As organisations further develop and improve CC management the verification audits provide additional data to model safety performance which shifts management focus from incidents (lagging measure) to proactive risk management and provides opportunities for predicting risks.

Limitations

The calculated control effectiveness 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 was 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.

Conclusion

The study confirmed the controls identified for the four MAE hazard categories (Lifting Operations, Mobile Plant & Equipment, Stored Energy, Working at Heights) were valid as Critical Controls in the control of energies associated with high-risk construction activities. The effectiveness of the CCs however deteriorated due to not being implemented or were not applied to the standard required.

Human performance factors were identified as contributing to inadequate implementation and sub-standard quality of the CCs including hazard identification, personal decision making and competency. Worker competency was attributed to inexperience or lack of training, or the competency to assess, adapt and apply CC to the work activity being conducted. The individual needing to be adaptive in the application of the CC to the situation not just following the 'rule' and stopping work when the 'rule' is found not to apply to the situation. In the absence of an organisation 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 organisation improving worker competency to assess and apply CCs across all high-risk tasks and competency of supervisors to verify CC implementation and effectiveness for the given task being undertaken.

Organisational factors also contributed to effectiveness of CCs, whereby supervisors reacting to construction schedule, changes in material, resourcing or other organisational pressures failed to undertake job planning, risk assessments or communicating the risks and CCs to the work team.

The study benefits construction organisations 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. Organisational 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.

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